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Preface

We are very pleased to hold the 10th International Conference on Construction Applications of Virtual Reality (CONVR2010). The CONVR started in 2000 in the United Kingdom, and the following conferences have been held in Europe, the United States, Southeast Asia and Oceania. This 10th anniversary conference is the first conference in East Asia, and is hosted by Miyagi University, jointly with Osaka University, Chuo University and Teesside University.

In the decade after the first CONVR, Information and Communication Technology has continued to advance rapidly, and in the area of architecture and civil engineering, utilizing computer-based visualization has become quite natural. Furthermore, research and development have been done extensively in laboratories in virtual reality, which is a more advanced technology in visualization, and augmented reality which aims to overlay the virtual image on the real world and augment the real world. The importance of Building Information Models (BIM) has come to be realized and four dimensional CAD systems have been developed for practical uses. The objective of this conference is to report and disseminate ideas, progress, and products of innovative international research activities in this exciting field and formulate strategies for future direction.

In response to our Call for Papers, we received 78 abstracts, of which 50 papers were finally accepted by the International Scientific Committee after two rounds of rigorous reviews (the first round was double-blind for abstract review and the second was single-blind for full paper). The proceedings include these 50 accepted papers with three keynote papers and one invited paper.

We hope that this 10th anniversary conference and the publication of the proceedings will contribute to the development of information technology in architecture and civil engineering in the future.

Koji Makanae (Chair, Miyagi University)
Nobuyoshi Yabuki (Co-Chair, Osaka University)
Kazuo Kashiyama (Co-Chair, Chuo University)

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KEYNOTE PAPERS

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ABSTRACT: *Civil and Architectural Engineering have had a long and successful history in adopting computing technologies, from computer graphics, CAD, engineering analyses, virtual simulations, to project management. As computer hardware, software and network technologies continue to advance, there are many new opportunities that can take advantage of the information and communication technologies in engineering practice. Recent developments in information modeling and web services will have significant impacts in engineering design and management. As the industry embraces building information modeling standards, engineering software interoperability and integration can now become a reality. As the concept of Software as a Service (SaaS) and cloud computing model become popular, web-based software services and business models are emerging. This note discusses a web-enabled model-based CAD environment that supports the integration of CAD, virtual simulations and enterprise integration, from design to procurement and supply chain management.*

KEYWORDS*: Building Information Modeling (BIM), computer-aided design (CAD), web services, simulation, online procurement,*

1. TECHNOLOGY TREND

As demands for functionalities increase, computer programs have become ever more sophisticated and complex. Software development has shifted from focusing on programming in the early days of computing towards focusing on software integration over the past couple decades. The desire for integrated solution in civil and architectural engineering is of no exception. As domain specific tools (such as finite element analysis, CAD, project management, etc.) began to mature, the industry has been demanding for information sharing among engineering tools (Eastman 1999). Data exchange standards have evolved from graphic and geometric entities, such as IGES (1983) to product models, such as STEPS (ISO 1991). As standards and technology for product and parametric models matured, the industry began to push for integration and interoperability to extend the capabilities of individual application to support project-wide activities, from planning, design construction to business transactions. In the civil and architectural engineering industry, the development of industry foundation classes (IFC 1997) has now led to the establishment of building information modeling (NBIM 2007) that includes the description of a facility and its product components as well as the process and project information. Although the concept of building information modeling is not new, the recent advancement in computer hardware and software technology has made the practical deployment of BIM a reality (Eastman et.al. 2008).

In parallel to the development in information modeling and management, the tremendous advancements in network and communication technologies have revolutionized our way of life. Network computing, especially with the emergence of the Internet, has allowed software services to be distributed on multiple locations. As communication protocols evolved from low level specifications, such as TCP/IP and RPC (Birrell and Nelson 1984), to the high level object-oriented schemes, such as COBRA (Pope 1998), SOAP (W3C 2000), Java JMI (Pitt and McNiff 2001), implementation of distributed services has been greatly facilitated. The computing environment has been transformed from stand-alone desktop applications to an interconnected web of autonomous services accessible inside and outside the boundary of an organization. A web service can be described generally as a specific function that is delivered over the internet to perform a service or to provide a specific information. Web-based information standards, such as XML (Young 2001), RDF (Brickley and Guha 1998), and OWL (Dean et.al. 2002), and web-based description languages, such as WSDL (W3C 2004) and BPEL4WS (Andrews et.al. 2003) have been developed to facilitate the description, reuse and integration of web services. The web service model has become a favorite approach for integrating software applications and extending the functionalities of an application by making it interoperable with other services. An engineering simulation can now involve a number of geographically distributed software applications. Online information can be dynamically integrated with an application. The Internet infrastructure can be leveraged to support interoperation between applications and collaboration between organizations.

2. WEB-ENABLED MODEL-BASED CAD ENVIRONMENT

Computer Aided Design (CAD), since its inception, has been widely used in facility design and construction. A web-enabled CAD environment could facilitate collaboration and enhance communication between designers and other stakeholders. As the Internet becomes ubiquitously accessible, a web-enabled CAD system can be extended to interact with online information and to integrate web services within the CAD application. As BIM standards continue to enrich the description of a facility, the information embedded in the CAD model can be used not only for design but also support design analysis, project management and other functions. The National Building Information Modeling Standard defines a BIM as "a computable representation of all the physical and functional characteristics of a building and its related project/lifecycle information" for the building owner/operator to use and maintain throughout the lifecycle of a building (NBIM 2007). A model-based CAD environment refers to an information-rich CAD platform that embraces the BIM concept and includes not only the geometry information of a CAD object but also the information that supports the activities involving the objects and their relationships with the other objects (Cheng et.al. 2010). By enabling a model-based CAD to interact with the web environment, users can query, incorporate and integrate online information and/or services within the CAD systems, therefore extending the scopes and functionalities of the CAD system.

Plug-in software can be built to render a CAD tool web-enabled. One example is the plug-in software, SpecifiCAD (see http://www.cadalytic.com), that can dynamically match user-defined building product content with online data such as the Google 3D Warehouse and other vendors. As illustrated in Figure 1, when the user clicks on a component object (say, a window in the Sketchup model), the tool displays the pre-defined object attributes, such as the product ID, supplier name, etc.. When the user switches to the catalogue module, the tool searches the online catalogues and displays similar products from partnering suppliers. The user can interactively replace the CAD component object with a selected product displayed on the search result page.

By capturing the information about the component objects, the model-based CAD application can be linked to simulation tools for performance analysis. Figure 2 shows an example of linking the Sketchup tool with the Integrated Environmental Solutions software (see http://www.iesve.com/) for energy and carbon emission analysis. Different design configurations, constructed using different online products, can be evaluated and compared (see Figure 3). With the building information stored in the database and linked to the web-enabled model-based CAD environment, project management and business transactions (such as procurement, scheduling and supply chain) can be integrated directly with a CAD application tool (Cheng 2009).

3. DISCUSSION

With the maturation of CAD and information modeling standards and Internet technologies, the vision of an Internet-based, or a web-enabled, CAD environment (Han et.al 1998, 1999) can now be fully realized. As the concept of Software as a Service (*SaaS*) and cloud computing become popular, web-based software services and business models will continue to emerge (Mell and Grance 2009, Kumar and Cheng 2010). This note discussed some of the potential benefits for a web-enabled model-based CAD environment that takes full advantage of the recent developments in building information modeling and web service technologies.

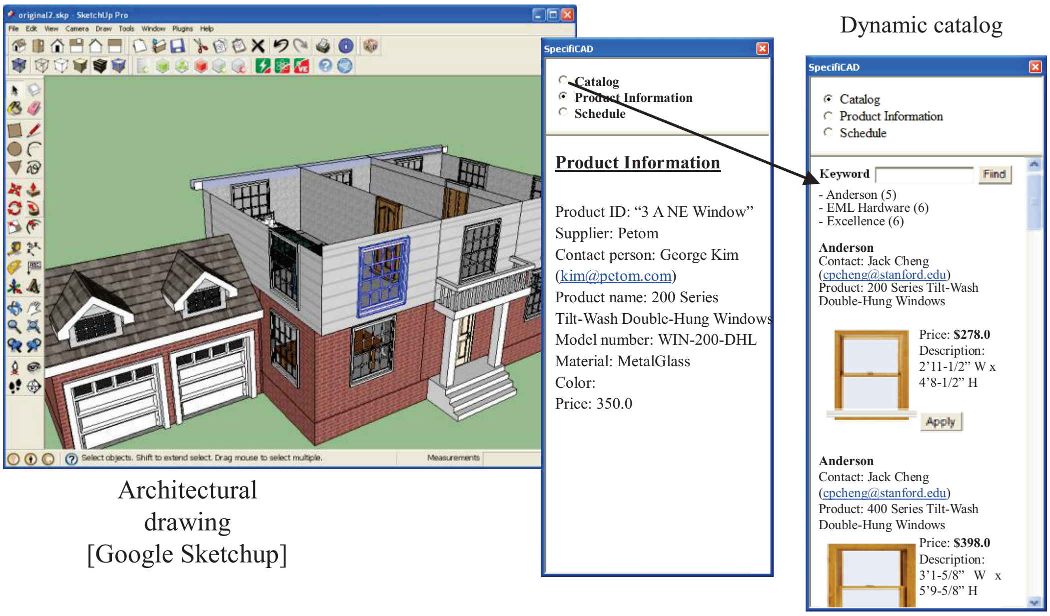

Figure 1: Web-enabled interactive tool in Google Sketchup leveraging the technology of SpecifiCAD

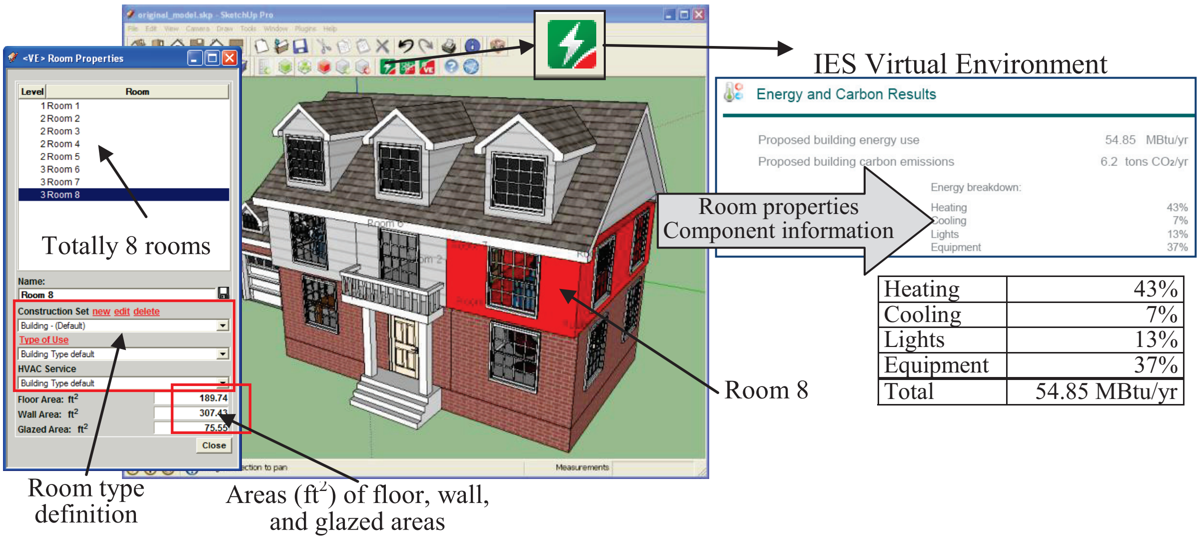

Figure 2: Energy and carbon emission analysis of a building


(a) Original model


(b) Double glazed windows replaced with triple glazed ones


(c) Replaced with larger windows


(d) Windows on the sides and at the back are removed

Energy	(a)		(b)		(c)		(d)	
Heating	23.6	43%	23.3	46%	23.9	41%	23.1	44%
Cooling	3.8	7%	1.6	3%	5.8	10%	2.1	4%
Lights	7.1	13%	7.3	14%	7.0	12%	7.8	15%
Equipment	20.3	37%	18.6	37%	21.6	37%	19.4	37%
Total (MBtu/yr)	$\boxed{54.8}$	100%	$\boxed{50.8}$	100%	58.3	100%	52.4	100%

Figure 3: Evaluation and comparison of different architectural design alternatives in terms of energy use

4. ACKNOWLEDGMENT

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Building Information Modelling: Scope for Innovation in the AEC Industry

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Abstract: *Building Information Modelling (BIM) has a key focus on collaborative working practices and technological innovations, which support the consistent and coordinated flow of accurate information across the lifecycle of a building project. Visualisation of BIM through 3D and Virtual Reality representation is vital to drive maximum value of BIM at every stage of the construction processes. The use of 3D/Visualisation parametric modelling tools is the foundation of the BIM framework, whereby building elements are represented in an intelligent digital environment as they are assigned with graphical and data driven attributes. Information from this primary phase can then be interrogated using environmental analysis, clash avoidance (visual/systematic), construction visualisation through 5D modelling, costing and facilities management systems. The interoperability of information across such systems has supported acknowledgement within industry that they are fundamental constituents of a truly integrated BIM approach. Furthermore the link between BIM and sustainability is becoming a growing trend; however there have been limited initiatives in this area which explore the methodologies for effectively implementing a viable system framework. This study will provide an overview of the UK industry status in respect to the adoption of BIM, whilst exploring the scope to exploit BIM workstreams and support innovation in the AEC industry. The paper also identifies current government and professional bodies in the UK.*

1. Introduction

Building Information Modelling (BIM) is growing at a phenomenal rate as organisations in the AEC industry understand the evident benefits in respect to enhancing efficiency throughout the lifecycle, Building Smart Alliance (2009)

The various BIM definitions amongst practitioners include descriptions relating to knowledge databases (Sah and Cory, 2009), 3D modelling technologies and multidisciplinary collaboration (Gerber and Rice, 2010). The key emphasis of BIM has been on interoperability and visualisation, whereby consistent and accurate information can be communicated across the lifecycle process,. Eastman, C. et al. (2008). Industry Foundations Classes (IFC), a file format developed by the International Alliance for Interoperability (IAI), remains a popular concept in supporting the exchange and use of data across technological platforms. Although shortfalls have been highlighted by various individuals and organisations in respect to implications of IFC use on information technology systems (Pazlar and Turk, 2007), the IAI continues to improve the IFC framework. Therefore the possibilities associated with the application and use of a single file format across a global scale, is a goal in proximity of realisation.

Autodesk Revit, Graphicsoft ArchiCAD and Bentley Microstation are amongst the top BIM solutions currently being utilised by industry professionals. The functionalities and attributes associated with these technologies range from 3D modelling, scheduling, reporting and the creation of construction drawings. Furthermore parametric design and intelligent processing are the core constituents of these technologies which differentiate them from competitors. It is important to emphasise that the capabilities of the three technologies are highly geared towards supporting the design process, rather then the full lifecycle approach. However the design process is the pivotal point whereby the structuring of data and information has a direct impact on downstream activities.

A study undertaken (Jurewicz, 2008) provides a detailed overview of the three main modelling technologies and their associated capabilities. The analysis conducted illustrates the similarities which exist between technological platforms, emphasising that the key focus is on supporting the creation, management and communication of data and information. Technologies have varying degrees of sophistication and selection decisions in respect to adoption are usually based on organisational preferences. The purpose of this study is not to provide recommendations on which technologies or systems are best suited in supporting organisational needs. However it is important to highlight the need for firms to benchmark solutions and explore how solutions can be integrated to enhance operational practices.

Furthermore beyond the initial stages of purchasing technology, training users and company wide adoption, there is a period when momentum declines in respect to the learning of new skills. For example results from a survey (Fig. 1) conducted in a design firm employing 80 technical staff, which have been using BIM technologies for a period of four years, illustrates the current divide in skill levels:

Fig. 2 illustrates that in order to sustain an increased growth in skill levels, it is imperative that organisations have a long term strategy in place to support continuous development. The successful adoption of technologies and exploitation of capabilities can only be fully realised when the supporting processes and strategies are aligned accordingly

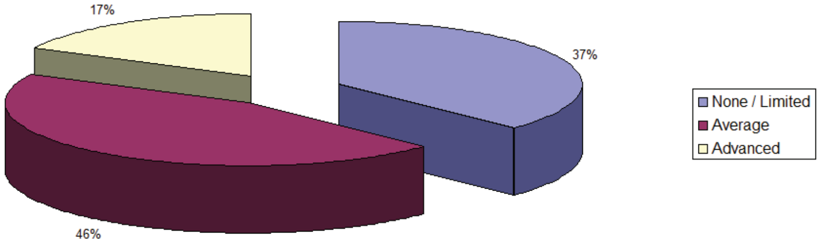

Fig. 1: Survey Results - Revit Expertise Levels

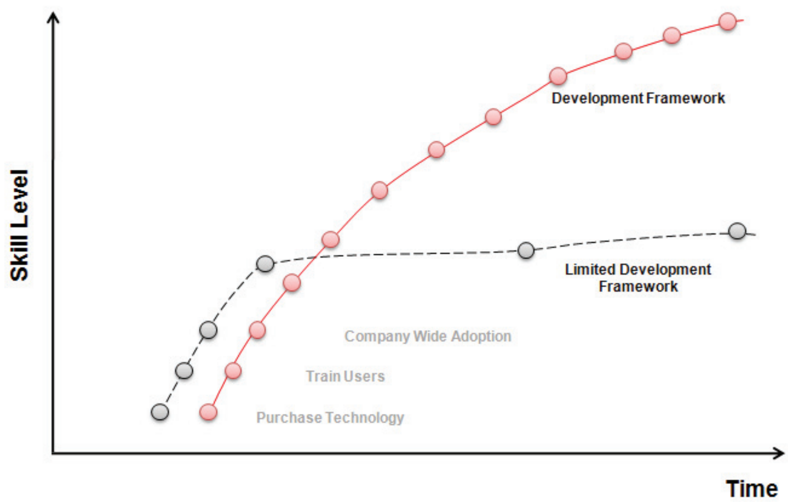

Fig. 2: Technological Adoption Strategy

2. Industry Trends

Rapid developments are occurring in other areas such as environmental analysis, construction planning and facilities management solutions. Whereby organisations in the AEC industry are continuing to explore how technologies and processes can be aligned to provide complete lifecycle solutions for clients. The evident benefits of BIM, namely; enhanced productivity, reduced construction errors, cost savings and increased collaboration between stakeholders (Aranda et al, 2008) continue to be realised in the AEC industry. Furthermore there is increased understanding that the adoption methodology is not a simple process, hence it cannot be successfully incorporated over a relatively short period of time, Smith D. and Tardif, M. (2009)

BIM adoption is gaining increased support from industry bodies and regulators within the US, such as the American Institute of Architects (AIA) and General Services Administration (GSA). In the United Kingdom the British Standards Institution (BSI) has recently released BS 1192 which provides guidelines to support collaboration and BIM implementation. Furthermore architects and engineers continue to drive awareness amongst clients and industry partners in order to share knowledge and understanding of the collective benefits associated with the BIM approach.

The integration of technology, processes and people is integral for organisations in order to successfully adopt BIM. Furthermore practitioners are moving beyond barriers associated with cost implications and infrastructure changes (Becerik and Pollalis, 2006). McGraw Hills Construction report (Young, 2009) confirmed early adopters are experiencing benefits across the operational infrastructure i.e. enhanced productivity, reduction in rework and improved communication.

Technological innovation continues to influence organisations in their adoption of BIM. Advancements in Laser Scanning and Point Cloud domains are set to have an explosive impact on industry, as the time required to capture data in the form of building geometry is reduced substantially. Developments are pushing towards creating techniques which will enable clouds to be fully manipulated and assigned attributes; hence they could be directly used by BIM systems.

Government workgroups in the United Kingdom, such as Construction Excellence are now beginning to support the establishment of a framework for the adoption of BIM. However the link to sustainability initiatives such as the Climate Change Act 2008, which is a legally binding framework introduced by the UK to tackle climate change needs to be integrated into the BIM lifecycle approach. The use of technology aligned with operational practices to support sustainable development requires greater integration and coordination.

Interviews with AEC organisations highlight that the adoption of BIM is favourable due to the competitive advantage offered and its role in enhancing operational practices and collaborative working. In respect to implementation strategies considerations need to cover business benefits, investment requirements, training initiatives and cultural resistance. Organisations fall short of effectively implementing BIM due to a variety of reasons, which includes the lack of willingness or drive within the organisation to support successful implementation. Clients also need to be aware that they have the authority to request the obligatory use of BIM on live projects. Such an approach means project stakeholders are inclined to support integrated practices, knowledge sharing and collaboration. Hence a project can be delivered on time and budget whilst adhering to sustainable practices and industry regulations.

3. BIM Process Review

The Royal Institute of British Architects (RIBA) has a distinct process for organising and managing building design projects through a number of key work stages i.e. A – L (Fig. 3). The process most commonly known as the 'Outline Plan of Work' is an integral part of the framework for design and construction projects within the UK. Furthermore it is important to emphasise that although the RIBA Outline Plan is commonly illustrated as a start to end process, in reality it is of an iterative nature, whereby information at various stages is reviewed and modified depending on project requirements. The study undertaken has demonstrated (Fig. 4) the link which exists between the RIBA process, BIM workstreams, technologies and the interoperability of information across technological platforms. Architectural practices have an opportunity within industry to lead in the adoption of BIM to support integrated project delivery. The BIM approach provides architects with the opportunity to regain lost ground in respect to their traditional status as leaders (Hiley and Khaidzir, 1999), as it enables enhanced control, coordination and management of building projects.

The practical implementation of BIM must have the full support of all project stakeholders, whereby individuals and organisations understand the various BIM workstreams in the context of the lifecycle (Fig. 5). Furthermore at the initial stages of project initiation it is compulsory that a BIM champion is selected to brief stakeholders of the approach and to manage its implementation until project completion.

In addition various bodies including Pennsylvania State University have highlighted the need for a ‘BIM Execution Plan’ (Building Smart Alliance, 2009) at the early stages of a project, which relates to BIM goals, uses, processes and information exchange. Industry recognises the need for the deployment of such a plan, however greater simplification is required in order to support its feasible implementation in a time constrained operational environment.

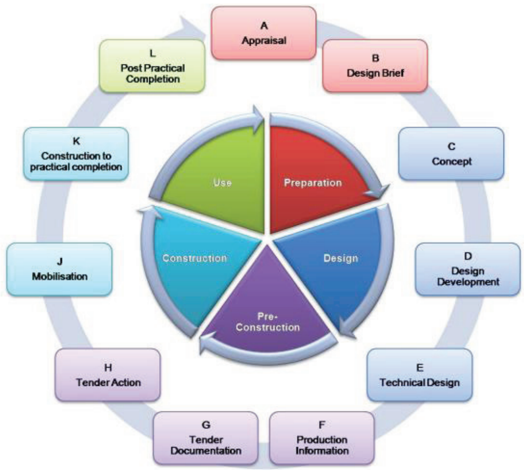

Fig. 3: RIBA Outline Plan of Work Process

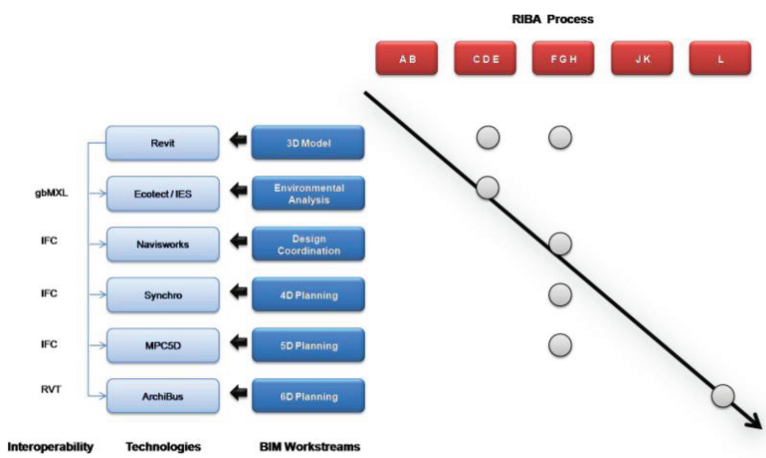

Fig. 4: BIM Process Framework

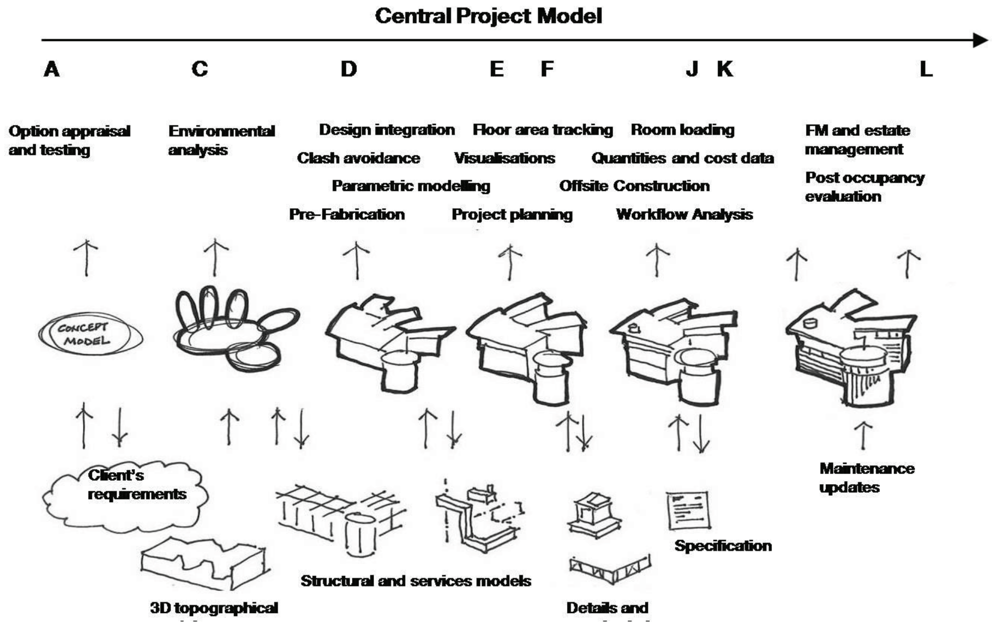

Fig. 5: BIM Lifecycle Process

4. UK Government and BSI views of BIM

UK Government-department for business innovation & Skill has stated that 'Government as a client can derive significant improvements in cost, value and carbon performance through open asset management system'. According to BS1192:2007, 'Collaboration between the participants in construction projects is pivotal to the efficient delivery of facilities. Organizations are increasingly working in new collaborative environments in order to achieve higher standards of quality and greater re-use of existing knowledge and experience, BSI 2010. A major constituent of these collaborative environments is the ability to communicate, re-use and share data efficiently without loss, contradiction or misinterpretation'. This implies that there are emphasis of new ways of working to drive a better value of construction processes and improve practices. According to BSI report on Constructing the Business Case for BIM: 'BIM continues to develop. Clearly, not all businesses will adopt systems and technologies at the same rate. However, just like organisations in the retail sector before them, BIM adopters will need to go though a managed process of change which encompasses not only their internal organisation but also the way they interface with their external supply-base and clients. The majority of the UK market is still working with Level 1 processes, and the best in class are experiencing significant benefits by moving to Level 2. It is clear that organisations adopting BIM now will be those most likely to capitalise on this advantage as the market improves'. Fig. 6 shows the different levels that BSI has introduced to bench mark applications of BIM in the Market.

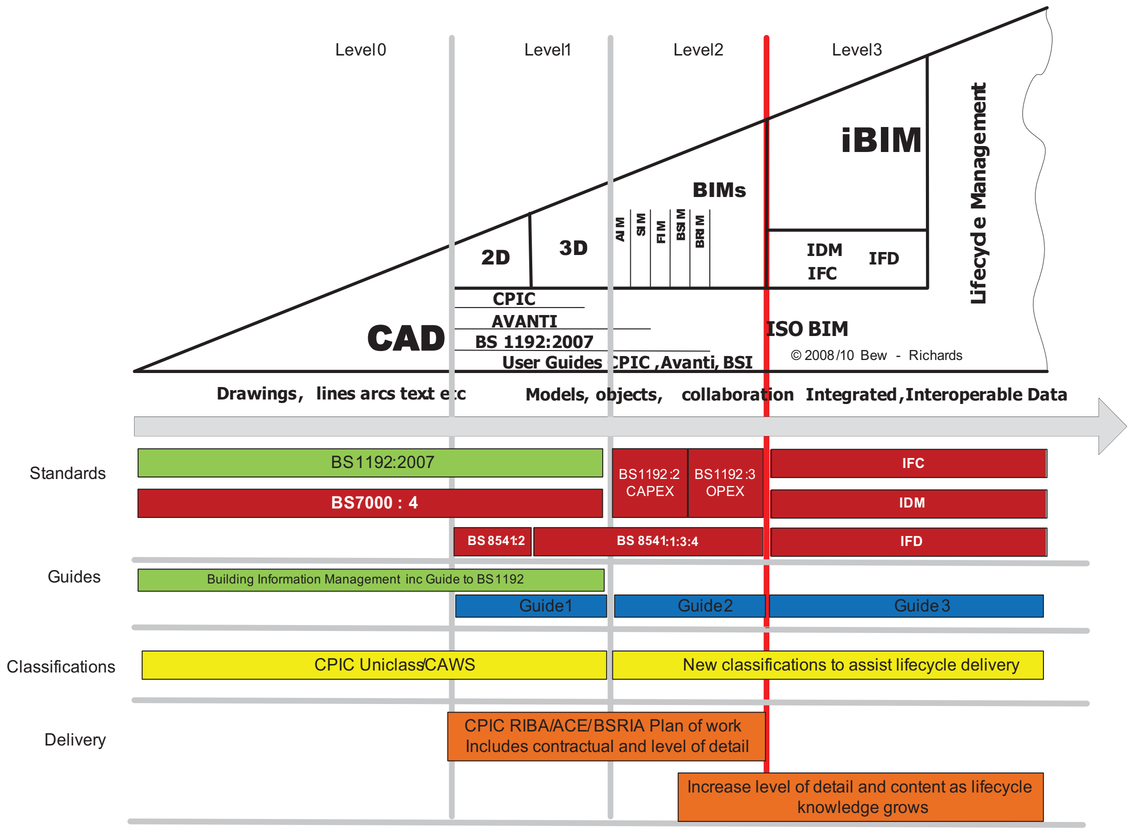

Fig. 6: Levels of information management, data sharing and collaborative working, source: BSI

5. Conclusions

The aim of this paper was to present BIM technologies and processes in the UK construction industry. The paper outlined current tools capabilities and briefly reviewed BIM processes in the context of RIBA plan of work. A process framework has been presented and mapped current commercial tools against RIBA processes.

Current Building Smart initiative has highlighted the level of penetration of BIM in the industry. Four Levels of information management, data sharing and collaborative working have been identified by BSI roadmap. Industry can identify their BIM capacities through mapping their current practices on this road map. It was concluded that the

majority of the UK market is still working with Level 1 processes, and the best in class are experiencing significant benefits by moving to Level 2.

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D^{4}AR – 4D Augmented Reality – Models for As-built Visualization and Automated Progress Monitoring of Civil Infrastructure Projects

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ABSTRACT: *One of the grand challenges as identified by US National Academy of Engineering (NAE) is to devise techniques to efficiently create records of the locations and up-to-date status of new and existing infrastructure. Nonetheless, significant part of efforts towards recognition, labeling, and documentation of infrastructure is spent on data collection and manual generation of 3D models. In addition, current representations are not convincing enough to maintain a realistic view of an actual site, which is yet another major challenge identified by NAE. This paper addresses these challenges by introducing a new approach for automated reconstruction, localization and visualization of civil infrastructure. In the proposed image-based 3D reconstruction approach, using unordered and un-calibrated images, as-built models of new or existing civil infrastructure are automatically reconstructed and images are geo-registered. Next, 3D as-planned models are superimposed with the as-built models, resulting in D^{4}AR – 4 Dimensional Augmented Reality – models. Finally, performance deviations are automatically measured in the D^{4}AR environment and represented at component-level using a simple traffic-light metaphor. This holistic visualization enables Architecture/Engineering/Construction professionals to intuitively observe current and expected status of an infrastructure, conduct various decision-making tasks, and minimize impacts of late decision-makings in an augmented-reality environment rather than the real world where is time-consuming and costly. This paper presents an overview of the D^{4}AR modeling technique and demonstrates experimental results from implementation of this technique on three building and infrastructure projects in US and Japan. It further discusses implementation and potential enhancement of this new technology for construction, operation, maintenance, and asset management of new and existing civil infrastructure projects.*

KEYWORDS*: 3D Reconstruction, Image-based Modeling, D^{4}AR Models, Visualization, Civil Infrastructure, Project Control*

1. INTRODUCTION

American Society of Civil Engineers is estimating that $2.2 trillion is needed over five year period to repair and retrofit US infrastructure to a good condition (ASCE 2010). This problem is not specific to the United States. The civil infrastructure in Japan and other developed and developing countries are also aging and failing. Although managing and maintaining infrastructure is not a new problem, nonetheless in recent decades, significant expansion in size and complexity of infrastructure networks have posed several new engineering and management problems on how existing infrastructure can be monitored, prioritized and maintained in a timely fashion. One of the grand challenges in restoring and improving urban infrastructure as identified by US National Academy of

Engineering (NAE) is to devise techniques to efficiently create records of the locations and up-to-date status of the civil infrastructure (NAE 2010). This problem is not only specific to existing infrastructure. New construction projects are also suffering from the lack of techniques that can easily and quickly *track*, *analyze* and *visualize* as-built status of a project and *monitor* performance metrics (Golparvar-Fard et al. 2009a).

In the last decade, capabilities of data collection technologies have significantly increased. These technologies include Barcode and RFID tags, laser scanners, GPS and wearable computers. Despite significant advancement in recent years, these technologies still need to be systematically maintained and operated. Moreover, these technologies do not address all inefficiencies related to tracking, analyzing and visualizing current status of infrastructure in a holistic manner. Currently there are mainly two practical solutions that holistically address all aspects of recognition, labeling, and documentation of new and existing infrastructure: (1) User-driven modeling: Which is the process of manually collecting and analyzing data and perhaps generating 3D models; and (2) 3D Laser Scanning: Which is the process of laser scanning, collecting data automatically and reconstructing 3D models. The user-driven modeling approach is long and error-prone and the 3D laser scanning strategy is also costly (in the range of $100-250K) and cumbersome. In addition, the current representations are not realistic enough to maintain a proper depiction of an actual site, which is yet another major challenge identified by NAE (NAE 2010). Although these technologies are introduced to facilitate and automate site data collection, yet they are adding a new *task* to project management; i.e., the project management team needs to have a systematic plan to maintain and operate these technologies.

To address these inefficiencies in an all-inclusive manner, this paper looks into developing a new technique by using two *existing* and *emerging* sources of information: (1) digital photographs and (2) Building Information Models (BIMs). More specifically this paper explores how by using these sources of information, current challenges of creating up-to-date records of new and existing civil infrastructure can be proactively addressed.

Nowadays, cheap, lightweight, and high-precision digital cameras, low cost memory and increasing bandwidth capacity have enabled capturing and sharing of photographs on a truly massive scale. For example, on a 200,000 S.F. building project in Champaign, IL an average of 200-500 photos/day is being collected by Architecture/Engineering/Construction (AEC) teams. Such a large and diverse set of imagery enable the as-built scene to be fully observed from almost every conceivable viewing position and angle during construction or operation lifecycle of a project. The availability of such rich imagery - which captures dynamic construction scenes at minimal cost –enables geometrical reconstruction and visualization of as-built models at high resolution which can have broader impacts for the AEC community. In the meantime, Building Information Models are also increasingly turning into binding components of AEC contracts. For example as of 2009, states of Texas and Wisconsin established themselves to be the first states requiring BIM models for public projects. While the application of BIMs is increasing, most focus has been on design development and pre-construction stages of a project. In this research, application of BIM is extended to the construction phase and further added-values from integrating BIMs (as sources of as-designed information) with as-built models are investigated.

Until very recently (Golparvar-Fard et al. 2009a), joint application of unordered image collections and BIM for the purpose of tracking, analyzing and visualizing actual status of a project was unexploited by researchers. A major reason is such imagery has not traditionally been in a form that is easily adaptable for image processing techniques; i.e., these images are usually unordered, un-calibrated, and have widely unpredictable and uncontrolled lighting conditions. Developing computer vision techniques that can effectively work with such imagery to track and represent as-built models is a major challenge. This paper looks into application of an innovative approach for tracking as-built elements from daily photographs based on a priori information (4D as-planned models). First using a Structure-from-Motion (SfM) technique, a 3D as-built point cloud model is generated and images are automatically registered. Subsequently similar to (Golparvar-Fard et al. 2010) the as-built point cloud model is registered with the as-planned model. At this stage, the as-built reconstruction is enhanced with a multi-view stereo algorithm and then a novel voxel coloring and labeling algorithm is used to generate a dense reconstruction of the site, labeling different areas according to consistent visibility while fully accounting for occlusions. Same labeling process is conducted on the as-planned model to identify occupied and visible areas that need to be monitored for performance deviations. Finally a Bayesian probabilistic model (Golparvar-Fard et al. 2010) is used to automatically recognize progress by comparing measurements of progress with dynamic thresholds learned through a Support Vector Machine (SVM) classifier. Unlike other methods that focus on application of laser scanners or time-lapse photography (Bosché 2009, Ibrahim et al. 2009, Zhang et al. 2009, Golparvar-Fard et al. 2009b), this approach is able to use existing information without adding the burden of explicit data collection on project management teams and reports competitive accuracies compared to (Bosché 2009, Ibrahim et al. 2009) especially in presence of occlusions (Golparvar-Fard et al. 2010). In the following section, an overview of the

D^{4}AR modeling approach is presented. Subsequently experimental results on applicability of this modeling approach for new and existing building and civil infrastructure projects are demonstrated.

2. OVERVIEW OF 3D/4D AND D^{4}AR INTERACTIVE VISUALIZATION AS WELL AS AUTOMATED PROGRESS MONITORING

Fig. 1 shows an overview of data and process in the as-built / D^{4}AR model visualization and automated progress monitoring system developed in Golparvar-Fard et al. (2010). First, images that are collected in one day or over several days in which no major progress is observed are placed into the system. Similar to Golparvar-Fard et al. (2009) and Snavely et al. (2007), Structure from Motion (SfM) technique is used to generate an underlying 3D as-built point cloud model and register images. Subsequently the as-planned BIM is superimposed with the integrated as-built point cloud and camera model. For registration, (Horn 1987) is used to get a closed-form solution to the least square problem of absolute orientation. In the developed system, this procedure needs to be performed only once to have the initial point cloud model registered to the 3D BIM. From that point after, newly generated point cloud models (from new photographs) only need to be registered to the underlying point cloud model. For this purpose, a set of photographs that are showing part of the scene which is not significantly changed from one-day to another is usually selected. An Iterative Closest Point (ICP) algorithm that can solve for scale (Du et al. 2007) is used to automatically superimpose point cloud models over one another. This method finds a random set of points from each point cloud and automatically aligns the new point cloud to the former one, in turn having the new point cloud registered with the as-planned model. This step generates 4D as-built point clouds wherein user can navigate and walk-through the as-built scene both spatially and chronologically. The 4D as-built registered with the 4D as-planned model enables expected and the actual status of a project to be compared as well.

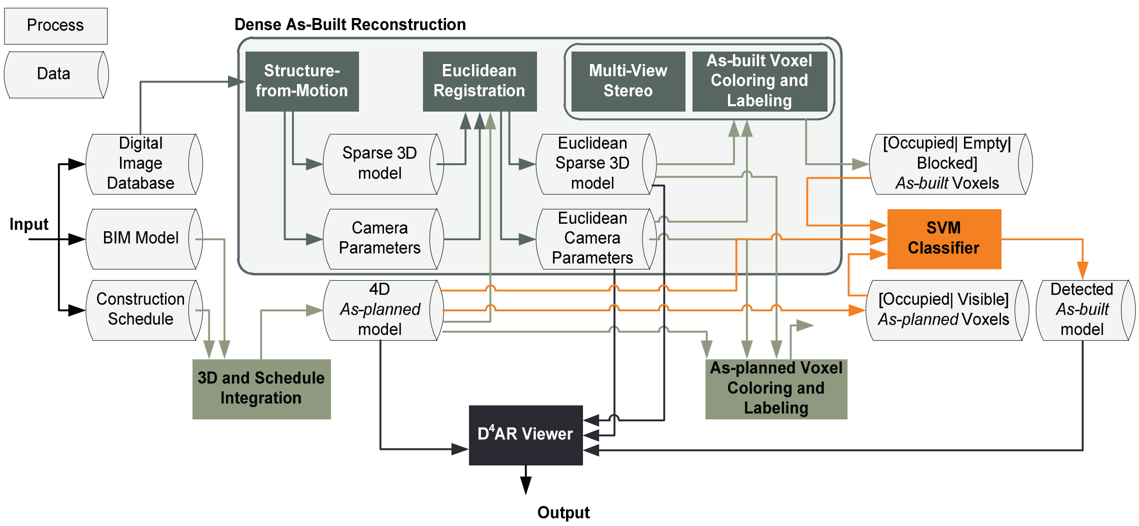

Fig. 1: An overview of process and data in the D^{4}AR visualization and automated progress monitoring system (adapted from Golparvar-Fard et al. 2010).

Once the D^{4}AR model is formed, similar to (Golparvar-Fard et al. 2010), the as-built reconstruction models are enhanced with multi-view stereo algorithm and then a novel voxel coloring and labeling algorithm is used to generate a dense reconstruction of the site, labeling different areas according to consistent visibility while fully accounting for occlusions. Same labeling process is conducted on the as-planned model to identify occupied and visible areas that need to be monitored for progress. Next, a Bayesian probabilistic model is introduced to automatically recognize progress by comparing measurements of progress with dynamic thresholds learned through a Support Vector Machine (SVM) classifier. Finally, using a traffic-light metaphor (Golparvar-Fard et al. 2009b), behind or ahead-of-schedule BIM elements are color-coded with red and green accordingly. For those elements with minimal visibility, progress is not being reported and hence they are color coded in gray. Such color-coding scheme makes it easy to visually observe the accuracy of progress detection, yet if needed, allows corrections to be made on a case-by-case basis.

Figure 2 shows an example of the D^{4}AR modeling and automated progress detection pipeline. In this case, 160 images with resolution of 3Megapixel are captured along the sidewalk of the basement area. As demonstrated in Figure 2.a, these photos are taken for different purposes; e.g., safety analysis, productivity measurements, and quality control. In the proposed approach, it is assumed that information on how these images are captured is unavailable; i.e., location and orientation of the field engineer during photography is unknown. These images can have different lighting conditions, different viewpoints and all possible affine transformations. Figure 2.b further shows the reconstructed as-built point cloud model. Finally in Figure 2.c, the as-planned BIM model is semi-automatically superimposed with the point cloud model, generating the D^{4}AR model. The integrated model is placed into the automated progress detection model and based on actual occupancy and expected visibility, physical progress is detected (See Golparvar-Fard et al. 2010 for more details).

Fig. 2: An overview of the D^{4}AR modeling and automated progress monitoring system. (a) Unordered daily construction photographs; (b) Generating 3D/4D as-built point cloud models and registering site images; (c) Generating D^{4}AR models by superimposing 4D as-planned Building Information Model with 4D point cloud model and registered images; and automatically detecting physical progress.

Table 1 further shows the performance of the D^{4}AR modeling pipeline for the case study presented. As observed, in all aspects of 3D as-built point cloud reconstruction, augmented reality registration and physical progress monitoring, the system shows a reasonable and reliable performance.

Table 1: Metrics of evaluating D^{4}AR modeling pipeline for the case study presented in Figure 2.

3D As-built Point Cloud Reconstruction				**As-built/ As-planned Registration**		**Physical Progress Detection**	
# of images	Image Resolution	Point Cloud Density	Generality[1]	# of corresponding Points	Δe_{mm}	# of BIM elements	Avg. Accuracy
160	2144×1424	721,300 points	1.0	7	0.62mm	152	82.89%

[1] Generality = # of successfully registered images/ # of images used.

3. APPLICABILITY EXPERIMENTS

In order to test applicability of the proposed as-built / D^{4}AR modeling as well as automated progress monitoring technique, a set of experiments on two real-world projects are further conducted. These experiments and the motivations for each are as follow:

3.1 Rebar Quality Control

It is the duty of a contractor to complete the work covered by the contract in accordance with the approved plans and specifications. Site inspection assures that the work being done is in accordance with the approved plans, specifications as well as manufacturer's recommendations for the use and installation of the material products. Throughout site inspection, various measurements are conducted and important parts/areas are photographed for as-built documentation purposes.

Particularly in the case of concrete reinforcement which is studied here, inspector needs to verify the grade and visual conformity of the rebar with the acceptable quality standards and the approved plans and specifications. Usually rebar is verified to make sure (1) it is adequately tied, chaired, and supported to prevent displacement during placement and concrete casting and (2) is adequate for the intended stresses. The minimum and maximum clear distance between bars and structural distance to the outside of concrete is also verified against a list of required clearances form the structural drawings. Finally the bar laps are verified for proper length, stagger and bar bends for minimum diameter, slope and length.

In countries like Japan that are prone to severe earthquakes or states such as California, contractors and owners are required to verify structural integrity of their reinforced concrete structures with conducting intensive quality assurance as mentioned above. Before casting concrete, contractors are always required to inspect and properly document rebar installations; i.e., whether the rebar is accurately installed in accordance with design, project specification and the reinforcement concrete construction codes specified by certain regulatory agencies. Nonetheless, the task of inspecting accuracy of the rebar placement, taking pictures from all possible viewpoints and recording them to secure product quality is time-consuming and tedious for on-site engineers. In order to address these inefficiencies, this paper proposes application of the D^4AR as-built image-based reconstruction technique. By only using photographs that are captured by the on-site engineers, as-built status of the rebar installation can be reconstructed in 3D and analyzed remotely. Figure 3 shows two examples where concrete rebar has been photographed and documented. In the first case, as shown in Figure 3.a and b, only 12 images with resolution of 1.2 Megapixel were used and within about 4 minutes the point cloud model is reconstructed and images are registered. In Figure 3.c and d another example is shown wherein by only using 7 images with resolution of 3 Megapixel, the point cloud model is reconstructed and images are registered. These reconstructed 3D point cloud models (even in cases wherein they are extremely sparse) in addition to registered imagery enable remote rebar inspection. For example, one can verify proper length and spacing of rebar remotely without the need for being on the site.

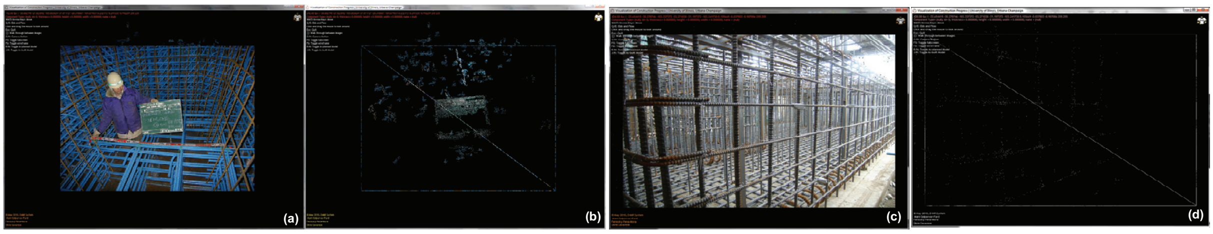

Fig 3: (a,b) and (c,d) Two examples of rebar inspection and documentation. In these cases, only 12 images with resolution of 1.2 Megapixel and 7 images with resolution of 3 Megapixel were used.

3.2 As-built infrastructure modeling and monitoring with vehicle mounted cameras

Over the past few years, terrestrial 3D laser scanning, 3D panoramic photography and videogrammetry have commonly being employed for highway and building surveys. Laser scanning instruments are slow and costly especially in cases where large areas need to be surveyed. Having a laser scanner mounted on a vehicle improves the productivity of data collection but still there are a number of inefficiencies such as uneven point spacing as well as computational time associated with geo-referencing of 3D scans. For significant areas, hundreds of scan positions need to be geo-references which create a significant challenge. Videogrammetry and 3D panoramic photography have also been used in many parts of the world as highway surveying techniques. Google Street View feature in Google Maps is an example where photos are taken with special 360-degree cameras and stitched together to mimic a virtual walk through experience. In other cases, instead of still photos, videos are being used. Nonetheless, there are significant challenges in creating 3D models with minimal human data processing. In some cases, laser scanners are added to these systems to improve the data processing workflows, which obviously complicate the data collection process and further lower the value of these technologies.

In this study, we acquired a set of images that are captured from video cameras mounted next to a laser scanner on a vehicle. The main interest is to investigate if dense 3D point cloud reconstruction presented in this work, can replace the laser scanning point cloud and camera calibration process. Therefore, a set of *un-calibrated* images were acquired and placed into the proposed system to test applicability and reliability of point cloud reconstruction. Figure 4 shows the results of the reconstruction using a video camera mounted on a vehicle. In this case, 19 images with resolution of 1200×2000 captured from the same viewpoint are being used. For this set of images, it is assumed that the calibration information is unavailable. Using these images, a point cloud model with a density of

230,266 point was reconstructed. Figure 4.c and 4.d show a synthetic view of the reconstructed point cloud and the actual view from the same viewpoint. Figure 4.a and 4.b, further illustrate density and accuracy of the reconstruction.

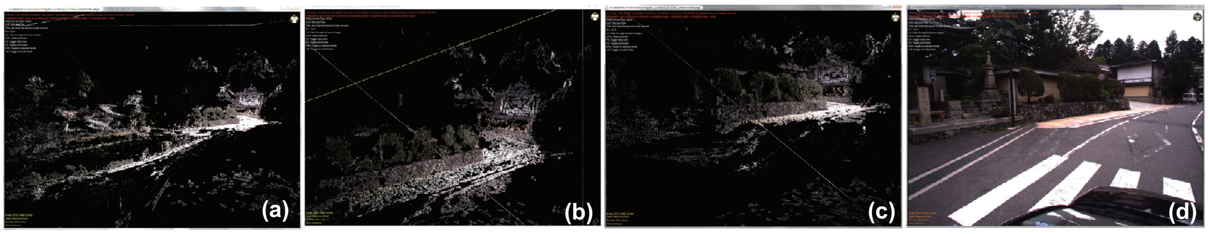

Fig. 4: (a) and (b) 3D as-built point cloud reconstruction with 19 images captured from a video camera mounted on a vehicle. (c) and (d) illustrate synthetic and actual view of the roadway from the same viewpoint.

Monitoring and as-built documentation issues are not specific to highways and buildings. Other aged infrastructure such as water and wastewater facilities installed many years ago also need to be properly maintained and timely replaced to minimize lifecycle costs. Traditionally, 2D GIS software technology has been used to analyze project priority and plan rehabilitation of the infrastructure. On the other hand, just as architects and engineers have looked into adoption of BIM to gain efficiencies and streamline workflows, infrastructure professionals and practitioners are looking into information modeling technologies similar to BIM to accelerate project scheduling, increase quality and reduce cost.

These complex projects are always under direct public attention. Leveraging the D^4AR image-based reconstruction enables generation of high quality visualizations that can ultimately help engineers communicate design intent to project stakeholders and speed up project approvals. The BIM process helps engineers generate coordinated and consistent documentation directly from the model due to the rich information model created as part of the BIM process. Using the proposed image-based modeling technique, a 3D as-built point cloud model of such infrastructure can be directly generated from site images. This in turn plays a major role in reducing time and cost associated with the current practice of surveying and manual documentation of an infrastructure.

4. CONCLUSION

An automated approach for data collection, analysis and visualization of new and existing civil infrastructure using unordered photographs and 4D as-planned models is presented. In the proposed approach, images can have low resolutions and are widely distributed, yet robustly generate dense point cloud models. Subsequently the underlying point cloud model is registered with other point cloud models as well as the as-planned model, generating integrated 4D as-built and as-planned models for as-built visualization and automated progress monitoring. The proposed as-built and as-planned voxel coloring demonstrates high accuracy in labeling construction scenes for occupancy and visibility which results in dense reconstruction and also demonstrates reliable results in detecting progress. This overall marks our approach to be the first of its kind to fully take advantage of daily site photographs and 4D as-planned models for automated progress monitoring. Application of our system is perceived to minimize the time required for data collection and data extraction; removing inspection subjectivity through a systematic detection; and finally interactive visualization to minimize the time required for discussions on progress coordination possibly leading to a better decision-making for project control. More conclusive experiments on the accuracy and reliability of the presented dense reconstruction and progress detection techniques need to be conducted (interior spaces and Mechanical/Electrical/Plumbing components). We also need to incorporate visual appearance detectors to enhance both reconstruction and progress monitoring.

AKNOWLEDGEMENTS

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affiliates, business partners, or customers.

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INVITED PAPER

HOW VIRTUAL REALITY FOR CONSTRUCTION PROCESSES ADVANCES IN GERMANY

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***ABSTRACT**: The current research in Germany is challenged by a considerably conservative construction industry with binding legal obligations (bidding procedures, standard contract clauses, working habits from craftsmen and small business units). Nevertheless research has increased enormously to develop better tools and techniques for the design-built complex in construction. This has also led to some very advanced solutions, which have already reached pilot character in connection with innovative construction and consulting companies. A wider application of research results and their developed methods, techniques and tools is now on the edge.*

The presentation given will focus on a broad overview about VR in construction in Germany This comprises current research initiatives as ForBAU led by the Technical University Munich, MEFISTO, presented by the Technical University of Dresden, ASIM working group "one-of-a-kind processes", led by the university of Kassel and SIMoFIT, initiated by the Bauhaus-University Weimar.

***KEYWORDS:** Simulation, virtual reality, construction processes, Building information model*

1. INTRODUCTION

Construction processes are very complex and of different variety. Whereas complex planning tools have been developed in the past and are still improving, while they are in use by many architects and engineers, appropriate tools for the construction industry still lack the ability to be incorporated within a larger data management frame. The interest of many companies in sharing their design tools seems to be very limited. On one hand the software industry is offering specialized products for the construction industry in order to support cost estimation, schedule control and cost control. On the other hand companies refrain from common data basis because of possible risks to loose control on their own data.

Also in Germany quite a number of design tools for construction companies exist, which are also adopted to the special situation of the German market, its norms and its customs in the construction industry. These stand-alone solutions have reached their limits, because the transfer of data from engineer to engineer in different companies is often interrupted due to incompatibilities between different software packages. Sequential work, where lots of data have to be transferred from one system to the other manually or by means of simple excel sheets, is no longer considered as being a solid basis for qualified engineering.

Since three to five years some challenging initiatives have been started in Germany in order to overcome this limiting situation of concurring systems and to develop holistic systems to integrate the data from various sources and keep them compatible within the whole process of planning. Some will be presented in the following chapters.

2. CURRENT INITIATIVES IN GERMANY

2.1 ForBAU, Munich

ForBAU, a Bavarian driven program led by the Technical University of Munich, concentrates on the merge between different established planning and scheduling tools in infrastructure as for example LANDxml, geotechnical 3D-modelling, geodesy surveying, site layout and simulation of excavation processes. Remarkable results were recently presented on a workshop in Munich. The informatics part in this project has already been presented on several international conferences by Rank and Borrmann, whereas the construction part and the integrative aspects of ForBAU are still less noticed by the international community.

The research project aims at collecting data from different phases of a construction project: This leads to virtual landscapes, through which the construction site "comes to life" (4D-information system of the construction site).
The thus emerging model can be used and constantly developed over all phases of the project.
In order to depict a complex building project as a holistic entity, it is necessary to integrate the data from various areas, such as construction and planning, surveying, task scheduling, controlling and the building site itself. This calls for a centralized data platform in the shape of a product data management system (PDM system) with standardized interfaces. By coupling the different CAD models (for the structure, subsoil, building site facilities, etc.) in a single site information model it is possible to exploit far-reaching optimization potential in terms of the temporal/spatial interdependence of the building sequences throughout the development. As the project progresses, the model can be dynamically updated in order to provide different users with the relevant technical and commercial information by collecting data from each project phase.
Crucial processes or workflow sequences can be simulated in advance using the virtual model of the building project, so that they can be implemented on the actual site without delays or unnecessary idle phases, when the time comes. The virtual models are also capable of predicting the economic success of a development during the early stages of the project. For the entire duration of the construction work, the real performance on the building site can be documented via mobile computer systems and incorporated in the existing virtual site model, thus creating a record of the progress made and allowing corrective measures to be introduced in good time, if there are any deviations in the planning.
Dynamic 4D site information models, which not only show the geometry and the time-line, but also model-based data such as quality-related documents, are the result.

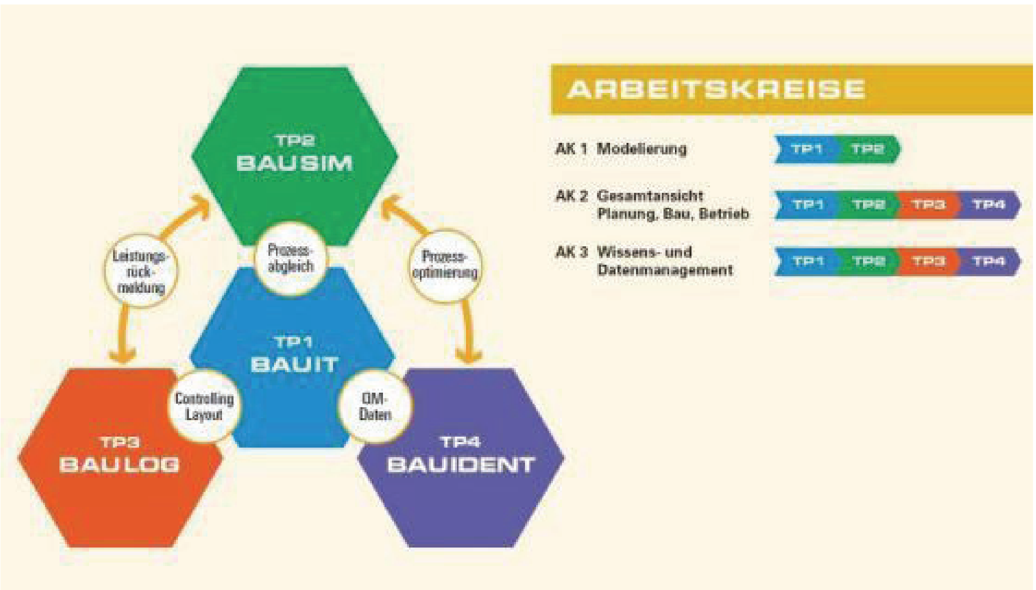


Fig. 1: Working groups of ForBAU Research project

A central idea of ForBAU is the close collaboration between sciences and industry. Especially construction companies as well as consulting offices are cooperation with the academic research teams from the Technical University Munich, the University of applied Science Regensburg and other research units in Bavaria. Academic staff and employees of the participating companies work together in the sub-projects. The job design is geared to the basic ideas of the virtual building site:

- Continuous 3D- modeling of the entire building project, so that the model can be used as a central communication and information tool during the planning process.
- Continuous project planning with innovative planning approaches from different industries. For instance data management via PDM-Systems.
- Creation of standardized procedures for planning and the following execution of the construction work, which allow for a consistent controlling.

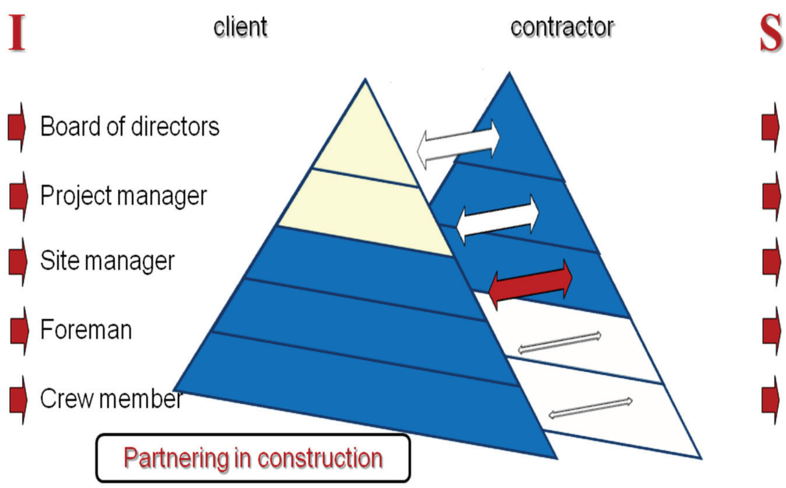
The research budget is about 7 Mio. €, from which more than 2/3 are raised by industry.

The author has been involved in this project as judge/expert in the initiation phase as well as during the yearly evaluation, last held on March 19, 2010. The research project is now in its third and final year of operation.

2.2 MEFISTO, Dresden

The MEFISTO ("Management, leadership, information and simulation in construction") project is led by the Technical University of Dresden and involves 12 project partners from industry, software development and universities. The partners from industry are engineering consultants, project management consultants and construction companies, these specializing in turnkey contracts. MEFISTO is a lead project of the German Federal Ministry of Education and Research with the objective to develop a platform for the execution of construction projects in the form of a management information system. This system will enable real-time and visually descriptive simulations on the basis of up-to-date operational data on all levels of abstraction.
The development of the management information system will yield:

- Visualisation of complex processes and interrelations as well as current operative data on all levels of abstraction in a construction project.
- Establishing a high level of transparency within the project as well as a better understanding between the involved partners of the project
- Knowledge management with the objective of accumulating and permanent storing of all knowledge information, which is brought into the project over time
- The characteristic production processes and the dynamic changes in site development shall be made transparent in site. They shall be controlled and optimized by the means of flexible and easily generated simulation models.



– *Fig. 2: The two faces client and contractor in an project*

Hence, complex interrelations become transparent and a dynamic risk management based upon the information model can be established. The resulting transparency in combination with the possibility to document and trace previous decisions bases promotes a consolidated level of comprehension among the project partners. As a result, this builds up trust between project parties, avoids misunderstandings and supports synergies and knowledge accumulation between the experts involved.

It is designed to develop means and common utility programs for a better controlling of construction projects on different levels of abstraction. Thus we develop the ontology for a transparent description of the cooperation on different levels of detail. One of these levels is for the simulation of construction operations with different agents, for example for the structural works and for the finishing works. The verification projects will be on some high rise construction sites in Frankfurt.

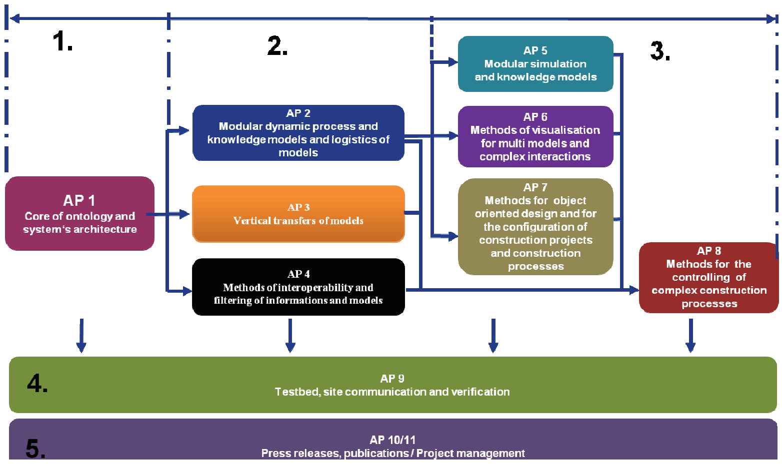


Fig. 3: working groups within the MEFISTO research project

The German Federal Ministry of Education and Research (BMBF) supports the lead project MEFISTO in the framework of the program IKT 2020 with a volume of 9.4 million Euros. The joint research project started on 1st April 2009 and will end on 31st March 2012.

The author is involved in three of 10 working groups, the process description of construction works (ontology), the simulation of construction processes and the verification.

2.3 ASIM working group "one-of-a-kind"-processes, Kassel

In the framework of the ASIM, "Arbeitsgemeinschaft Simulation" in Germany, several researchers from chairs of construction engineering, construction management and for informatics in construction in 2008 have established the working group "Unikatprozesse". This research group is dedicated to the special simulation methods for any processes, which have the character of one of a kind. Here construction processes as well as ship building as well as industrial plants are discussed in order to develop common methods and tools, which can be applied in different industries and can easily be adapted to some of the neighbouring branches.

Major topics in this working group are the modelling of construction processes, the interrelations between the informatics view on the subject as well as the construction manager's view. Also different perspectives from the client, from the turn-key contractor, the site manager as well as from the subcontractors are discussed.

On the bi-yearly ASIM conference for simulation in production and logistics, in October 2010 held in Karlsruhe, one whole stream has been dedicated to simulation in construction. In 2012 this conference will be jointly held together with the winter simulation conference in Berlin, which will be the first time at a venue outside of the United States.

The author is co-chairman of the working group '"one-of-a-kind"-processes.

2.4 SIMoFIT, Weimar

The Program SIMoFIT ("simulation of outfitting processes") is operating in shipbuilding as well as in construction. It is an already 5 year long cooperation of the Bauhaus-University Weimar together with a shipbuilding company in Flensburg. Here we developed a special toolkit for the simulation of construction processes for finishing works. Also we developed a constraint based simulation using hard and soft constraints in order to describe the very different types of parameters and boundary conditions in construction. Since the end of 2009 we enlarged this cooperation to the University of Bochum as well.

The common objective is the development of universally useable simulation models for the efficient subsistence of construction scheduling in the outfitting and finishing phases of buildings and ships. The processes in construction and in ship building have many similarities. Nevertheless the historically developed building codes differ to a great extend. This enables the partners to have large benefit of this cooperation.

3. CONSTRAINT BASED SIMULATION CONCEPT

Within the SIMoFIT cooperation (*Simulation of Outfitting Processes in Shipbuilding and Civil Engineering*) a constraint-based simulation approach has been developed to improve execution planning. Construction scheduling problems can be described by *Constraint Satisfaction,* which is a powerful paradigm for modeling complex combinatorial problems. Classical constraint satisfaction problems are defined by sets of variables, domains, and constraints. Accordingly, modeling the construction scheduling problems as constraint satisfaction problems, the construction tasks, material, employees, equipment, and construction site layout are represented by variables. Different scheduling constraints can be specified between these variables. Typical Hard Constraints of construction processes are technological dependencies between execution activities, needed capacity of certain equipment and employees, availability of material, and safety aspects like specific needed working areas or maximum allowed durations.

Fig. 4: homepage of SIMoFIT, a cooperation of ship building and construction engineering

The solutions of constraint satisfaction problems are valid execution orders of the construction tasks, where all associated constraints are fulfilled. The constraint-based approach guarantees a high flexibility of modeling construction processes. If additions or new prerequisites occur, the model can be easily adapted by adding or removing certain constraints. Normally, solving complex constraint satisfaction problems analytically is extremely time-consuming. In this connection, simulation can be used to investigate and evaluate different scenarios very quickly. Therefore, the constraint satisfaction approach was integrated into a discrete event simulation application.

The simulation concept enables the generation of different events during the discrete simulation by the procedures *Starting Tasks* and *Stopping Tasks*. A task can only be executed if all its associated constraints are fulfilled. In the Figure 5 the procedure of starting tasks is depicted. If a new event occurs, all not started tasks are checked on fulfillment of their associated stringent constraints. This leads to a set of next executable tasks. In the next step one of these executable tasks is selected for starting. Its presupposed objects, like material resources or employees, are locked during its execution and cannot be used by other tasks. The procedure is repeated until no more tasks can be started at the current time. If the remaining time of a construction task is expired, the task is marked as finished. Its presupposed objects are unlocked and can be used by other construction tasks.

The starting and stopping routines are performed consecutively until all construction tasks are finished. All events, i.e., starting and finishing tasks and locking and unlocking resources, are recorded. Thus, one simulation run calculates one execution schedule with the corresponding material flow as well as the utilization of employees and equipment where all stringent construction constraints, like technological dependencies or resource and spatial requirements, are fully complied with. Based on this concept, different practicable scheduling strategies – not binding, but rather functional conditions of the construction process – should also be considered during the generation of schedules.

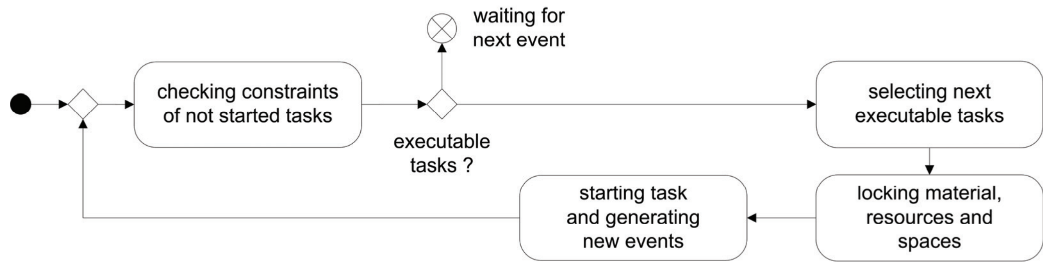


Fig. 5: Starting tasks within constraint-based simulation

Fig. 6: outfitting processes in shipbuilding within a fire protection zone

4. SOFT CONSTRAINTS FOR CONSTRUCTION PROCESSES

Generally, in the context of Constraint Satisfaction, a *Soft Constraint* specifies a practicable or advisable restriction. In contrast to stringent constraints, or so-called *Hard Constraints*, Soft Constraints can be violated within a specific range. The violation of a Soft Constraint is represented by a cost factor. Consequently, different schedules can be evaluated with regard to their fulfillment of specific strategies using these cost factors. Different well-known execution strategies are specified and classified according to different planning aspects. Some of these aspects are shown in Table 1.

Table 1: Execution Strategy Constraints for Construction Scheduling

Structural strategies	Spatial strategies	Productive strategies
• Avoid soiling • Avoid damage • Avoid interference	• Distance • Adjacency • Orientation	• Production flow principles • Human strain factor

To describe implicit knowledge such as strategies for the execution, different Soft Constraint concepts can be applied. Typical Soft Constraint representations are *Weighted Constraints*, *k-Weighted Constraints,* or *Fuzzy Constraints*. Detailed information about these Soft Constraint concepts and execution strategies formalization can be gathered from BEISSERT 2010).

5. CLOSING THE GAPS

Whereas the different software applications grow seemingly together, powered by the above mentioned research initiatives as well as by other software developments by the established companies, still a huge amount of data about construction material, construction regulations, construction practices and other experience has to be collected and made available. One special company offering this service are the DBD (Dynamische Baudaten = dynamic construction data), the former standardized book of bill of quantities in Germany. This version of dynamic construction data operates on an internet base and is regularly updated in the net. The service is offered for a small fee, so that every architect and engineer in the German market can access standardized descriptions of work for different trades.

Based on the knowledge data a prototype tool has been developed for roofing, which enables the roofing company to very easily take the quantities from a plan or from an aerial view. Using the special logic for roof construction, the bill of quantities can be developed directly at the clients home, so that offers can be calculated within 30 minutes and together with the client. This powerful tool is designed especially for roofers. Considering the big success of this tool, further applications might soon be developed for other trades.

The author is on the board of experts for this development of an expert's system for special trades, which is sponsored by a federal research grant.

6. CONCLUSION

The current developments in software for product data management are very dynamic in Germany. They will offer a sound basis for application and facilitate the future engineering processes in construction. Even if the developments are designed for use in international environments, still quite a large number of individual solutions will be in operation, which is based on the odds of the German construction market. So it will still take some time, until internationally compatible standards will emerge between the different solutions.

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FORBau: , http://www.fml.mw.tum.de/forbau
MEFISTO: Management – Führung – Information – Simulation im Bauwesen. www.mefisto-bau.de
Plant Simulation: www.plm.automation.siemens.com/en_gb/
Simcomar: www.simcomar.com
SiMOfIT: Simulation of outfitting processes, www.simofit.de

I. MIXED REALITY IN AEC

MIXED REALITY FOR MOBILE CONSTRUCTION SITE VISUALIZATION AND COMMUNICATION

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ABSTRACT: *The goal of the Finnish national research project AR4BC (Augmented Reality for Building and Construction) is to bring the full potential of 4D BIM content and visualization directly to the construction site via mobile augmented reality solutions. This article gives an overall presentation of the AR4BC software system, consisting of the following modules. The 4DStudio module is used to read in BIMs and link them to a project time table. It is also used to view photos and other information attached to the model from mobile devices. The MapStudio module is used to position the building model on a map using geographic coordinates from arbitrary map formats, e.g. Google Earth or more accurate ones. The OnSitePlayer module is the mobile application used to visualize the model data on top of the real world view using augmented reality. It also provides the ability to insert annotations on the virtual model. The OnSitePlayer may be operated either stand-alone, or in the case of large models, as a client-server solution. The system is compatible with laptop PCs, hand held PCs and even scales down to mobile phones. Data glasses provide another display option, with a novel user interface provided by a Wiimote controller. A technical discussion on methods for feature based tracking and tracking initialization is also presented. The proposed system can also be used for pre-construction architectural AR visualization, where in-house developed methods are employed to achieve photorealistic rendering quality.*

KEYWORDS*: BIM, 4D, augmented reality, mixed reality, tracking, rendering, mobile devices, client-server.*

1. INTRODUCTION

The real estate and building construction sector is widely recognized as one of the most promising application fields for Augmented Reality (AR). Recent developments in mobile processing devices, camera quality, sensors, wireless infrastructure and tracking technology enable the implementation of AR applications in the demanding mobile environment. The AR technologies and applications seem to be converging towards more mobile solutions that can almost be characterized as commodities. This is particularly welcomed by the real estate and construction sector where the implementations and benefit realisation of new technologies have been often hindered by cost. The overall convergence towards simpler and more accessible solutions has been more generally identified as a development trend in (Marasini et al. 2006).

The following presents some main use-cases of applying Augmented Reality in the real estate and building construction sector:

1. *Visualization and verification of tasks and plans during construction work.* At some advanced construction sites, 3D/4D Building Information Models (BIMs) are starting to replace paper drawings as reference media for construction workers. However, the model data is mostly hosted on desktop systems in the site office, far away from the target situation. Combined with Augmented Reality, 4D BIMs could facilitate on-the-spot comparisons of the situation at the construction site with the building's planned state and properties at any given moment.

2. *Interactive presentations of newly designed solutions in the context of existing artifacts*. This particularly covers the modernization of existing facilities and building renovations. Such operations are responsible for a continuously growing share of the building construction business in many countries. Therefore solutions for visualizing new designs over currently existing environments are also of importance.

3. *Interactive presentations of temporary objects and their placing*. A construction site is a continuously changing working environment where temporary work arrangements are commonplace. One key application is to produce realistic visualizations and simulations for site personnel to improve site safety and productivity.

4. *Characteristics of the built environment solutions during their life-cycle presented with the actual building object*. BIM information used for visualizing the building elements during construction could often serve also for the building's life-cycle applications.

Altogether, mobile augmented information available at the construction site would have various applications in construction work planning, verification, training and safety, life-cycle management as well as for communication and marketing prior to construction work. The related camera tracking technologies open up further application scenarios, enabling the implementation of mobile location-based visual feedback from the construction site to the CAD and BIM systems. The tracking and interaction techniques can thus be made to serve the complete spectrum of Mixed Reality (Milgram and Kishino 1994), forming a seamless interaction cycle between the real world (augmented with virtual 3D/4D model data) and digital building information (augmented with real world data).

The goal of the Finnish national research project AR4BC (Augmented Reality for Building and Construction) is to bring the full potential of 4D BIM content and visualization directly to the construction site via mobile augmented reality solutions. This article gives an overall presentation of the AR4BC software system, its current state and future plans. The article is organized as follows. Section 2 gives a brief discussion of earlier work in this research field. Section 3 gives an overview of the software architecture. Section 4 explains the implementation and functionality of the core software modules in several subchapters accordingly. The camera tracking solutions are discussed in Section 5, followed with methods for photorealistic rendering in Section 6. Items for future work are pointed out in Section 7 and concluding remarks are given in Section 8.

2. RELATED WORK

The use of Augmented Reality for building and construction applications has been studied by various authors over the years. The first mobile system for general AR applications was presented by Feiner et al. (1997). Extensive research on outdoor AR technology for architectural visualization was carried out a decade ago by Klinker et al (2001). Reitmayr and Drummond (2006) were among the first to present robust feature based and hybrid tracking solutions for outdoor mobile AR. Izkara et al. (2007) provide a general overview of today's mobile AR technology, with specialized applications in safety evaluation. The thesis by Behzadan (2008) gives a wide discussion of AR application in construction site visualizations. Schall et al. (2008) describe a mobile AR system for visualizing underground infrastructure and extend it to state-of-the-art sensor fusion for outdoors tracking in (Schall et al. 2009). These general leads provide a wealth of further references to other related work in the field.

Among our own work in the field, (Woodward et al. 2008) gives a discussion of our general AR related work in the building and construction sector, including mobile, desktop and web based augmented reality solutions. Our work on mobile AR applications dates back to the client-server implementation on PDA devices (Pasman and Woodward 2004; VTT video 2003). Our next generation implementation, "Google Earth on Earth" (Honkamaa et al. 2007; VTT video 2005), provided a marker-free solution for architectural visualization by combining the building's location in Google Earth, the user's GPS position, optical flow tracking and user interaction for tracking initialization. Our mobile AR solution was generalized in (Hakkarainen et al. 2009) to handle arbitrary OSG formats and IFC (instead of just Google Earth's Collada), 4D models for construction time visualization (instead of just 3D), and mobile feedback from the construction site to the design system ("augmented virtuality").

In this article we present the most recent developments and implementation issues with the AR4BC system. These include: managing different map representations; overcoming situations where technology fails to produce automatic solutions (e.g. GPS and map accuracy, tracking initialization and reliability); other mobile interaction issues (e.g. operation with HMD); client-server solutions to handle arbitrarily large models on mobile devices with real time performance; and general discussions of outdoors tracking and photorealistic rendering methods. It is expected that the above issues, regarding practical implementation of two-way mobile mixed reality interaction with complex 4D BIM models, will be of help to other researchers working in the field as well.

3. SYSTEM OVERVIEW

The AR4BC system architecture presented in (Hakkarainen et al. 2009), has been revised and is shown as a schematic illustration; see Figure 1.

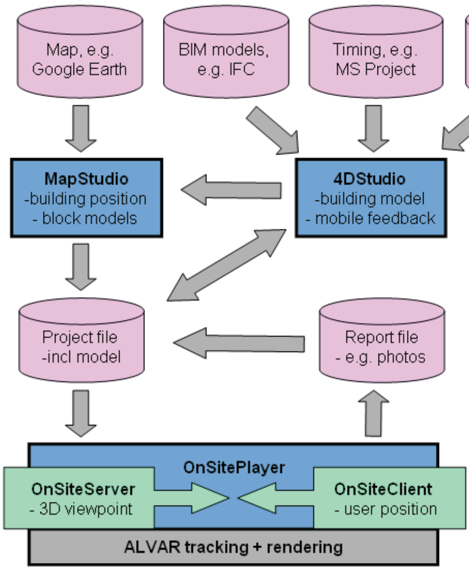

Fig. 1: System overview.

The *4DStudio* module is responsible for handling and modifying the 4th dimension, i.e. the timing information of the BIM. It allows the user to define timelines for the construction steps, as well as visualize the workflow for given time ranges. 4DStudio also provides the user interface to browse and visualize incoming reports created by the mobile user with OnSitePlayer.

The *MapStudio* module is used to position the BIMs on a map using geographic coordinates (position and orientation). It takes as input a map captured from Google Earth or other map data bases. MapStudio can also be used to add some additional models around the construction site, to mask the main construction model or to add visual information of the surroundings.

The *OnSitePlayer* module provides the user interface for augmented reality visualization, interaction and capturing feedback from the construction site. OnSitePlayer is able to augment the models in the right position (location, orientation and perspective) in the real world view by utilizing the model's geographic coordinates in combination with the user's position. User positioning can be automatically computed using GPS, or manually defined using a ground plan or a map of the site.

The *OnSiteClient* module provides a lightweight mobile version of OnSitePlayer. Rendering of complex models is accomplished by using 2D spherical mappings of the model projected to the client's viewing coordinates. The viewing projection is provided by the server module, *OnSiteServer*, which only needs to be updated once in a while (not in real-time). The goal is that the user should not even be aware of communicating with a server, and have the same user experience as with the stand-alone OnSitePlayer.

Our *ALVAR* software library provides generic implementations of marker-based and markerless tracking. For rendering, OpenSceneGraph 2.8.2 is used and the GUI is built using the wxWidgets 2.8.10 framework. The applications can handle all OSG supported file formats via OSG's plug-in interface (e.g. OSG's internal format, 3DS, VRML) as well as IFC, using the parser module developed by VTT.

4. IMPLEMENTATION

This Section presents the overall implementation of the system. Emphasis is put on new functionality that has been implemented since our previous article (Hakkarainen et al. 2009). The discussion is given mainly from the user interface and interaction point of view, omitting most technical and mathematical details. Tracking and rendering issues are treated in two separate Sections, with a discussion reaching also beyond the current implementation.

4.1 4DStudio

The 4DStudio application takes the building model (in IFC or some other format) and the construction project schedule (in MS Project XML format) as input. 4DStudio can then be used to link these into a 4D BIM. To facilitate the linking, the application uses project hierarchies. This means that a large number of building parts can be linked together at once. Once the linking has been performed, 4DStudio outputs project description files including the model itself and the timing information as an XML file.

A recently implemented feature is the ability to read in 4D BIMs defined with Tekla Structures. Version 16 of Tekla Structures contains a new module called Task Manager, which can be used to define the building tasks and link them with building parts. The model data loaded with Tekla Structures is exposed through the Tekla Open API. Using this API, the tasks and links defined in Tekla Structures Task Manager can be written to an XML file. 4D Studio can then read this XML file and import the building tasks and links.

Various tools are provided for visualization and interaction with the 4D BIMs; see (Hakkarainen et al. 2009). 4DStudio has a list of all the building parts, a list of all building project tasks, as well as a list of all linked tasks, from which the user can select desired elements for visualization. Also, feedback report items are shown in a list. The report items describe tasks or problems that have been observed at the construction site by workers. Each item contains a title, a task description, a time and location of the task, and optionally one or several digital photos. The user can easily move from the report items list to the spatial 3D model and back.

4.2 MapStudio

The MapStudio application is used to position the models into a geographical coordinate system, using an imported map image of the construction site. Geographical coordinates denote the combination of GPS position and rotation around the model's vertical axis. The models are imported from 4DStudio, and can be of any OSG compatible format or IFC format. The model can either be a main model or a so-called block model. A block model has an existing counterpart in the real world, usually a building or more generally any object in the real world. Block models can be used to enrich the AR view, or these models are used to mask the main model with existing buildings, in order to create the illusion that real objects occlude the virtual model. If needed, the system can also add clipping information to the models, for example the basement can be hidden in on-site visualization.

As one option, the geographical map can be imported from Google Earth. First, MapStudio initializes the Google Earth application. Second, the user locates the desired map position in Google Earth's view and selects the viewing range to allow for the addition of building models, user position and other information (see below) on the map. However, Google Earth maps are not very accurate and can contain errors in the order of tens of meters. Therefore, MapStudio has recently been enhanced with the option to use raster geospatial data formats like GeoTiff. The image import is done using the open source Geospatial Abstraction library. GDAL supports several geospatial raster formats, which typically offer much better accuracy than Google Earth maps.

After the required view is defined in Google Earth or another map source, the user switches back to MapStudio. MapStudio captures the chosen view of the map and gathers the view's GPS values via Google Earth COM API or GDAL. Now the map layout is available in MapStudio and the GPS information is transferred to the rendering coordinates and vice versa. The user can finally position the BIM models on the map, either by entering numerical parameters manually or by interactively positioning the model with the mouse. See Figure 2.

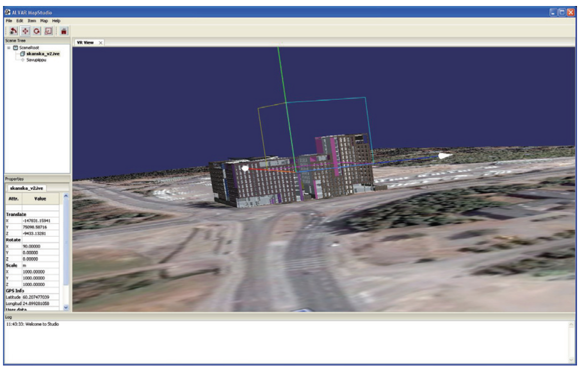

Fig. 2: Building model placed in geo coordinates using MapStudio.

Once the main model has been defined, additional block models and other information may be added and positioned in geographical coordinates. Finally, the AR scene information is stored as an XML based scene description, the AR4BC project file, ready to be taken out for mobile visualization on site.

4.3 OnSitePlayer

The OnSitePlayer application is launched at the mobile location by opening a MapStudio scene description, or by importing an AR4BC project file containing additional information. The application then provides two separate views in tabs; a map layout of the site with the models including the user location and viewing direction (see Figure 3) and an augmented view with the models displayed over a real-time video feed (see Figure 4).

The user is able to request different types of augmented visualizations for the model based on time. The default settings show the current work status based on the current time and planned work start time. The system uses different colors to display different phases (finished, under construction, or not yet started). The user can also define the visualization start-time and end-time freely (e.g. past work or planned tasks for next week). The model can be clipped on the view by using clipping planes (6 clipping planes, 2 for each axis). The model can also be shown partially transparent to see the real and existing structures behind the virtual ones.

The OnSitePlayer is able to store augmented still images and video from the visualization, to be reviewed at the office. The user is also able to create mobile reports, consisting of still images annotated with text comments. Each report is registered in the 3D environment at the user's location, camera direction, and moment in time. The reports are attached to the BIM via XML files and are available for browsing with 4DStudio, as explained above.

4.3.1 Interactive positioning

Normally, the user's location on the site is determined using an external GPS device via a Bluetooth connection. However, GPS positioning does not always work reliably (e.g. when indoors) and is also the source of several errors. Therefore, the user has an option to indicate their location interactively. The system presents the user with the same map layout as used in the MapStudio application and an overlayed camera icon representing the location and viewing direction. The latter can be adjusted using simple mouse interactions. See Figure 3.

Fig. 3: User position, building model and placemark on the map layout.

Interactive positioning is strongly recommended when using Google Earth maps and/or consumer level GPS devices. The GPS accuracy is roughly 10-50 meters, and if there is also an error in the map's geographical information the total error is even more significant. By using manual positioning, the errors in model and user-location positioning are aligned and thus eliminated from the model orientation calculation.

4.3.2 Aligning options

Once the position of the user and the virtual model are known, they provide the proper scale and perspective transformations for augmented reality rendering. Combined with compass information, model based tracking initialization, feature based tracking and hybrid methods, the system should now be able to automatically augment the model over the live video feed of the mobile device. In practice however, some part of the tracking pipeline may always fail or be too inaccurate; thus we provide also interactive means for initial model alignment before tracking methods take over. The aligning of the video and the models can be achieved in several ways.

Once the scene is loaded and the user's position is initialized, the models are rendered as they look from the user perspective, although not at right location yet. The user can then interactively place the model in the right location in the view. This is a reasonably easy task if the user has some indication of how the building model should be placed in the real world. For example, during construction work the already installed building elements can be used as reference. Placing an architect's visualization model on the empty lot can be more challenging. Therefore, two additional interactive positioning options are provided; block models and placemarks.

Block models, as described above, are 3D versions of existing features (like buildings) in the real world. By placing the virtual block model on top of the real world counterpart, the user is able to intuitively align the video view and models. However, this approach requires modeling parts of the surrounding environment which might not always be possible or feasible. A more general concept is to use the placemarks and viewfinder approach.

In MapStudio, the author is able to place placemarks on the view (see Figure 3). The placemarks only have GPS coordinates as properties. The placemarks should mark clearly visible and observable elements in the real world (e.g. street corner, chimney, tower, etc.). With OnSitePlayer, the user then selects any of the defined placemarks and points the viewfinder towards it. When the user presses a key to lock the placemark with the viewfinder, the system calculates the "compass" direction accordingly and aligns the actual models to the view. Afterwards the models are kept in place by tracking methods. See Figure 4.

Fig. 4: Mobile video showing viewfinder for the placemark, and building model augmented with OnSitePlayer.

4.3.3 HMD and Wiimote

In bright weather conditions, the laptop's or hand held device's screen brightness might not be sufficient for meaningful AR visualization. Head mounted displays (HMD) offer a better viewing experience, but they also create issues for user interaction. When aligning the model and video over a HMD, the user should not have to operate a mouse/stylus or find the right keys from the keyboard to press. To overcome this problem, a Nintendo Wiimote is integrated into the system and used as an input device. With a Wiimote, the user is able to select between placemark and model based aligning, as well as lock the model to the view. The user is also able to use Wiimote to change the viewing direction (compass) and altitude value to meet the real world conditions.

4.4 Client-server implementation

Virtual building models are often too complex and large to be rendered with mobile devices at a reasonable frame rate. This problem is overcome with the development of a client-server extension for the OnSitePlayer application. Instead of trying to optimize the 3D content to meet the client's limitations, we developed a 2D image based visualization technique that replaces the 3D model with a spherical view of the virtual scene surrounding the user (Hakkarainen and Kantonen 2010).

The client extension, OnSiteClient, is used at the construction site while the server extension, OnSiteServer, is running at the site office or at some other remote location. The client and server share the same scene description as well as the same construction site geographical spatial information. The client is responsible for tracking the user's position in the real world, while the server provides projective views of the building model to the client. The projective views are produced for a complete sphere surrounding the user's current position, and the client system chooses the correct portion of the sphere to be augmented by real time camera tracking.

Our solution generally assumes that the user does not move about while viewing. This is quite a natural assumption, as viewing and interacting with a mobile device while walking would be quite awkward or even dangerous, especially on a construction site. The user's location in the real world is transmitted to the server, and augmenting information is updated by the user's request. Data communication between the client and server can be achieved using either WLAN or 3G. The communication delays from a fraction of a second to a couple of seconds are not an issue, since the projective views used for real time augmenting only need to be updated occasionally.

After receiving the user's position, the server renders the scene for a whole sphere surrounding the corresponding virtual camera position. In the implementation, the sphere is approximated by triangles, an icosahedron in our case. An icosahedron was chosen since it is a regular polyhedron formed from equilateral triangles, therefore simplifying the texture generation process. The number of faces is also an important parameter as increasing number of faces increases the resolution of the resulting visualization and at the same time increases the number of images to be transferred to the client.

To create the triangle textures required for the spherical view around the user's position, the server aligns the virtual camera so that each triangle is directly in front of the camera, perpendicular to the viewing direction, and with one of the triangle edges aligned horizontally. The view of the scene is then rendered and the resulting image is capture and stored for use as a triangle texture in the client side rendering. For each image, the depth information of the picture is analyzed at the pixel level to verify whether there is 3D model information present or not. If there is no model information present, the pixel's alpha value is set fully transparent to allow the client's video feed to be visible. If the entire image does not contain any 3D model information, it is considered as fully transparent.

After the spherical 2D images are created, they are sent to the client. Since the client has the same faceted sphere representation as the server, the client is able to create a 3D illusion of the scene from the user's view point by positioning the sphere at the virtual camera and rendering the textured sphere over the video image. After aligning the view with the current viewing direction, the user is able to use camera tracking to keep the 2D visualization in place and pan/tilt the view in any direction as desired. The same sphere visualization can be used as long as the user remains in the same place.

5. TRACKING

Camera tracking is one of the most important tasks in video-see-trough augmented reality. In order to render the virtual objects with the correct position and orientation, the camera parameters must be estimated relative to the scene in real-time. Typically, the intrinsic parameters of the camera (e.g. focal length, optical center, lens parameters, etc.) are assumed to be known, and the goal is to estimate the exterior parameters (camera position and orientation) during tracking. The combination of several sensors, from GPS to accelerometers and gyros, can be used to solve the problem, but computer vision based approaches are attractive since they are accurate and do not require extra hardware. Markerless tracking methods refer to a set of techniques where the camera pose is estimated without predefined markers using more advanced computer vision algorithms. A comprehensive review of such methods can be found in (Lepetit 2005).

We developed two markerless tracking methods to be used in different use cases. With the OnSiteClient application, the user is assumed to stand at one position, relatively far from the virtual model, and explore the world by panning the mobile device (camera). Thus, the pose estimation and tracking problem is reduced to estimating the orientation only. On the other hand, with the stand-alone OnSitePlayer, we allow the user to move around the construction site freely, which requires both the position and orientation of the camera to be known. In both cases, we assume that the scene remains mostly static.

In the first option, we use GPS to obtain the initial position, and the orientation is set interactively with the help of a digital compass. As the user starts to observe the virtual model and rotate the camera, we detect strong corners (features) from the video frames and start to track them in the image domain using the Lucas & Kanade algorithm as implemented in the OpenCV computer vision library. Every image feature is associated with a 3D line starting from the camera center and intersecting the image plane at the feature point. As the tracker is initialized, the pose of the camera is stored and the update process determines the changes in the three orientation angles by minimizing the re-projection errors of the 3D lines relative to image measurements. We use a Levenberg-Marquardt (LM) optimization routine to find the rotation parameters that minimize the cost. However, moving objects such as cars or people and drastic changes in illumination like direct sunlight or reflections can cause outliers to become tracked features. Hence, we apply a robust Tukey M-estimator in the optimization routine. After each iteration loop, the outliers are removed from the list of tracked features by examining the re-projection errors of each feature, and deleting the ones with a re-projection error larger than a pre-defined limit. New features are added to the list when the camera is rotated outside the original view, and features that flow outside the video frame are deleted.

In the second option, we use the actual 3D coordinates of the tracked features for updating the camera pose. We obtain them by first initializing the camera pose and rendering the depth map of the object using OpenGL. Then, we detect strong corners from the video, and calculate their 3D coordinates using the depth map. The features that do not have a depth are considered as outliers and removed from the list. The tracking loop proceeds similarly to the first case, except that all of the six exterior parameters of the camera are estimated. The initial position of the camera is acquired interactively by defining six or more point pairs between the 3D model and the corresponding image of the model within the video frame. As the point correspondences are defined, the direct linear transformation (DLT) algorithm is used to find the pose which is then refined using LM.

Fig. 5: OnSitePlayer using UMPC, and underlying features for tracking.

Although the presented methods allow us to visualize different stages of the construction on-site, they suffer from the same problems: drift and lack of automated initialization and recovery. Since the features are tracked in the image domain recursively, they eventually drift. Additionally, the pose estimation routines are recursive, and they proceed despite drifting features and severe imaging conditions such as a badly shaking camera. When the tracking is lost, the user must re-initialize it manually. To overcome these problems, we have two solutions planned. First, we will take advantage of feature descriptors like SURF and Ferns, and store key poses along with corresponding features and descriptors. The initialization and recovery could be then performed by detecting features from the incoming video frames and pairing them with the stored ones to find the closest key pose. Second, we will use the initial pose from the digital compass and GPS as *a-priori*, and render the model from the corresponding view. Then, the rendered model could be compared to the video frame to fine-tune the camera pose parameters. We will also study the possibility of applying these approaches to detect and compensate for drift.

6. RENDERING

Photorealistic real-time rendering techniques are important for producing convincing on-site visualization of architectural models, impressive presentations to different interest groups during the planning stage and accurate building renovation mock-ups. We have experimented with some rendering and light source discovery methods described in (Aittala 2010) and integrated them into the OnSitePlayer application. However, on-site visualization of architectural models differs somewhat from general purpose rendering. For optimal results, the methods should be adapted to the particular characteristics of the application. In the following, we present some key characteristics that are typical for on-site visualization applications.

Typical architectural models originate from 3D CAD programs, which are often geared towards design rather than photorealistic visualization. The data is often stored in problematic format from rendering standpoint. Polygons may be tessellated very unevenly. For example, a large exterior wall may be represented by a single polygon, whereas the interiors may contain highly detailed furniture (of course, invisible from outside). Elongated polygons and flickering coplanar surfaces are also common. Hence, methods which are insensitive to geometric quality are prefered; for example shadow maps to shadow volumes.

The lighting conditions can be complex due to a wide variance of skylight and sunlight in different weather conditions and throughout the day. Regardless, the illumination can be characterized as a linear combination of very smooth indirect skylight and intense, directional and shadow casting sunlight. In terms of rendering, the former provides hints for ambient occlusion methods and the latter for soft shadows. Combining these two components in different colors, intensities, sunlight direction and shadow blurriness can produce a wide array of realistic appearances.

We have experimented with a screen-space ambient occlusion method and a soft shadow map algorithm as described in (Aittala 2010). However, it appears that high frequency geometric details found in most architectural models cause severe aliasing artifacts for the screen-space ambient occlusion method. The aliasing can be reduced by supersampling (rendering to a larger buffer), but this comes with an unacceptable performance penalty, especially for mobile devices. We are planning modifications to the algorithm based on the observation that the model and the viewpoint are static. Coarse illumination could be computed incrementally at high resolution and averaged across frames. Likewise, the present shadowing method occasionally has problems with the high depth complexity of many architectural models. We plan to experiment with some alternative shadow mapping methods.

Determining the lighting conditions can be simplified and improved by considering the lighting as a combination of ambient light (the sky) and a single directional light (the sun). The direction of the sunlight is computed based on the time of day, the current orientation and GPS information. What remains to be determined are the intensity and the color of both components, as well as the shadow sharpness. Our lightweight and easy to use inverse rendering method (Aittala 2010) is based on a calibration object, such as a ping pong ball. We plan to adapt it to the particular two-light basis of this problem. More complex methods would make use of physical skylight models and attempt to recover the model parameters. Changing the lighting also presents a challenge; while the sun direction and the sky color themselves change little over reasonable periods of time, drifting clouds may block the sun and cause notable illumination changes during a single viewing session.

Finally, the real world camera aberrations are simulated in order to produce a more convincing result when embedding the rendered images over the video. The quality of rendered images is often unrealistically perfect, whereas the actual cameras exhibit a wide range of imperfections. This makes the rendered models stick out and look artificial over the video, even if the rendering itself is realistic. Effects such as unsharpness, noise, Bayer interpolation, in-camera sharpening and compression are simulated as post-processing effects (Klein and Murray 2008). Other considerations related to images, are with the use of properly gamma corrected color values at all stages. For example, linearized values are used up until the final display. Also multisample antialiasing is used, which is particularly helpful with typical high-frequency geometric detail such as windows.

7. FUTURE WORK

Up to now, we have conducted field trials mainly with architectural visualization, for example, the new Skanska offices in Helsinki (Figures 2-4; VTT video 2009). Experiments including 4D BIMs have been conducted with models “taken out of place”, without connection to the actual construction site. Field trials at a real construction sites are planned to start at end of year 2010. In the pilot test cases, we look forward to not only demonstrating the technical validity of the system, but also obtaining user feedback to be taken into account in future development.

Our goal is to complete the AR4BC system with the intended core functionality in the near future. Plans for tracking and rendering enhancements were discussed in the two previous Sections. For example, in the AR visualization of a new component in the Forchem chemical plant (Figure 5; VTT video 2010), feature based tracking was not yet fully integrated with the AR4BC geographic coordinate system, and tracking initialization was done manually. Photorealistic rendering is another area where a lot of the required technology already exists, but there is room for improvements for long time to come.

Since the OnSiteClient software is free of all heavy computation (3D tracking, rendering, etc.) it could actually be ported also to very lightweight mobile devices. Current smart phones and internet tablets offer GPS, WLAN and other connectivity, compass, accelerometer, large and bright screens, touch interaction and other properties all at affordable prices. This makes them a perfect choice for future mobile AR applications, both for professional use as well as for wider audiences.

8. CONCLUSIONS

In this article we have given an description of the AR4BC software system for mobile mixed reality interaction with complex 4D BIM models. The system supports various native and standard CAD/BIM formats, combining them with time schedule information, fixing them to accurate geographic coordinate representations, using augmented reality with feature based tracking to visualize them on site, applying photorealistic rendering for a convincing experience, with various tools for mobile user interaction as well as image based feedback to the office system. The client-server solution is able to handle arbitrarily complex models on mobile devices, with the potential for implementation on lightweight mobile devices such as camera phones.

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A PROJECTIVE MOBILE DEVICE FOR PRESENTING LOCATION-BASED BUILDING INFORMATION IN A CONSTRUCTION SITE

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ABSTRACT: *We have developed a wearable device called iHelmet that projects construction drawings and related information according to users' needs. This device avoids engineers carrying bulky construction drawings to the site and reduces the effort required in looking for the correct drawings to obtain the information they need. This device includes four modules: the information integration module, the display module, the positioning module and the manipulation module. The information integration module is used to transfer the information in the building information model (BIM) into images to enable the onsite retrieval from the device we developed. The position module enables users to input their locations and automatically search for the images that the users might need. The manipulation module can analyze the gestures of the users from the touch screen and accelerometer in the devices, and then crop the images to eliminate the unneeded information. The display module, which directly links to the projector, can continually calculate the images processed by the previous three modules and scale the images accordingly, ensuring that the projection results in a correct scale. We also developed a hardware device to implement the four modules. It consists of a construction helmet (weight: 460g), an iPod Touch (weight: 115g) and an Optoma LED projector (Weight: 114g). To validate the usability of the iHelmet onsite, we conducted a user test with 34 participants. We compared the efficiency and effectiveness of retrieving building information using the iHelmet with using the traditional 2D drawings approach. The results showed that the mean completion times were significantly shorter for participants using the iHelmet (iHelmet: 44 seconds, traditional approach: 99 seconds). The mean success rates of participants arriving at the correct answers were also significantly improved for those using the iHelmet (iHelmet: 91.6%, traditional approach: 64.3%).*

KEYWORDS*: Building information model, augmented reality, mobile device, projector, wearable computing.*

1. INTRODUCTION

1.1 Challenges in Exploring Building Information

One of the key challenges faced by construction engineers in the exploration of building information is the efficient and effective retrieval of onsite construction information from 2D drawings and their interpretation. Many engineers have highlighted the cumbersome and inefficient nature of the exploration and selection of building information from the large format 2D drawings at the construction site.

There are three main problems with current practices of using 2D drawings to explore building information. Firstly, 2D drawings have poor portability and maneuverability. Two-dimensional drawings are printed on large format paper and on different sheets to present the large amount and range of required information. Their large size makes them very inconvenient and even dangerous to carry around in the complex and dynamic construction site environments. This problem is further compounded by users having to sift through numerous reference drawings to find the correct drawing that corresponds with the particular onsite location. Secondly, the dimensional limitation of representation on 2D drawings presents difficulties for representing spatial relationships between building elements in a 3D environment. Users are loaded with the additional cognitive step of translating information from 2D to 3D visualizations to match the real environment. Thirdly, users encounter browsing and readability problems. These problems arise due to the use of numerous predefined symbols for different construction components in 2D drawings, and this tends to hinder the clarity of information and intended meanings for users. Users would normally need to peruse the 2D drawings numerous times to clarify a symbol's meaning, making this process inconvenient and inefficient.

With the rapid advances in computer technology, particularly in the area of graphics capabilities, the concept of using 3D computer models for the exploration of building information using powerful desktop computers has seen increasing interest. However, desktop computers are not very mobile and would be inconvenient for use at construction sites.

1.2 Related Works

Various approaches have been attempted to solve the above-mentioned problems related to information access, dimensional representation, visualization and display. These approaches can be classified as innovations in information integration, information display, and harnessing of mobile devices.

1.2.1 Information integration

Several attempts have been made to improve information integration to increase the efficiency of browsing building information. Some approaches involve the use of model-centric information for 4D modeling (Chang et al., 2009, Chau et al., 2005, McKinney and Fischer, 1998, Staub-French and Khanzode, 2007, Tsai et al., 2010), *n*-dimensional modeling (Aouad et al., 2006), and Building Information Model (BIM) modeling (Koo and Fischer, 2000, Bouchlaghem et al., 2005, Goedert and Meadati, 2008) to integrate the information, and represent the required information in 3D model format.

1.2.2 Information display

Many attempts have also been made to enable better readability and visualization of building information by using innovative display methods. Some notable innovations have taken advantage of virtual reality (VR) and augmented reality (AR) technologies for the immersive display of building information. VR is commonly applied to computer-simulated environments that enable users to interact with virtual environments or virtual artifacts (Maruyama et al., 2000). AR can be viewed as an extension of VR where virtual objects are inserted into predominantly real world situations. This, in turn, enhances an individual's perception of his or her environment due to the increased availability and explicitness of the virtual objects (Wang and Dunston, 2006, Kamat and El-Tawil, 2007).

1.2.3 Wearable and mobile devices

Numerous researchers have also taken advantage of the rapid advances in wearable and mobile devices, employing them innovatively in construction sites (Williams, 2003). Present mobile devices have very advanced capacities and capabilities for storage, retrieval and management of detailed information on a wide range of construction materials, site data and equipment data (Lipman, 2004, Reinhardt et al., 2005). There appears to be increasing popularity of the use of wearable and mobile computing tools to support construction work (Williams, 1994).

1.3 Research Goals

Our aim for this research was to develop a lightweight device that could project construction drawings and related information based on users' locations. We leveraged on BIM and AR technologies to develop a system which could not only simply provide better integration of information, but also provide information display that would be more readable and easily visualized compared to traditional technologies and approaches. The developed system and device was to be lightweight, portable and maneuverable, and suitable for users at construction sites. Given that helmets are necessary onsite equipment in the architecture, engineering and construction (AEC) industry, we designed our solution around this essential onsite safety equipment.

2. System Architecture

The system and device that we have developed is called iHelmet. The system architecture of the iHelmet system is shown in Fig. 1. The iHelmet system architecture comprises three layers, namely the user interface layer, data process layer and data storage layer. Each layer is made up of the functional modules shown in Fig. 1. The directions of the connecting arrows in Fig. 1 represent the direction of data processing or message transfer.

The **user interface layer** comprises three modules: the display module, the positioning module, and the manipulation module. It provides the manipulation and interaction to the image-based model for user and sent the feedback to the user visually through the display module.

The **data process layer** contains the image-based model which is a component of the information integration module. Depending on the manipulation commands sent from the user, the image-based model will execute the corresponding changes. As the image-based model changes, the projection will adjust simultaneously.

The **data storage layer** is made up of the BIM model, another component of the information integration module. The BIM model is used for storing all the components of the room and the information of the various components. In this system framework, a user can directly manipulate the image-based model and obtain immediate visual feedback.

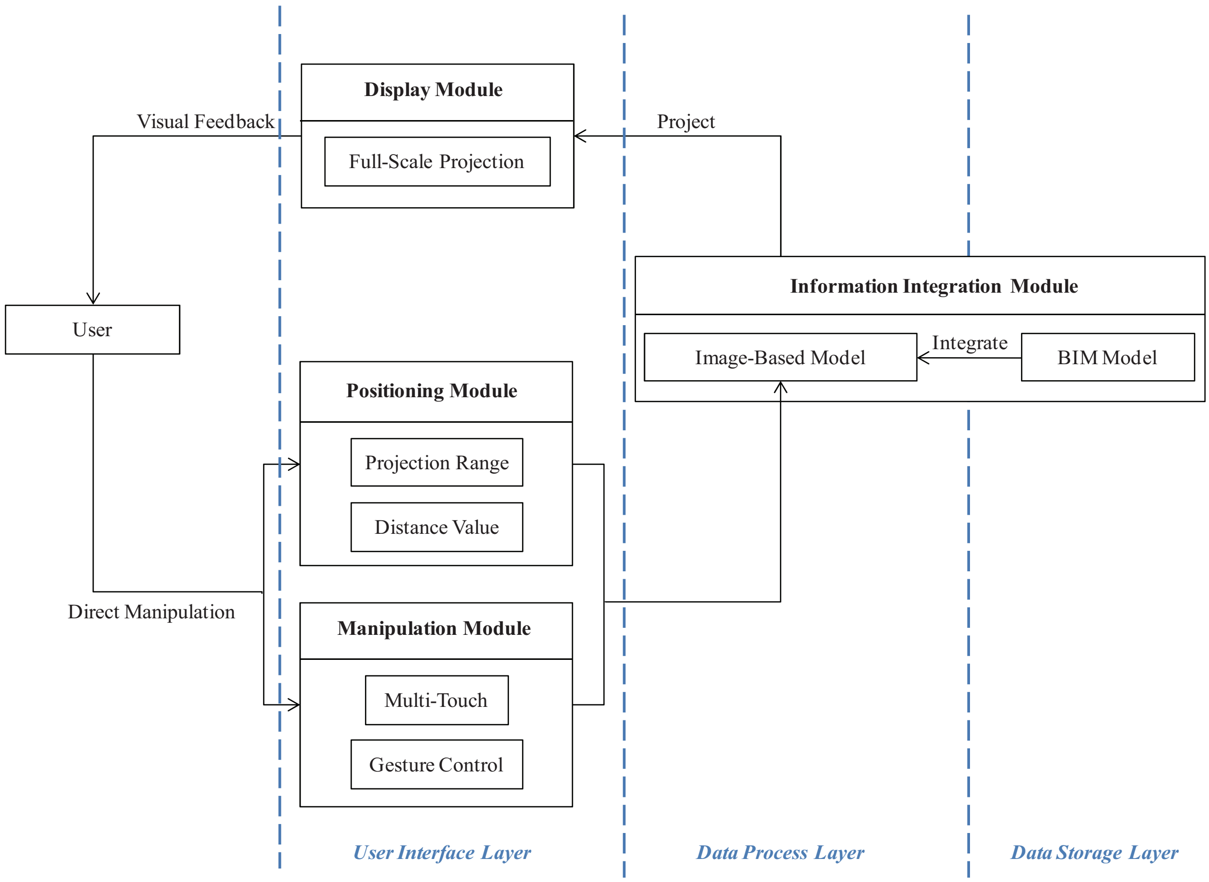


Fig. 1: System architecture

3. Design and Implementation of iHelmet

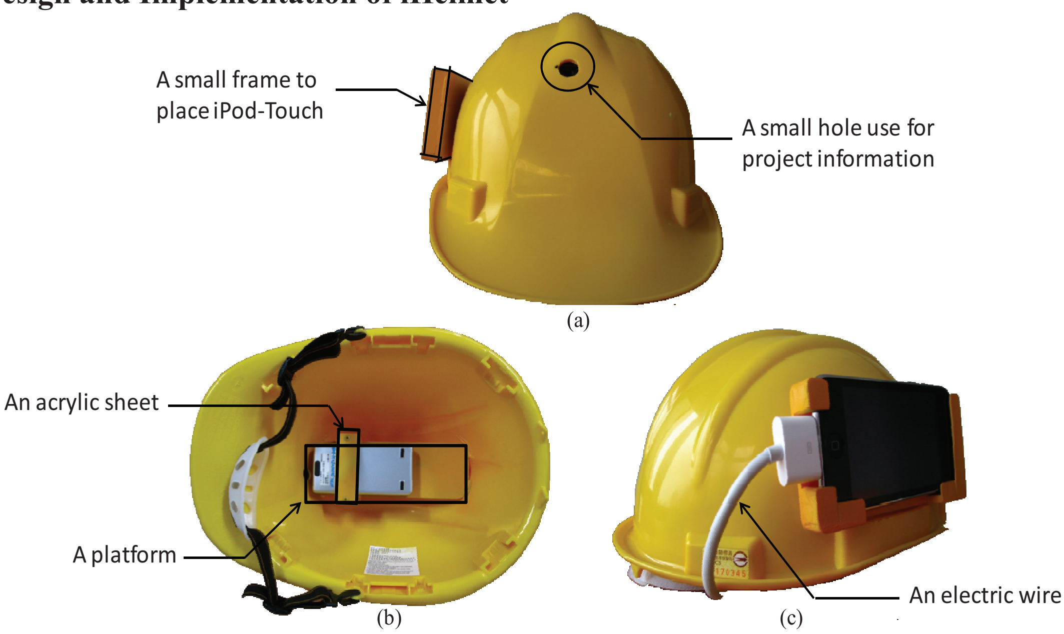


Fig. 2: The hardware setting of iHelmet: (a) A small hole and a small frame on the helmet; (b) A platform and an acrylic sheet inside the helmet; (c) An electric wire to connect the mobile device with the projector.

We based our design around a helmet (an essential piece of onsite equipment in the AEC industry, as mentioned above) that would fit both the iPod-Touch and the projector. As shown in Fig. 2, some modifications were made to the helmet. A small frame was set up on the right side of the helmet to secure the mobile device, as shown in Fig. 2 (a). We created a small hole to allow the mini projector to project the building information, and installed a platform inside the helmet to fit the projector. To secure the projector to the helmet, a small piece of acrylic sheet was used, as shown in Fig. 2 (b). We used an electric wire to connect the iPod-Touch to the projector, as shown in Fig. 2 (c).

4. Module Implementations

We designed and implemented four modules for the iHelmet system: the information integration module, the positioning module, the manipulation module, and the display module. The following describes these modules in detail.

4.1 Information Integration Module

The information integration module retrieves building information from a BIM model and integrates the information into an image-based model. The main advantage of an image-based model is the efficiency in loading and displaying the model. The image-based model displays the building information through a series of images. The efficiency of loading and displaying only depends on the resolution and compression format of the image. Therefore the image-based approach can improve the efficiency of browsing information.

In this research, we used Autodesk Revit to build a BIM model. This BIM model contains all of the building information including floor plans, section plans, piping plans, electric plans, and detailed information about building elements such as the dimensions of pipes and rebars, and the information of each socket. Information was retrieved from this BIM model in an image format and these images were integrated into an imaged-based model.

4.2 Positioning Module

The positioning module can be specified by the location of a user, which is an essential step to provide location-based information. Fig. 3 shows the procedure of positioning. The users first need to select a floor in order to obtain the floor plan. Then, users need to select a view unit such as a room in the floor plan. The view unit represents a room or public area where the users are in. The users then specify their location. We provided two instructions (distance value and projection range) to help specify the user's position, in order to make the positioning more precise. The users can then obtain related detailed information based on their location.

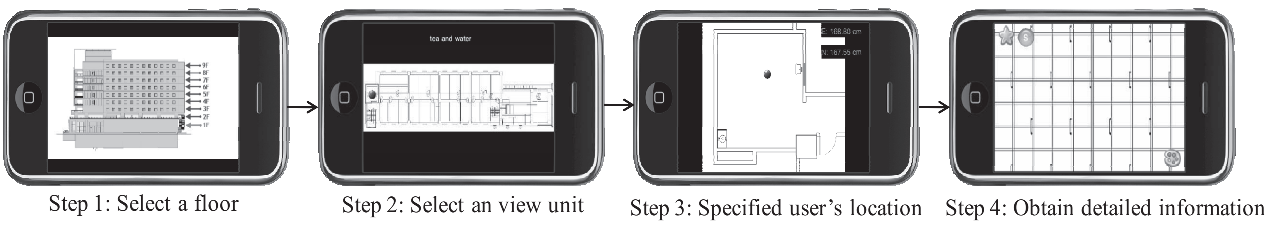


Fig. 3: Procedure of positioning

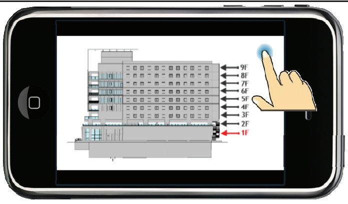
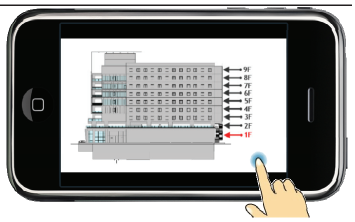
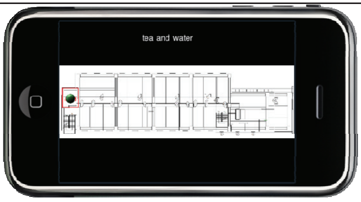
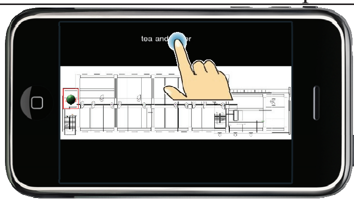
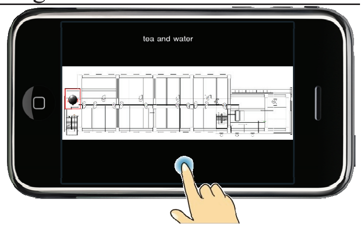
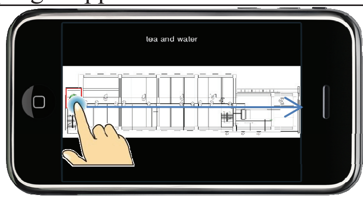
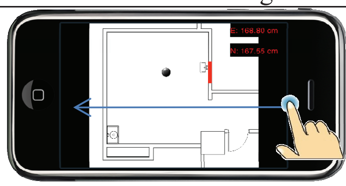
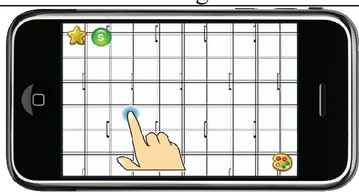
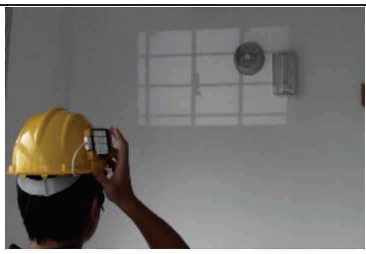
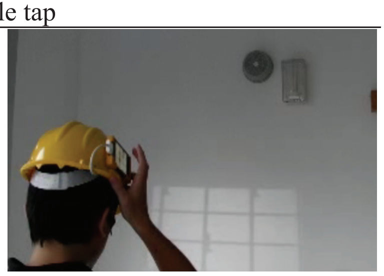
4.3 Manipulation Module

The manipulation module can simplify the process of browsing information so users can browse and diagnose problems from the information efficiently. Users are allowed to remove the iPod-Touch from the helmet to specify their location. After specifying the location, users would re-mount the iPod-Touch on the helmet so as to exploit the accelerometer on the iPod-Touch for gesture control. We proposed four kinds of control types, as shown in Table 1.

4.4 Display Module

In order to provide users with more intuitively visualized and realistic information, we proposed using a full-scale projection to display the information. Different positions should have different scale ratios to generate full-scale projection. We first have to specify user's position, as discussed in Positioning Module. Then we calculate the scale ratio of the projection. We can get the projector's throw ratio (Distance/Width) from the user manual of the projector. Using the throw ratio, we can calculate the scale ratio.

Table 1: Four kinds of control types

Control Type	Purpose	Description
Tap	Select a floor	  Tap right upper side to select upper floor; Tap right lower side to select lower floor
	Select a view unit	 Tap and drag
	Lock/Unlock the view unit	  Tap right upper side; Tap right low side
Slide	Enter the next view	 Slide from left to right
	Return to previous view	 Slide from right to left
Double Tap	Obtain detailed information	 Double tap
Gesture control	Change vertical view range	  Look up; Look down

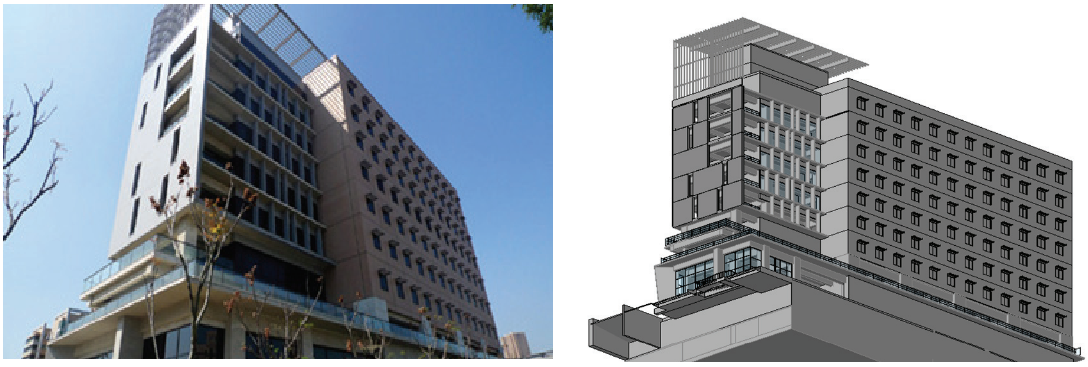
5. Validation

To validate the usability of iHelmet, we conducted a user test. In the following sections, we will introduce details of the user test, including an example case, the test plan, test participants, test environment, results, and findings from this user test.

5.1 Example Case

We created an example case to validate the practicality of using iHelmet. We built a virtual research building model, which has 4163 elements in the 3D model. Here we intended to verify how effectively iHelmet can help users to explore and understand relevant construction information. We also investigated, via a user test, whether users can effectively obtain specific building information by exploring information from iHelmet. The details are described as follows.

In this example case, we used the Civil Engineering building at National Taiwan University as a reference for our BIM model, as shown in Fig. 4. The example case involves eleven ground floors and one underground floor.



(a) (b)

Fig. 4: Example case: (a) a photo of the research building; (b) the BIM model of the research building

5.2 Test plan

As shown in Fig. 5, the test plan followed the 2×4 arrangement (2 is for reference types and 4 is the four levels of questionnaires). All users needed to perform with two reference types, i.e. using iHelmet as their reference and using 2D drawings as their references. Users were also required to answer four levels of questions. The following section explains the test plan in more detail.

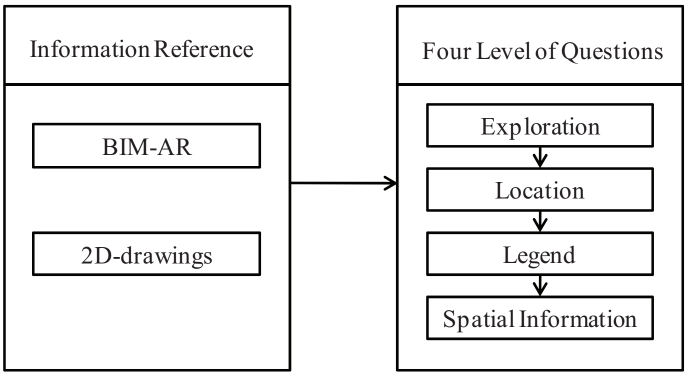


Fig. 5: User test procedure

5.2.1 Information of different reference types

iHelmet: We used an iPod-Touch as the mobile device to store building information and provide an interaction interface. A small battery-powered projector (Optoma LED projector, W × H × D: 50mm × 15mm × 103mm) was installed inside the helmet to project information.

2D drawings: We printed out five series of 2D drawings on A3-size paper, including architecture floor plans, structural floor plans, plans of structural reinforcement, piping plans and electrical plans. Each plan contained a legend to help users to understand the meaning behind the simple symbols.

5.2.2 Questioning

In construction practice, to find specific information on a building, one usually follows some regular steps. The participants were asked to answer four levels of questions which were designed according to these steps. They were: (1) finding the relevant drawing, (2) finding the relevant area, (3) looking up the legend, and (4) translating spatial information. Our test questions were related to these designated steps. They can be briefly described as follows:

Exploration: exploring the relevant drawings in order to find the building information related to the drawings.

Location: finding the location on the map based on the user's location or a specific building element's location in the drawing.

Legend: getting more information about the equipment from the legend.

Spatial information: translating spatial information in order to understand the spatial relationship between the map and the physical reality.

Before the test, we spend about 5-10 minutes to familiar participants with the set of reference drawings that were related to the building project. Participants were asked to provide written responses to each test question. An exception was the spatial information task, where participants marked the correct location directly on the wall using markers we had provided.

5.3 Test participants

There were 34 participants in the user test, 27 male and 7 female. Their ages ranged from twenty-two to thirty-four years. The participants included 11 civil engineers and 23 graduate students with a civil engineering background. All participants had studied construction management related courses.

5.4 Test results

An α level of 0.05 was used for all statistical tests and analysis. The test results assessed how quickly and accurately participants performed the task when using iHelmet. To do so, we measured the completion times and success rates when using iHelmet. They are summarized as follows:

Completion times: The statistical results, including mean value and standard deviation for five dimensions are shown in Fig. 6. All of the questions were considered significant ($p<0.05$) in the t-test. Users of iHelmet spent less time than required for the 2D drawings. In addition, we found that when participants had used 2D drawings as references, an experienced user tended to perfprm better, whereas no difference was observed in the use of iHelmet as reference.

Success rates: The success rates are shown in Fig. 7. Based on the results, we concluded that using iHelmet led to a higher average success rate in three out of four test questions. We also used statistical methods, the t-test and the chi-square test, to see the difference between groups of subjects. We found that the total success rate of testing questions achieved statistical significance.

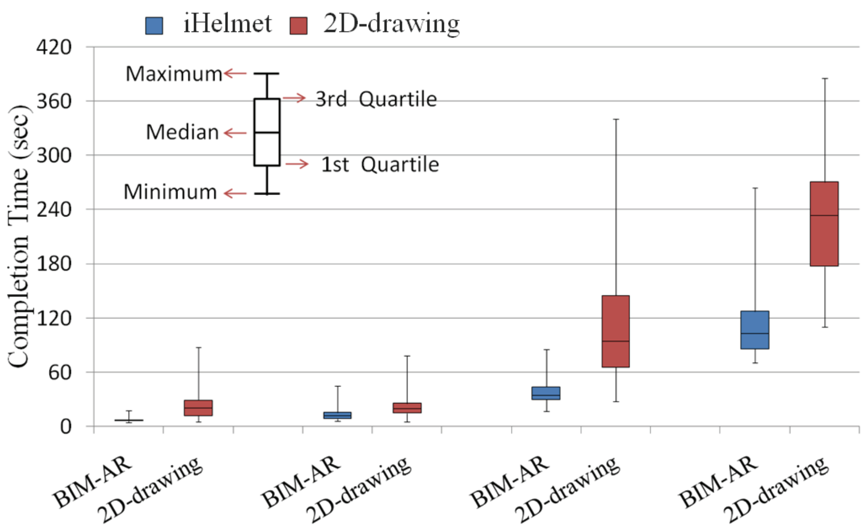


Fig. 6: Test completion times: iHelmet versus 2D-drawing

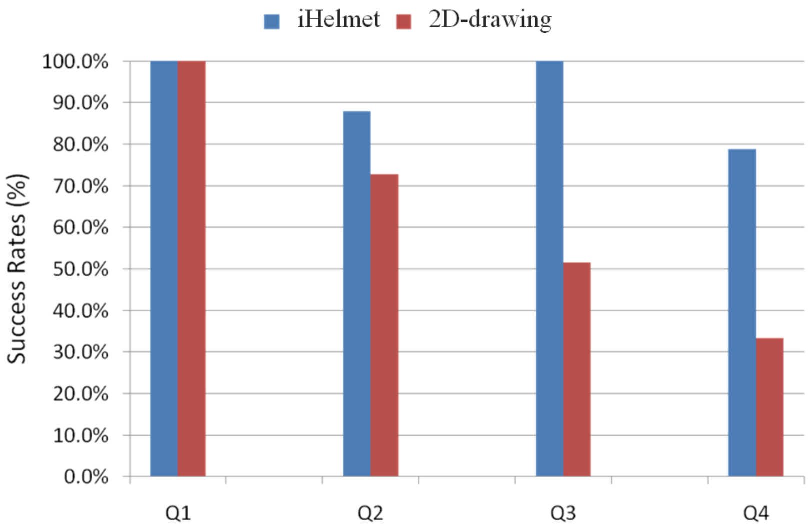


Fig. 7: Test success rates: iHelmet versus 2D-drawing

5.5 Findings from the user test

Overall, the test results were positive regarding the use of iHelmet as a presentation tool for interactive information presentation. We found conclusive evidence in four aspects:

First, we have combined a mobile device and a small projector with a helmet. Most users deemed it to be quite practical for use in construction, because it avoids the need to carry additional equipment and frees the user's hands. A few users opined that they felt uncomfortable with the electronic equipment on their heads.

Secondly, some users pointed out that their line of vision was covered by the helmet, obscuring the projecting information. This problem is due to the helmet's original design, and will continue to be present unless we change the helmet's pattern.

We used a full-scale projection for presenting spatial information. All users agreed that this made it so that they could visualize the information and deliver the information in a more intuitive way. Good presentation of the real-scale projection that is compatible and favorable for presentation will aid users in understanding the information.

Finally, all users agree that this interaction mechanism to browse building information was better than before. They felt that iHelmet could improve the user's cognitive power required to find building related information more precisely.

6. Possible Applications

The iHelmet will be of benefit to the AEC industry, because it has been shown to improve the efficiency of browsing information, and it offers more visualized information to users. Some possible applications of iHelmet include:

Group communication: The iHelmet displays the information through a projection, which offers the opportunity for all members of a group to browse the same information at the same time.

Project review: The iHelmet offers more visualized information to the users based on the location of the users. When reviewing a project, users can find out the information they need more efficiently; moreover, they can easily understand the information even though they don't have related professional knowledge.

Construction lofting: The iHelmet provides full-scale projection to the users. Users can directly exploit the projection to do the construction lofting, which is more convenient for the users.

Maintenance: When doing maintenance, a maintenance worker can easily find out the detailed information of specific equipment using the iHelmet as it integrates all of the information about a building, offers more visualized information based on the location of the users, and provides a more intuitive manipulation to the users.

7. Research Limitation

Despite its many advantages over 2D drawings, the iHelmet has some limitations that could be overcome in future studies. While projecting the information, a display surface (such as a screen or wall) is always needed onsite to view the information, which may sometimes be difficult to find on site, depending on the state of completion of the building. Moreover, enlarging the information image makes the display figures blurred, and decreases the visibility and clarity of the information. Natural lighting may also interfere with the projection quality.

8. Conclusion

The main contribution of this research is the development of a wearable device, iHelmet, to solve the problems of information retrieval in construction sites. The four modules, information integration, positioning, manipulation and display, were implemented in iHelmet to allow engineers to search and obtain the required information in a more efficient and intuitive way. iHelmet allows engineers to input their location in the site, and automatically retrieves the related information in an image format. It can process the images in the real time and then project them in the construction site at the correct scale. Because iHelmet is equipped with a multi-touch screen and an accelerometer, it allows engineers to control the system by gestures. From the user test (N=34) in this research, we compared the users' behaviors to retrieve onsite information using iHelmet with the ones using traditional 2D drawings. We found that users can obtain the information more efficiently and accurately due to the augmented information using iHelmet. This research provides evidence that using the gesture control and augmented reality in iHelmet can reduce the difficulties to retrieve the information on actual jobsites. The construction helmets, which are mandatory for personnel on construction sites, are ideal candidates for storing and displaying onsite building information.

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Resolving Incorrect Visual Occlusion in Outdoor Augmented Reality Using TOF Camera and OpenGL Frame Buffer

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ABSTRACT:

Augmented Reality (AR) has the potential of being an effective visualization tool for planning and operations design in construction, manufacturing, and other process-oriented engineering domains. One of the primary challenges in creating AR visualizations is to project graphical 3D objects onto a user's view of the real world and create a sustained illusion that the virtual and real objects co-exist across time in the same augmented space. However regardless of the spatial relationship between the real and virtual objects, traditional AR scene composing algorithm displays the real world merely as a background, and superimposes virtual objects in the foreground. This creates incorrect visual occlusion artifacts, that in effect breaks the illusion that real and virtual objects co-exist in AR. The research implements and demonstrates a robust depth sensing and frame buffer algorithm for resolving incorrect occlusion problems in outdoor AR applications. A high-accuracy Time-of-flight (TOF) camera capable of suppressing background illumination (e.g. bright sunlight) in ubiquitous environments is used to capture the depth map of real-world in real time. The preprocessed distance information is rendered into depth buffer, that allows the interpolation of visual or hidden elements in the OpenGL color buffer to generate the composite AR scene. An optimized approach taking advantage of OpenGL texture and GLSL fragment processor is also proposed to speed up sampling distance value and rendering into frame buffer. The designed algorithm is validated in several indoor and outdoor experiments using SMART AR framework. The AR space with occlusion effect enabled demonstrates convincing spatial cues and graphical realism.

KEYWORDS: *Augmented Reality, Occlusion, Time-of-flight camera, OpenGL, depth buffering,*

1. Introduction

As a novel visualization technology, Augmented Reality (AR) has gained widespread attention and seen prototype applications in multiple engineering disciplines for conveying simulation results, visualizing operations design, inspections, etc. For example, by blending real-world elements with virtual reality, AR helps to alleviate the extra burden of creating complex contextual environments for visual simulations (Behzadan, et al., 2009a). As an information supplement to the real environment, AR has also been shown to be capable of appending georeferenced information to a real scene to inspect earthquake-induced building damage (Kamat, et al., 2007), or in the estimation of construction progress (Golparvar-Fard, et al., 2009). In both cases, the composite AR view is composed of two distinct groups of virtual and real objects, and they are merged together by a set of AR graphical algorithms.

Spatial accuracy and graphical credibility are the two keys in the implementation of successful AR graphical algorithms. Spatial accuracy requires the virtual content to be registered with the real world, which means the virtual objects must always appear at their intended location in the real environment with correct pose. In their prior work, the authors have designed and implemented a robust AR mobile computing framework called SMART and ARMOR (Dong, et al., 2010). SMART is a generic software architecture including accurate registration and projection algorithms, and ARMOR is a modular mobile hardware platform tracking user's position and orientation in the outdoor environment. Graphical credibility implies a persistent illusion that the real and virtual content in AR co-exists in the augmented space and is merged seamlessly together. There are mainly two research branches aimed at minimizing the artifacts brought by virtual objects. One of them is photorealism, which mainly deals with lighting effects, like shadows, reflections, etc. The other one is occlusion (Grau, 2006).

The primary focus of this research is exploring a robust occlusion algorithm for ubiquitous AR environments. In an ideal scenario, AR graphical algorithms should have the ability to intelligently blend real and virtual objects in all three dimensions, instead of superimposing all virtual objects on top of a real-world background as is the case in most current AR approaches. The result of composing an AR scene without considering the relative depth of the involved real and virtual objects is that the graphical entities in the scene appear to "float" over the real background rather than blending or co-existing with real objects in that scene. The occlusion problem is more complicated in outdoor AR where the user expects to navigate the space freely and the relative depth between involved virtual and real content is changing arbitrarily with time. Fig. 1 (Behzadan, et al., 2009b) presents a snapshot of a simulated construction operation, where two real objects (tree and truck) are closer than the virtual excavator model to the viewpoint, and should be consequently blocked by the real objects. The right side image shows visually correct occlusion where the boom and bucket are partially hidden from the scene. However the left side image shows the scene in absence of occlusion, producing an incorrect illusion that the excavator was in front of the tree and truck.

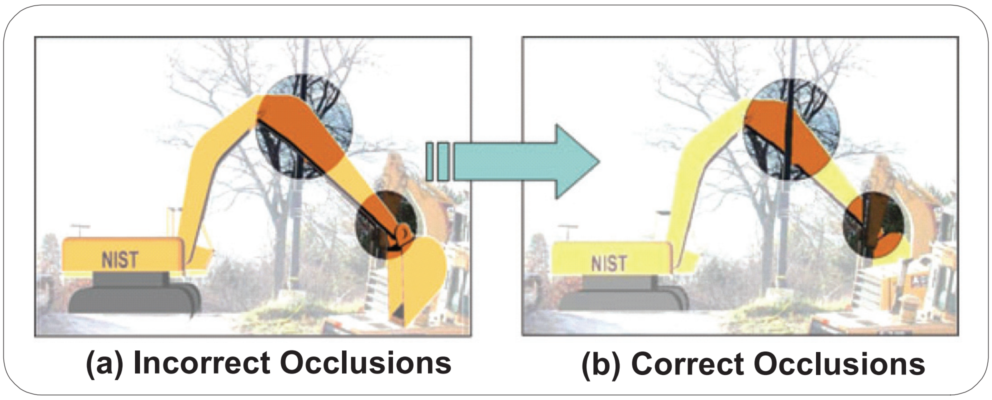

Fig.1: Example of occlusion in an outdoor AR scene

Several researchers have explored the AR occlusion problem from different perspectives: (Wloka, et al., 1995) implemented a fast-speed stereo matching algorithm that infers depth maps from a stereo pair of intensity bitmaps. However random gross errors blink virtual objects on and off and turn out to be very distracting; (Berger, 1997) proposed a contour based approach but with the major limitation that the contours need to be seen from frame to frame; (Lepetit, et al., 2000) refined the previous method by a semi-automated approach that requires the user to outline the occluding objects in the key-views, and then the system automatically detects these occluding objects and handles uncertainties on the computed motion between two key frames. Despite the visual improvements, the semi-automated method is only appropriate for post-processing; (Fortin, et al., 2006) exhibited both model-based using bounding box and depth-based approach using stereo camera. The former one only works with static viewpoint, and the latter is subject to low-textured areas; (Ryu, et al., 2010) tried to increase the accuracy of depth map by region of interest extraction method using background subtraction and stereo depth algorithms, however only simple background examples were demonstrated; (Tian, et al., 2010) also designed an interactive segmentation and object tracking method for real-time occlusion, but their algorithm fails in the situation where virtual objects are in front of real objects.

In this paper, the authors propose a robust AR occlusion algorithm that uses real-time Time-of-flight (TOF) camera data and the OpenGL frame buffer to correctly resolve the depth of real and virtual objects in AR visual simulations. Compared with previous work, this approach enables improvements in three aspects: 1) Ubiquitous: TOF camera capable of suppressing background illumination enables the algorithm and implemented system to work in both indoor and outdoor environments. It puts the least limitation on context and illumination conditions compared with any previous approach; 2) Robust: Due to the depth-buffering employed, this method can work regardless of the spatial relationship among involved virtual and real objects; 3) Fast: The authors take advantage of OpenGL texture and OpenGL Shading Language (GLSL) fragment shader to parallelize the sampling of depth map and rendering into the frame buffer. A recent publication (Koch, et al., 2009) describes a parallel research effort that adopted a similar approach for TV production in indoor environments with 3D model constructed beforehand.

2. Depth Buffer Comparison Approach

In this section, the methodology and computing framework for resolving incorrect occlusion are introduced. This approach takes advantage of OpenGL depth buffering on a two-stage rendering basis.

2.1 Distance Data Source

Accurate measurement of the distance from the virtual and real object to the eye is the fundamental step for correct occlusion. In the outdoor AR environment, the distance from the virtual object to the viewpoint is calculated using Vincenty algorithm (Vincenty, 1975) with the geographical locations of the virtual object and the user. Location of the virtual object is documented in the data preparation phase. Meanwhile, location of the user is tracked by Real-time Kinematic (RTK) GPS. The ARMOR platform utilizes Trimble AgGPS 332 along with Trimble AgGPS RTK Base 450/900 to continuously track the user's position up to centimeter level accuracy.

On the other hand, TOF camera estimates the distance from the real object to the eye with the help of time-of-flight principle, which measures the time a signal travels, with well defined speed spends, from the transmitter to the receiver (Beder, et al., 2007). The chosen PMD CamCube 3.0 utilizes Radio Frequency (RF) modulated light sources with phase detectors. The modulated outgoing beam is sent out with a RF carrier, and the phase shift of that carrier is measured on the receiver side to compute the distance (Gokturk, et al., 2010). Compared with traditional LIDAR scanners and stereo vision, TOF camera possesses ideal features of being deployed in real-time applications: captures a complete scene with one shot and speeds up to 40 frames per second (fps). However TOF camera is vulnerable to background light, like artificial lighting and sun that also generates electrons and confuses the receiver. Fortunately the Suppression of Background Illumination (SBI) technology allows PMD CamCube 3.0 to work flexibly in both indoor and outdoor environment. (PMD, 2010)

2.2 Comparison of Heterogeneous Distance Data Source

The distance from the virtual and real object to the viewpoint cannot be compared directly since they are represented in heterogeneous forms. While the distances from the real object to the viewpoint are directly given for each pixel by TOF camera, the distance between the viewpoint and virtual object occupying a group of fragments cannot be retrieved until all the vertices are processed through the OpenGL graphics pipeline and reach the depth buffer. (Shreiner, et al., 2006)

Depth buffering, also known as z-buffering, is the solution for hidden-surface elimination in OpenGL and is usually done efficiently in the graphics card or GPU. Depth buffer is a two-dimensional array that shares the same size with the viewport, and always keeps record of the closest depth value to the observer for each pixel. For a new candidate color arriving at a certain pixel, it will not be drawn unless its corresponding depth value is smaller than the previous one. If it is drawn, then the corresponding depth value in the depth buffer will be replaced by the smaller one. In this way, after the entire scene has been drawn, only those items not obscured by any others remain visible.

Depth buffering thus provides a promising approach for solving the AR occlusion problem, and Fig. 2 shows the two rendering stage method: In the first rendering stage, the background of the real scene is drawn as usual but with the depth map retrieved from TOF camera written into the depth buffer at the same time. In the second stage, the virtual objects are drawn with depth buffer testing enabled. Consequently, the invisible part of virtual object, either hidden by real object or another virtual one, will be correctly occluded.

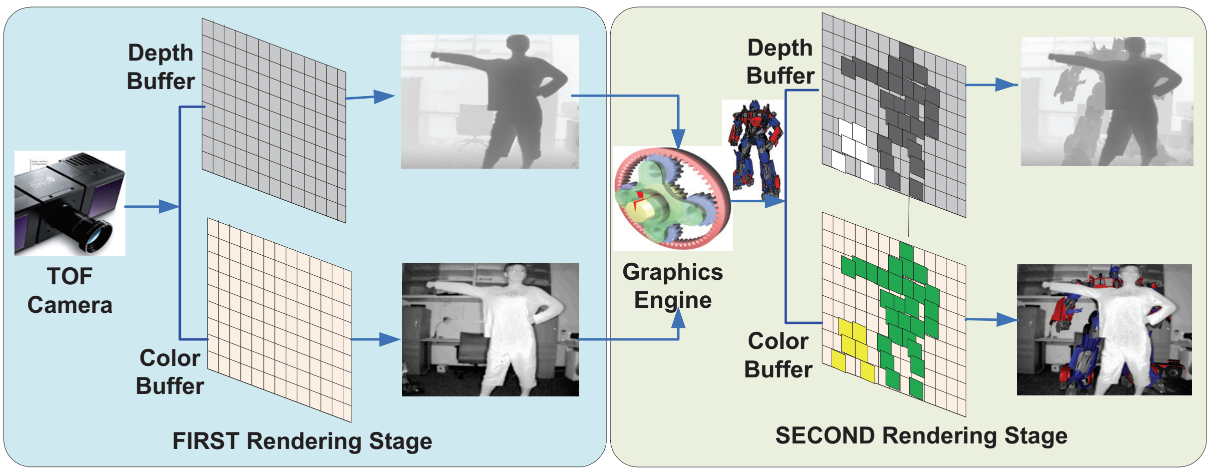

Fig.2: Two Stages Rendering

2.3 Problems with Depth Buffering Comparison Approach

Despite the simplicity and straightforward approach of depth buffering, there are several challenges when feeding depth buffer with TOF camera distance information:

1) Depth buffer value does not represent the actual distance between the object and the viewpoint but the distance after a projection transformation, division and normalization to the range [0, 1]. The conversion process from actual distance to depth buffering distance will be addressed in section 3.

2) Traditional glDrawPixels() command can be extremely slow when writing a two-dimensional array into the frame buffer. Section 4 introduces an alternative and efficient approach using OpenGL texture and GLSL.

3) The resolution of TOF depth map is fixed as 200*200 while that of the viewport and depth buffer can be arbitrary. This implies the necessity of interpolation between the TOF depth map and the depth buffer. Section 4 also takes advantage of OpenGL texture to fulfill interpolation task efficiently.

4) There are three cameras for rendering an AR space: Video camera captures RGB or intensity values of the real scene as the background, and its result is written into the color buffer; TOF camera acquires the depth map of the real scene, and its result is written into the depth buffer; OpenGL camera projects virtual objects on top of real scene with its result written into both color and depth buffer. To ensure correct registration and occlusion, all of them have to share the same projection parameters: aspect ratio and field of view. While the projection parameters of OpenGL camera are adjustable, video camera conflicts with TOF camera in three aspects: a) The centers of camera do not agree; b) video camera usually comes with aspect ratio of 640:480, but CamCube has its aspect ratio as 200:200; c) vertical field of view of ordinary video camera is around 32°, but CamCube reports wide field of view as 40°. The alignment of the TOF camera with the video camera is still an issue under study as shown in Fig. 3. Currently the authors take advantage of gray scale image captured by TOF camera simultaneously with distance information, to work around the mismatching projection parameters problem.

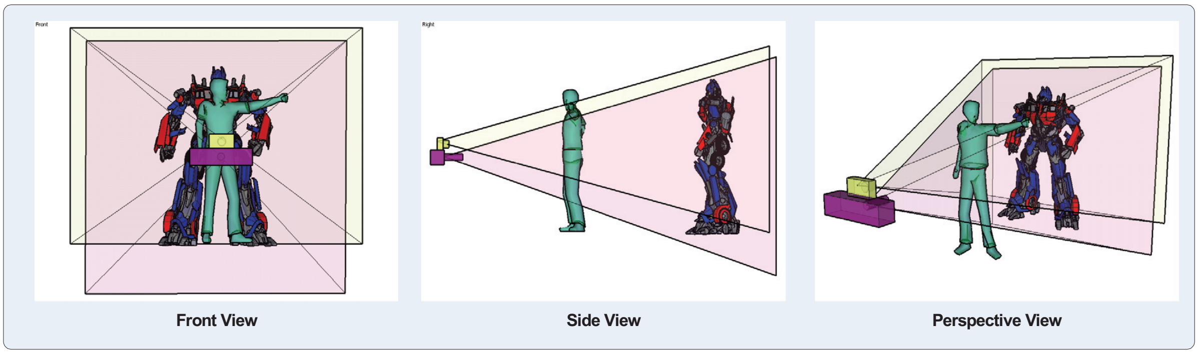

Fig.3: Projection parameters disagreement between TOF Camera (Purple) and Video Camera (Yellow)

3. Raw Data Preprocessing

Before feeding any gray scale image and depth map into the color buffer and depth buffer respectively, both of them need to be preprocessed to meet the data type and pixel format requirement of the frame buffer.

3.1 Preprocessing of Gray Scale Image

Since unsigned byte (8 bits represents 0 ~ 255) is the data type for showing intensity values, the raw gray scale image needs to be refined in two aspects. First of all, the raw intensity values spread from 1000 to 20,000 and thus have to be redistributed on [0,255]; secondly, the gray scale image is represented by close contrast values, and histogram equalization is helpful in spreading out the most frequent intensity values on the histogram for better visual effects. The basic idea of equalization is to linearize the cumulative distribution function (CDF) across the histogram from 0 to 255. The transformation can be described by the formula.1 (Acharya, et al., 2005) .CDF is the cumulative distribution function of a given gray scale image; *v* is the original intensity value of a given pixel, *P(v)* is the intensity value after equalization for that pixel; *Level* is the total number of gray scale after equalization. An accelerated equalization algorithm is presented in Appendix A:

$$P(v) = \frac{CDF(v) - CDFmin}{(width * height) - CDFmin} * (Level - 1) \quad (1)$$

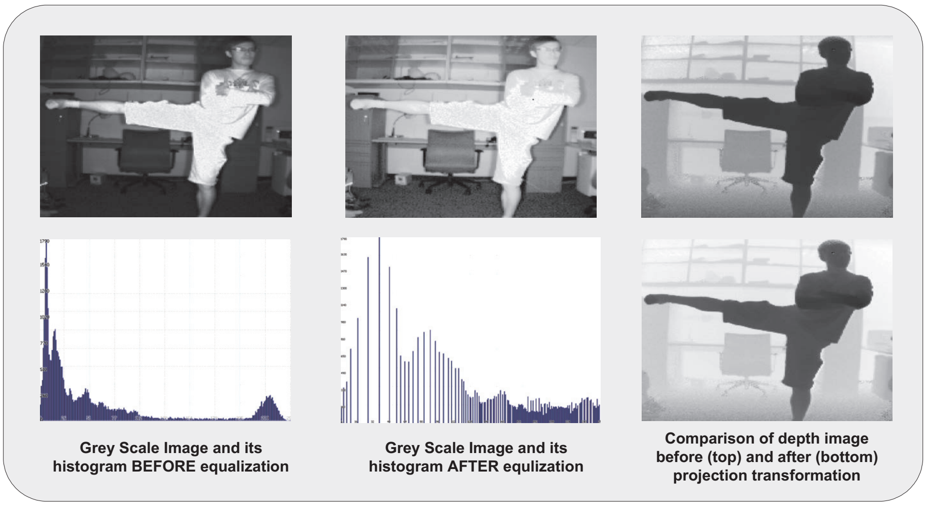

Fig.4: Preprocessing of the TOF gray scale and depth image

3.2 Preprocessing of Depth Map

Since TOF camera is aligned with video camera (section 2.3), the distance value provided by TOF camera is treated within the eye coordinate system as z_e (actual distances from vertices to the viewer in viewing direction). In the OpenGL pipeline, several major transformation steps are applied on z_e before its value is written into the depth buffer. Table 1 summarizes the transformation procedure, and more detailed information is available from (Mcreynolds, et al., 2005): 1) clip coordinate z_c (distance values in clip space where objects outside the view volume are clipped away) is the result of transforming vertices in eye coordinate by projection matrix; 2) z_c divided by w_c (homogenous component in clip space) is called perspective divide that generates z_{ndc}; 3) Since the range of z_{ndc} (distance values in normalized device coordinate (NDC) space that encompasses a cube and is screen independent) is [-1,1], it needs to be offset and scaled by the depth buffer range [0,1] before it is sent to the depth buffer.

Table 1: The transformation steps applied on the raw TOF depth image.

Name	Meaning	Operation	Expression	Range
Ze	Distance to the viewpoint	Acquired by TOF camera		(0, +∞)
Zc	Clip coordinate after projection transformation	$M_{ortho} * M_{perspective} * [Xe \quad Ye \quad Ze \quad We]^T$	$Zc = \frac{Ze*(f+n)}{f-n} - \frac{2*f*n*We}{f-n}$ n and f is the near and far plane, *We* is the homogenous component in eye coordinate, and usually equal to 1	[-n,f]
Zndc	Normalized device coordinate	*Zc / Wc* (*Wc = Ze, and* is the homogenous component in clip coordinate	$Zndc = \frac{f+n}{f-n} - \frac{2*f*n}{Ze*(f-n)}$	[-1,1]
Zd	Value sent to depth buffer	*(Zndc+1) / 2*	$Zd = \frac{f+n}{2*(f-n)} - \frac{f*n}{Ze*(f-n)} + 0.5$	[0,1]

4. Using Texture to Render to Frame Buffer

This section describes how to efficiently render to the color and depth buffer using texture and GLSL. After preprocessing of the gray scale image and the depth map, they are ready to be written into the frame buffer. However a challenging issue is how to write to frame buffer fast enough so that real time rendering is possible: 1) the arbitrary size of the color and depth buffer requires interpolation of the original 200*200 image. While software interpolation can be very slow, texture filtering presents a hardware solution here since texture sampling is so common that most graphics cards implement it very fast; 2) even though glDrawPixels() command with GL_DPETH_COMPONENT parameter provides an option for writing array into depth buffer, no modern OpenGL implementation can efficiently accomplish this since data is passed from main memory to OpenGL to graphics card on every single frame. On the other hand, texturing a QUAD and manipulating its depth value in GLSL fragment shader can be very efficient.

Texture is the container of one or more images in OpenGL (Shreiner, et al., 2006), and is usually bound to geometry. Here the OpenGL geometric primitive type GL_QUADS is chosen as binding target, and two 2D textures are pasted on it (Fig. 5). One is gray scale image texture, and the other one is depth map texture. The quad shares the same size with the virtual camera's viewport, and projected orthogonally as the background.

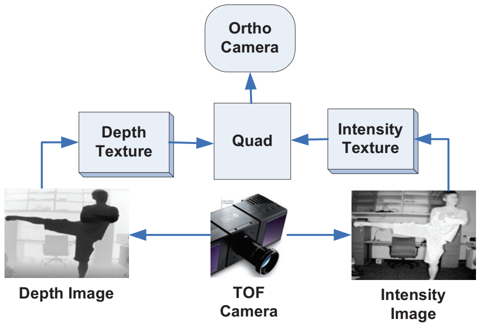

Fig.5: General structure of attaching multiple textures to the quad that is the real scene background.

4.1 Gray Scale Image Texture

Since modifying the existing texture object is computationally cheaper than creating a new one, it is better to use glTexSubImage2D() to replace repeatedly the texture data with new TOF images. (Shreiner, et al., 2006) However the TOF image must be loaded to an initial, larger texture with size in both directions set to the next biggest power of two than 200, namely 256. Accordingly the texture coordinates are assigned as (0, 0), (200/256, 0), (200/256, 200/256), (0, 200/256) in counterclockwise order of the quad.

4.2 Depth Map Texture

The same sub image replacement strategy is applied on depth map texture. However even though internalformat of texture is set to GL_DEPTH_COMPONENT, the depth value written into depth buffer is not the depth map texture, but the actual depth value of the quad instead. Therefore the depth value of the quad needs to be manipulated in fragment shader according to the depth map texture. A fragment shader operates on every fragment which is produced by rasterization. One input for the fragment processor is interpolated texture coordinates, and the common end result of the fragment processor is a color value and a depth for the fragment (Rost, et al., 2009). These features make it possible to redefine polygon depth value so that the TOF depth map can be written into the depth buffer. The basic GLSL source code is listed in Appendix B.

5. Validation

5.1 Indoor Validation Experiment

Fig.6: Indoor validation experiment

The indoor validation experiment is carried out in the authors' office. Optimus Prime (model accredited to MANDUN from Google 3D Warehouse community) is located approximately 2.5m away from the TOF camera, and the author is standing right behind Optimus Prime "grabbing" its waist and shoulders. A series of images (Fig. 6) shows correct occlusion effects where the author is largely hidden by Optimus Prime except his arms, that are spatially in front of Optimus Prime.

5.2 Outdoor Validation Experiment

Despite the outstanding performance of TOF camera in speed and accuracy, the biggest technical challenge of it is the modular error, since the receiver decides the distance by measuring the phase offset of the carrier. Ranges are mod the maximum range, which is decided by the RF carrier wavelength. For instance, the standard measurement range of CamCube3.0 is 7m. (PMD, 2010) If an object happens to be 8m away from the camera, its distance is represented as 1m (8 mod 7) on the depth map instead of 8m. This can bring incorrect occlusion in outdoor condition, where ranges can easily go beyond 7m. The authors have been looking into object detection, segmentation etc. to mitigate the limitation. For now, the experiment range is intentionally restricted to within 7m.

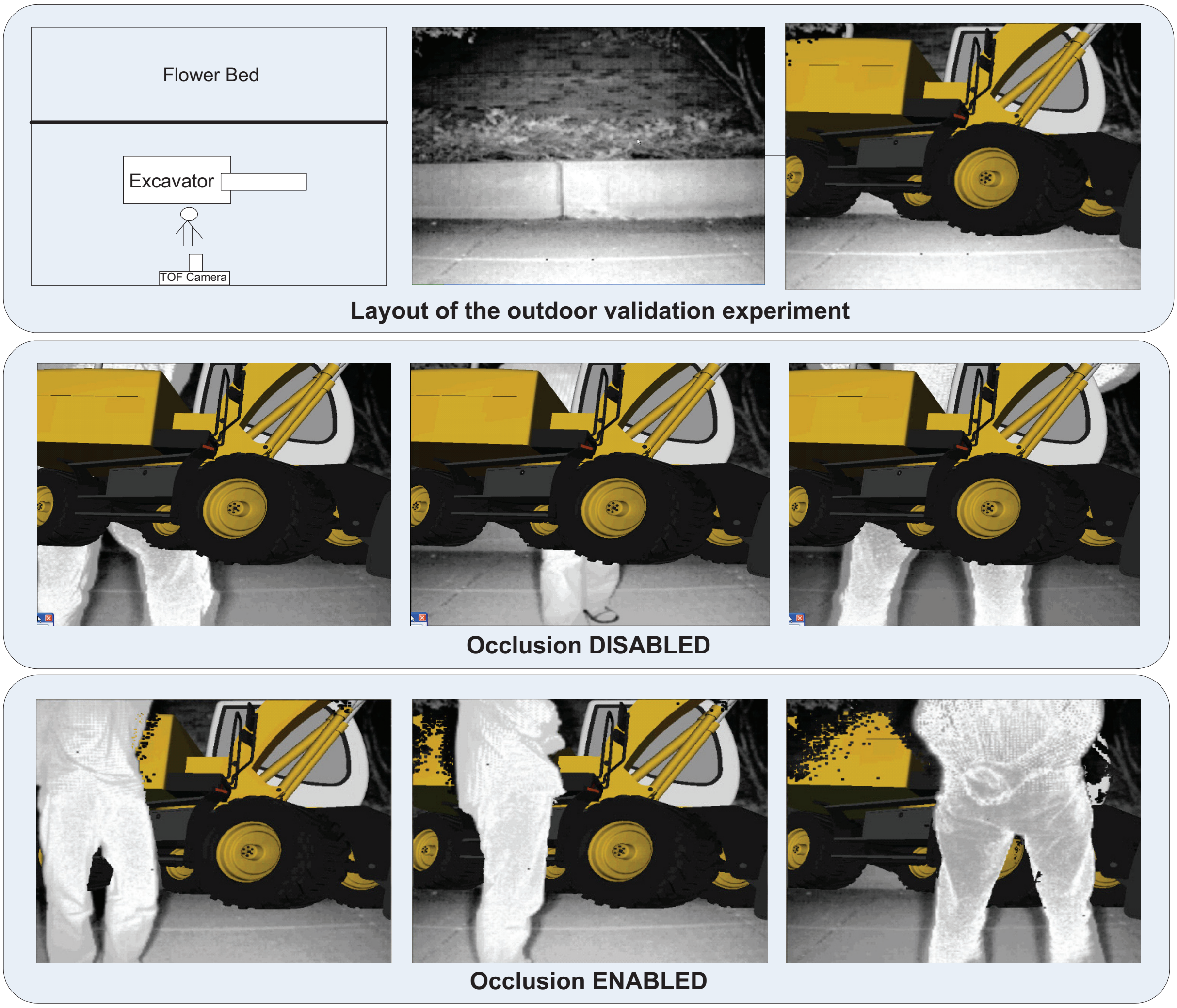

Fig.7: Outdoor Validation Experiment

A layout of the experiment is shown in Fig. 7. The TOF camera is positioned approximately 7m away from the wall of a building, which is surrounded by a flower bed. A small excavator model (accredited to J-m@n from Google 3D Warehouse community) is positioned about 3m away from the TOF camera, and the author is standing in front of the excavator. Scenarios for both occlusion function enabled and disabled are shown. It is obvious that occlusion provides much better spatial cues and realism for outdoor AR visual simulation.

6. Conclusion and Future Work

This paper described research that designed and implemented an innovative approach to resolve AR occlusion in ubiquitous environments using real-time TOF camera distance data and the OpenGL frame buffer. The first set of experimental results demonstrated promising depth visual cues and realism in AR visual simulations. However, several challenging issues remain outstanding and are currently being investigated by the authors. For example, the gray scale image captured by TOF camera is currently displayed as a background and thus no extra geometric transformation needs to be applied on distance values from TOF camera. The authors are attempting to align projection parameters of TOF camera with that of video camera so that the background can be drawn in full color. Secondly, the authors acknowledge that the current 7m average operational range of TOF camera puts a limitation on fully outdoor simulation visualization. However the occlusion algorithm designed here is generic and scalable so that future hardware with improved range and accuracy can be plugged into the current AR visualization system with little modification to the core algorithm. Meanwhile, the authors are studying the feasibility of implementing hybrid methods, like stereo vision and object detection, to mitigate this limitation.

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Appendix A

Step 0: Initialize image array, auxiliary gray level array, cumulative histogram;

```
Raw_Image_Array[width*height];
Aux_Gray_Level_Array[width*height];
LEVEL=256; CumHistogram[LEVEL];
```

Step 1: Looping the Raw_Image_Array[] to find the MaxVal, MinVal and Range = MaxVal-MinVal;

Step 2: Build the cumulative histogram and Aux_Gray_Level_Array[];

```
For i = 0: (width*height-1)
  Aux_Gray_Level_Array[i] = Raw_Image_Array[i] / Range * (LEVEL-1);
  ++ CumHistogram[Aux_Gray_Level_Array[i]];
End For;

For i = 0 : (Level-1)
  Accumulation += CumHistogram[i];
  CumHistogram[i] = Accumulation / (width*height) * (LEVEL-1);
End For;
```

Step 3: Linearization of the cumulative histogram can be fulfilled by assigning cumulative histogram value at a certain gray level to all pixels at the same gray level;

```
For i = 0 : (width*height-1)
  Raw_Image_Array[i] = CumHistogram[Aux_Gray_Level_Array[i]];
End For;
```

Appendix B

```
// Function Texture2D receives a sampler2D which is DepthTex or IntensityTex here, fragment texture
// coordinates. And it returns the texel value for the fragment.
    vec4 texelDepth = texture2D(DepthTex, gl_TexCoord[1].xy);
// The final depth of the fragment with the range of [0, 1].
    gl_FragDepth = texelDepth.r;
// Since a fragment shader replaces ALL Per-Fragment operations of the fixed function OpenGL pipeline, the
// fragment color has to be calculated here as well.
    vec4 texelColor = texture2D(IntensityTex, gl_TexCoord[0].xy);
// The final color of the fragment.
    gl_FragColor  = texelColor;
```

II. BIM AND PROCESS MODELING

INTUITIONISTIC APPROACH TOWARD CAPTURING AND MODELING DESIGN REQUIREMENTS

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ABSTRACT: *This paper discusses suitability of complex information models – based on intuitionistic and mediative fuzzy logic – for developing design requirements and integration with BIM. Intuitionistic logic is capable of capturing information while preserving multilayered richness of alternate options, ambiguity and contradiction. Mediative logic is a recently proposed methodology for solving intuitionistic datasets. To understand the potential benefits of these approaches, we analyzed the shortcomings of traditional tools used for developing design requirements. We also detailed the extent, to which information is simplified, suppressed and discarded while preparing a typical spatial relationship diagram. We further explained the engrained rigor of bi-valued logic and its discriminating effect: although qualitative terms like 'connected' or 'isolated' are used to build the diagram, these terms are subjected to the constraints of single-value assignment and the law of excluded middle. The intuitionistic approach breaks with the limitations of exclusive and complementary treatment of the opposites. Instead, it introduces a dimension of other options. Such approach is well suited for modeling ambiguities and contradictions – traits that are common in the practice of developing design requirements. An intuitionistic version of a spatial relationship diagram and an algorithm for solving such intuitionistic dataset is being proposed and explained. Furthermore, we discuss the role of such complex modeling of design requirements in the overall BIM scheme. We argue the need for providing design inputs that are capable of adequately matching the adaptive performance of modern parametric design tools. Parametric CAD, which is typically the design delivery engine of BIM, facilitates modeling in adaptive and easy to edit way. However, the design requirements are still processed as a static, often overly simplified snapshot. Advanced modeling of design requirements is a logical step in developing comprehensive BIM systems, where the performance and the fidelity of information processing are closely matched across all component blocks.*

KEYWORDS*: Design requirements, fuzzy logic, intuitionistic, mediative, BIM.*

1. INTRODUCTION

Building Information Modeling (BIM) is rapidly taking the leading role (Penttilä, 2007) among technologies, which form the intermediate link (Figure 1) between humans and their built environments.

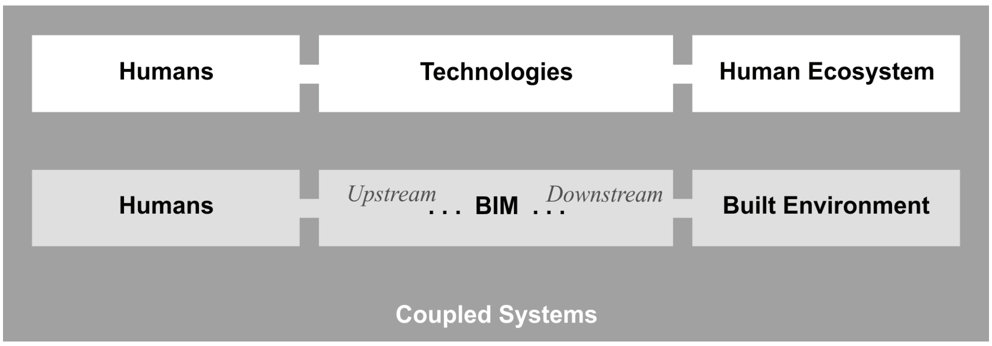

Fig. 1: Humans and their environment as a coupled system.

Built environments are immediately noticeable and, in a physical sense, most representative of human activity. They define the human ecosystem. An emerging trend among researchers is to view social interactions, human activity and the human ecosystem as examples of coupled systems rather than closed-loop repeatable and predictable processes (Dubois and Gadde, 2001; Liu et al, 2007; Orton and Weick, 1990). Blocks in a coupled system exchange actions and reactions without constraints of an external governing algorithm. Such repeated exchanges may result in reactions that gradually depart from previously established patterns and exceed all assumed limits. Therefore, coupled systems are open-ended and can become evolving and unpredictable. In our view, BIM has the potential to be a critical factor in the delicate balance of human-environment coupled system, and the capacity to influence the dynamics of changes in the human ecosystem. Hence, our motivation to examine the broader context of BIM, and to discuss in detail the initial steps in BIM workflow.

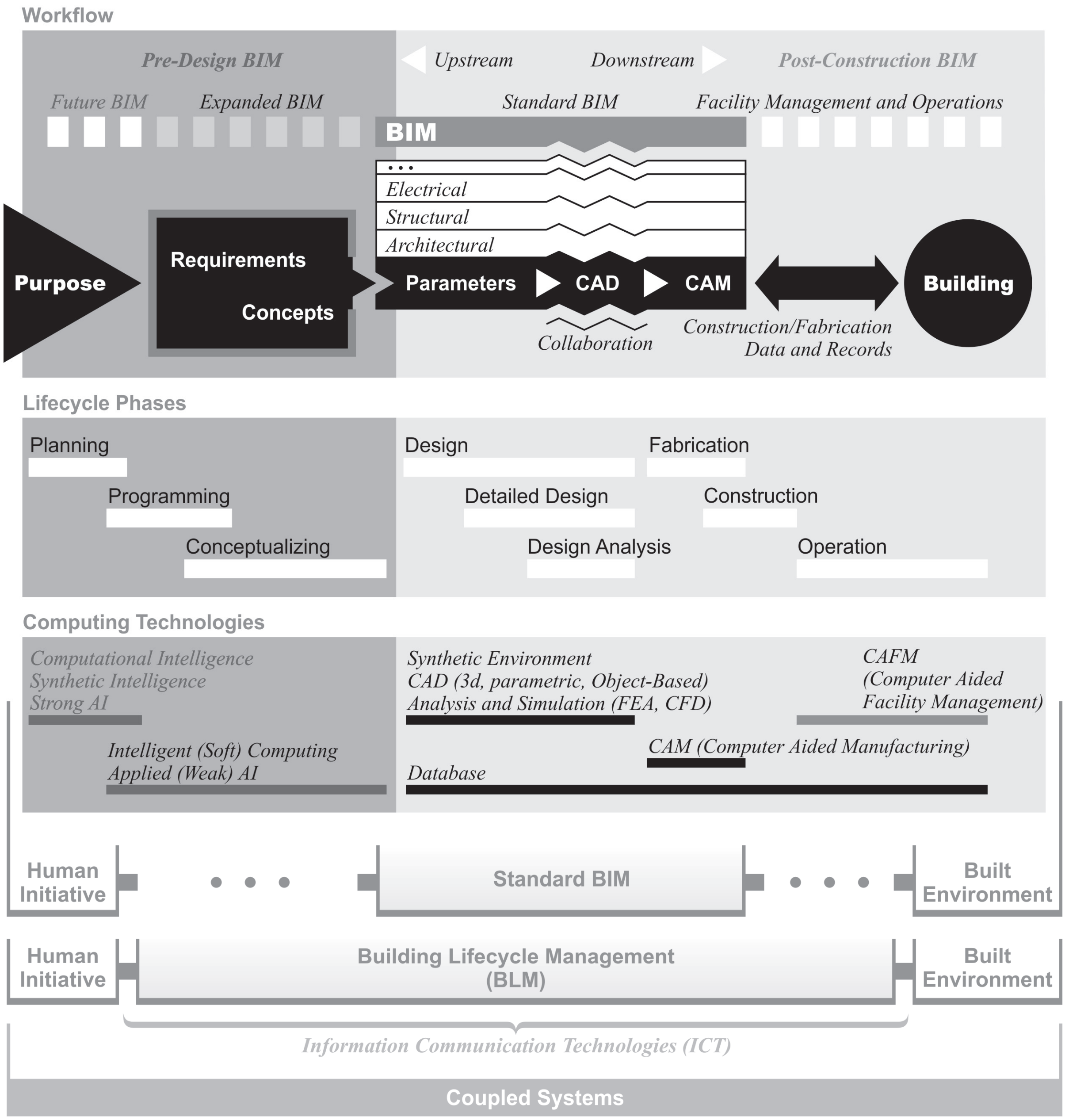

Fig. 2: BIM in the context of project workflow, building lifecycle and computing technologies.

Researchers generalize information management and CAD technologies as Information Communication Technologies (ICT) (Aouad and Arayici, 2010). BIM is considered as the main component of ICT for building design and construction. As such, it is aimed at streamlining and integrating numerous, traditionally disparate Architectural-Engineering-Construction (AEC) workflows (Aouad and Arayici; Eastman et al, 2008; Kymmell, 2008; Penttilä, 2006; Succar, 2009). Though BIM definitions are diverse (Aranda-Mena et al, 2008), researchers acknowledge that BIM systems are built around parametric and object-based 3-D modeling (Eastman, 2009; Kymmell, 2008; Penttilä, 2006). The built-in interoperability between various AEC CAD workflows is the source of BIM's effectiveness (Shelden, 2009; Kymmell; Penttilä, 2006). Extending in opposite directions from this core functionality, are two areas for BIM development: pre-construction and post-construction (Kymmell), or upstream and downstream (Shelden).

The focus of this study is the interface between the human intent and the BIM. Figure 2 sketches a broad context of BIM, where a blue shade highlights the 'upstream,' the 'pre-design' area of our interest. Researchers note that this area of capturing design requirements, architectural programming and early conceptualization is still in need of much development (Eastman; Manning and Messner, 2008; Penttilä, 2007). Furthermore, they caution that the growth of BIM effectiveness depends on how well complex information structures can be input and accessed (Kymmell, 2008). Notable is the argument that BIM must transcend simplistic data quantification and become able to use 'soft data' (Ottchen, 2009). Ottchen warns against simplifying the complexity of available information while fitting it to the limited templates of BIM inputs. Researchers point out that the technology did not change the mechanism of designing, which remained an iterative process of comparing the evolving concept with the initial intent (Kymmell; Shelden). However, since BIM provides an easy access to design reviews, it is necessary to capture and access the initial design requirements in as much detail as possible (Kymmell; Ottchen).

Intuitionistic fuzzy logic and mediative fuzzy logic are examples of renewed interest of researchers in information modeling that is increasingly more sophisticated and capable of capturing not only data as absolute and objective values, but is also capable of analyzing a complex interplay of alternative solutions, ambiguity and contradictions (Montiel et al, 2007). Applications of intuitionistic and mediative approach have been significantly more demanding in terms of computational processing than traditional models based on binary logic (Castro et al, 2007). Only recent advances in computing hardware have made such applications viable.

We investigate the suitability of these sophisticated information models for capturing design requirements. Furthermore, we propose that employing intuitionistic data mining and mediative data processing can be advantageous for driving parametric CAD, which is typically BIM's design delivery tool. Parameter driven design enables developing context sensitive and adjustable entities. It allows streamlined coordination across all involved technical disciplines and facilitates edits or changes. However, this study argues, the traditional methods of developing design requirements involve significant simplification of data thus preventing model parameterization that accurately reflects the complexity of design inputs.

2. TRADITIONAL METHODS OF DEVELOPING DESIGN REQUIREMENTS

Commonly used matrices of spatial relationships (Figure 3) are examples of how tools, which are intended to capture initial design requirements in their most unprocessed form, often apply significant data discrimination, filtering and interpretation. Spatial relationships are qualitative in nature and they are often expressed using phrases like connected, strongly-connected, isolated, separated, neutral, positive, or negative. Matrices provide flexible and easy to read snapshots of general spatial dependencies. They use qualitative, open-ended descriptors arranged in a format that avoids making unnecessary topological assumptions (Duerk, 1993; Evans et al, 1969; Voordt et al, 2005) thus bearing the characteristics of an objective instrument capable of capturing early design intentions.

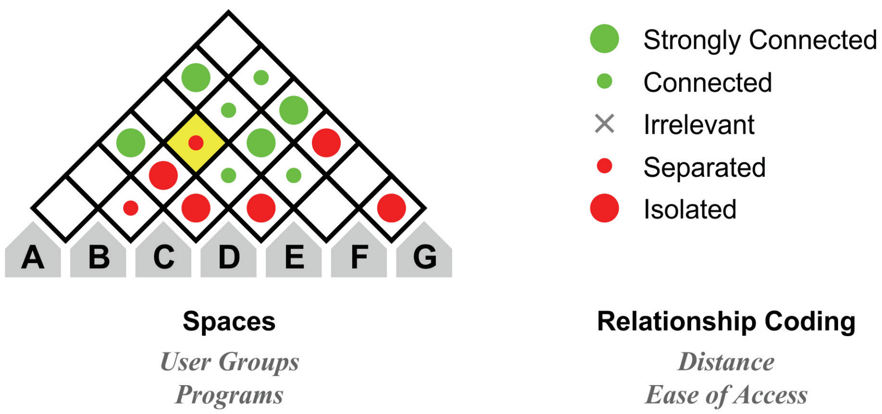

Fig. 3: Spatial relationship diagram.

However, a detailed examination reveals the complexity and the extent of interpretative process that is involved during preparation of such matrices. In reality, each space represents a usage program – a function. The relationship requirements between spaces B and E (highlighted), if considered through specifics of the program B, may be different from the corresponding requirements stemming from specifics of the program E. Yet, the graphically concise traditional grid of a half-square – an actual half-matrix – provides limited means of assigning only a single attribute to each spatial relationship. The resulting mapping does not reveal which program's specific needs weighed while assigning relational attributes. These attributes are the outcome of an arbitrary synthesis of the initial considerations into singular values that can record within the constraints of a simplified grid.

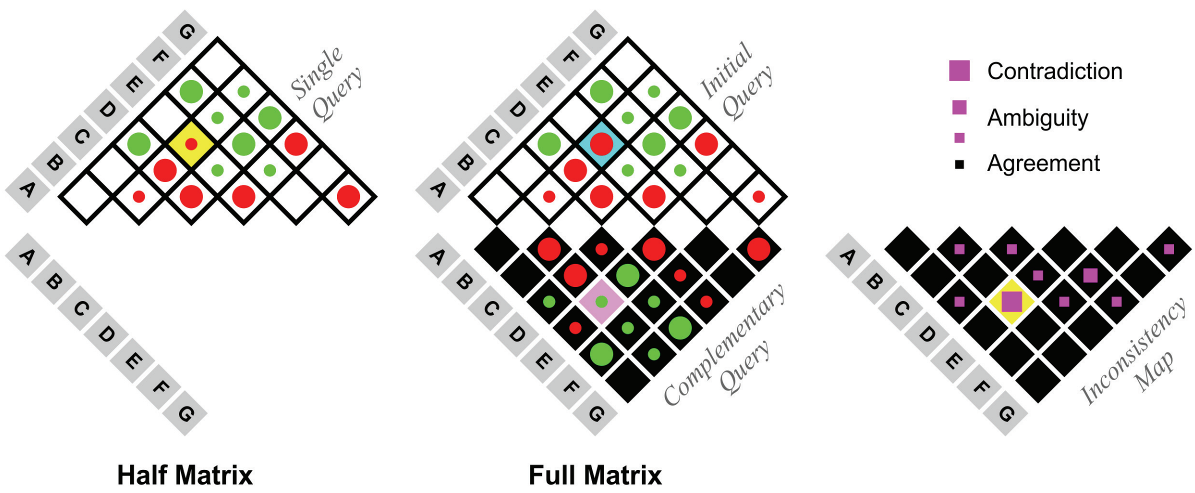

Fig. 4: Spatial relationship diagram as an intuitionistic dataset.

Transposing such mapping onto a full-square, table-like grid (Figure 4, center) reveals the nature of simplifications involved by using the half-matrix scheme. The same relationship, between B and E, is highlighted. The full matrix allows mapping the relationship requirements between each pair of spaces as two distinct attributes derived from individual specifics of corresponding spaces. The blue highlight indicates a relationship between B and E derived from the specifics of the program E while the pink highlight indicates the same relationship derived from the specifics of the program B. Such distinction is not possible when using the half-matrix grid – the yellow highlight. These separately derived relationships need not to be identical. This is precisely the advantage of a full-matrix scheme: different source considerations yield different results. In this example, the specifics of B yield a *Connected* relationship while the specifics of E yield an *Isolated* relationship. Reducing this mapping to a half-matrix scheme requires interpreting the pair of differing relationships as a single best fitting assignment – a Separated. If such half-matrix mapping is used then for the design development, the initial complexity of the source requirements is lost. The design is driven by the simplified data instead. Obvious advantages are the ease and the convenience of dealing with consistent and coherent data. On the other hand, the full-matrix's ability to capture the complexities of initial considerations is also responsible for the inherent element of ambiguity and contradiction. Figure 4 (right) illustrates disagreements between the differently derived relationships. Such multi-layered and complex data models (Castro, 2007) cannot be readily integrated with traditional workflows that require relatively consistent, unambiguous inputs. Nevertheless, scholars point out the importance of careful consideration of the complexity of initial requirements for successful ideation (Barton, 2000; Stokes, 2006) as well as the need for developing effective requirement modeling tools (Lubart, 2005).

3. INTUITIONISTIC APPROACH TOWARD INFORMATION MODELING

This study proposes that affordances of the recent advances in intuitionistic mathematics and intuitionistic logic (Montiel et al, 2007) open the way for effective integration of complex data structures into design workflows. The traditional dominance of binary logic engrained with proliferation of computing technologies brought along certain intolerance toward ambiguity and indetermination. This intolerance, pointedly expressed as 'the law of excluded middle,' has been generally accepted as the underlying norm for creative, industrial, engineering and research workflows. Obvious benefits of such approach include convenience of simplicity and processing efficiency. However, the systemic, virtually transparent bias against information that is ambiguous or contradictory encourages simplifications to the point where potentially important data may be discarded (Linsey et al, 2008).

3.1 Fuzzy logic

Interestingly, the traditional soft computing exemplifies the omnipresence of crisp discrimination as fuzzy logic duly obeys the law of excluded middle: though expressed as a non-binary values, input entities are still deterministically tied to their negations in a mutually exclusive complement (Karray and da Silva, 2004). If a value of an entity is known, its opposite is also automatically assumed to be known as a simple product of mathematical negation. For example, the answer to a question if a given object is *LONG*, a so-called fuzzy assignment, can be any value between 0 and 1 and is typically represented as a plot versus the range of actually measurable property (Figure 5a). The answer to a question if the object is *NOT-LONG* can be derived as a mirrored plot. If the *NOT-LONG* plot is then inverted, it coincides perfectly with the *LONG* plot (Figure 5b). In qualitative terms, this means that a given entity will always yield the same value regardless of perspective, from which it is examined.

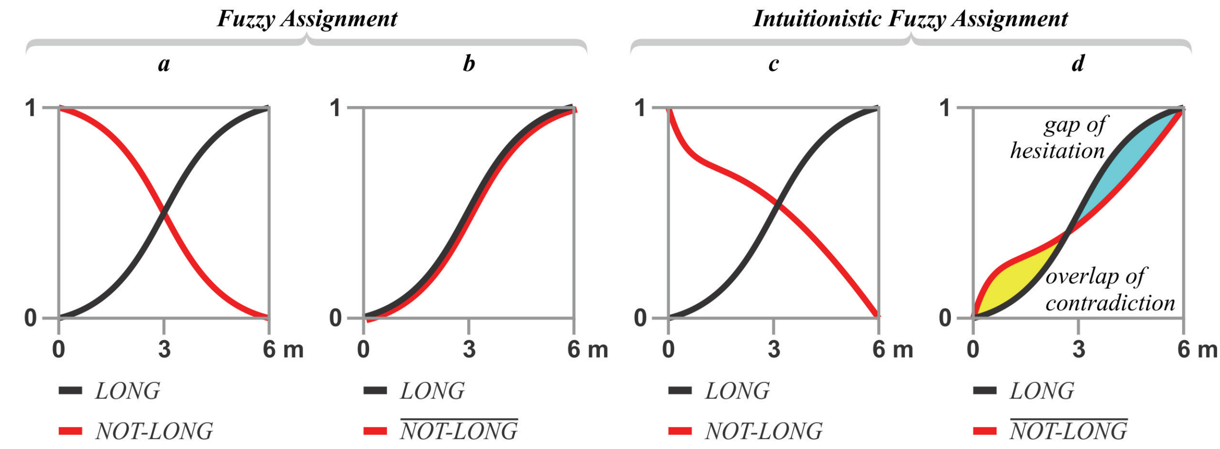

Fig. 5: Fuzzy and intuitionistic fuzzy assignments.

3.2 Intuitionistic fuzzy logic

The intuitionistic approach breaks with the limitations of exclusive and complementary treatment of the opposites. Instead, it introduces a dimension of other options. Mathematically, it does so by defining the negation as entirely independent from its original statement (Atanassov, 1999). The answer to a question if the object is *NOT-LONG* is not anymore a mirrored image of the *LONG* plot (Figure 5c). The increased complexity of expressing a statement and its negation by means of two independent plots allows to model subtle and computationally elusive aspects of human reasoning (Torres et al, 2007). If such mutually independent functions are superimposed like before, they do not coincide. Instead, they form gaps and overlaps (Figure 5d). The gaps (blue areas) represent a cautious assignment – hesitation. The overlaps (yellow areas) represent a simultaneous assignment of opposing values – a contradiction. It is important to realize that intuitionistic approach requires doubling the inquiry effort, as subjects need to be considered from two different and mutually opposing viewpoints.

3.3 Mediative fuzzy logic

Recent research has proposed computable, mathematical methods for solving intuitionistic datasets (Castillo et al, 2003; Montiel et al, 2007). The approach is based on constructing two traditional fuzzy inference systems (FIS): one for the initial statements and one for their negations. The outcome is computed as a weighted product of both FIS where the weighting is controlled by the nature of the differences. The advantage of the approach described by Montiel is the application of the traditional and widely available fuzzy logic computing for solving intuitionistic datasets.

3.4 Adapting intuitionistic approach

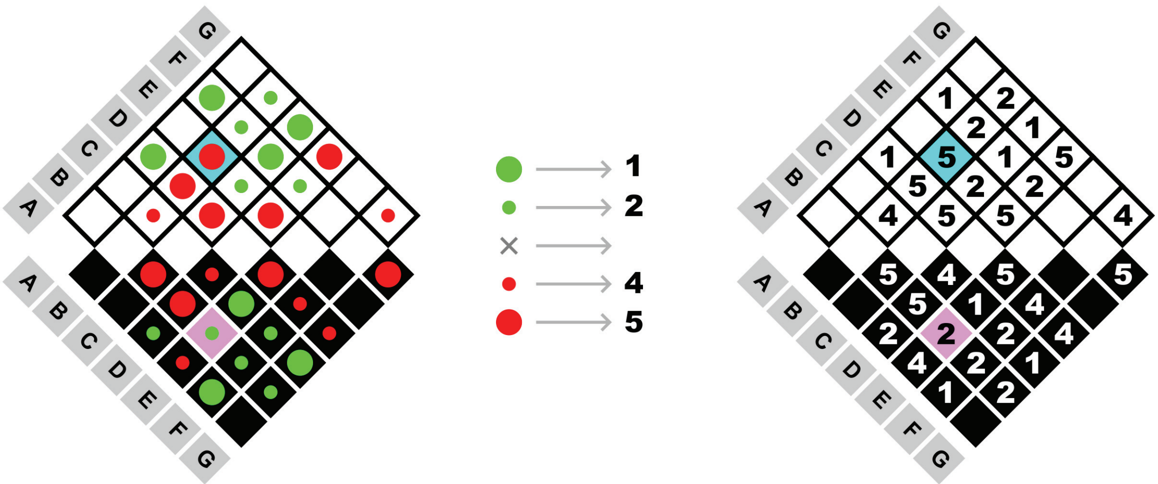

Fig. 6: Numerical coding of spatial relationships.

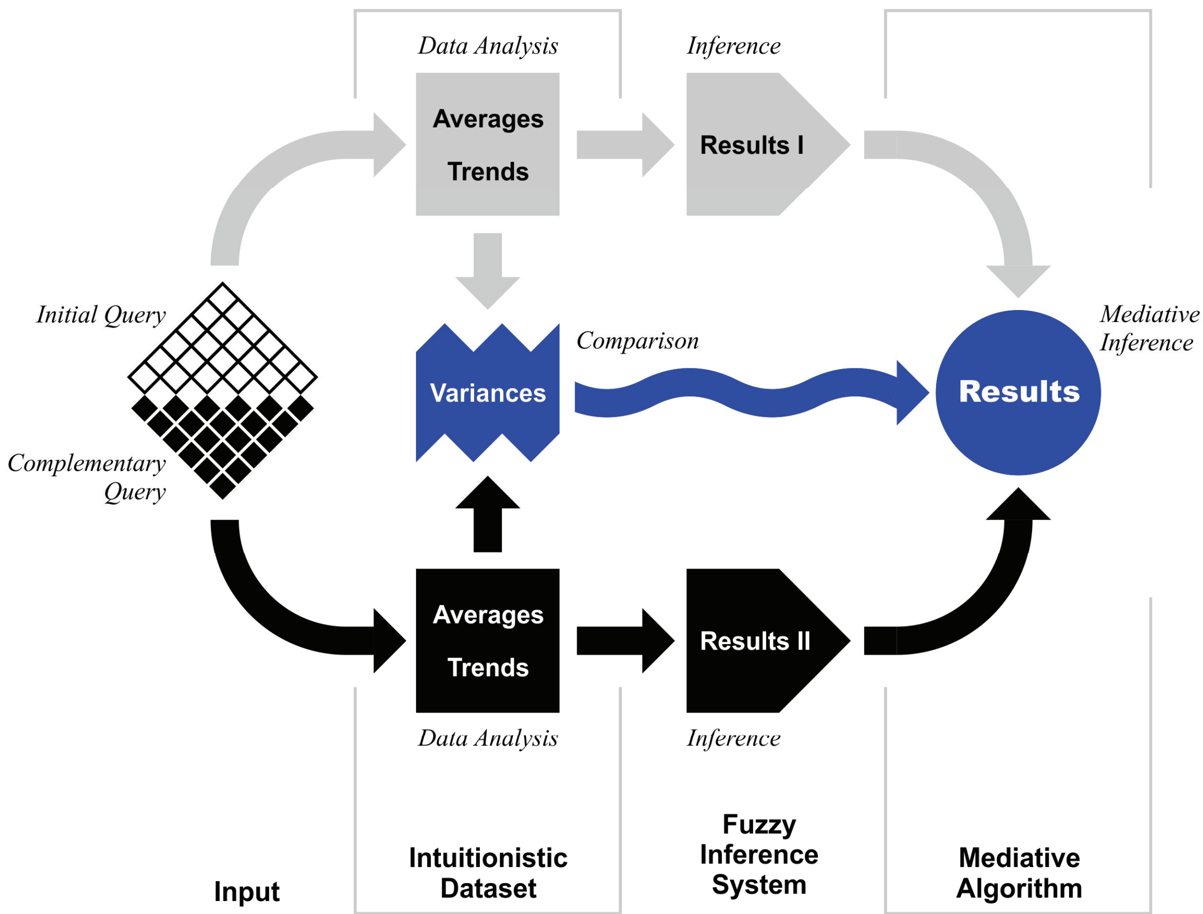

Fig. 7: Developing spatial relationship requirements using intuitionistic dataset and mediative inference.

This study proposes a generalized approach toward developing intuitionistic datasets where a strict mathematical negation can be substituted with any logically complementary information. The earlier discussed spatial relationship diagram provides a good example of how a complementary yet inconsistent in the traditional sense datasets can be derived. Translating the qualitative terms describing the spatial relationships into numerical values (Figure 6) enables processing of the collected information using mathematical tools as well as using it in fuzzy inference systems. The complementary spatial relationship queries form two data paths with two intermediate outputs: 'Results I' and 'Results II' (Figure 7). The differences between these datasets are then analyzed and used to combine the intermediate outputs into the final result. Fuzzy Inference Systems (Figure 8) are used for deriving the intermediate results (Distance FIS) and for deriving the final output (Mediative FIS).

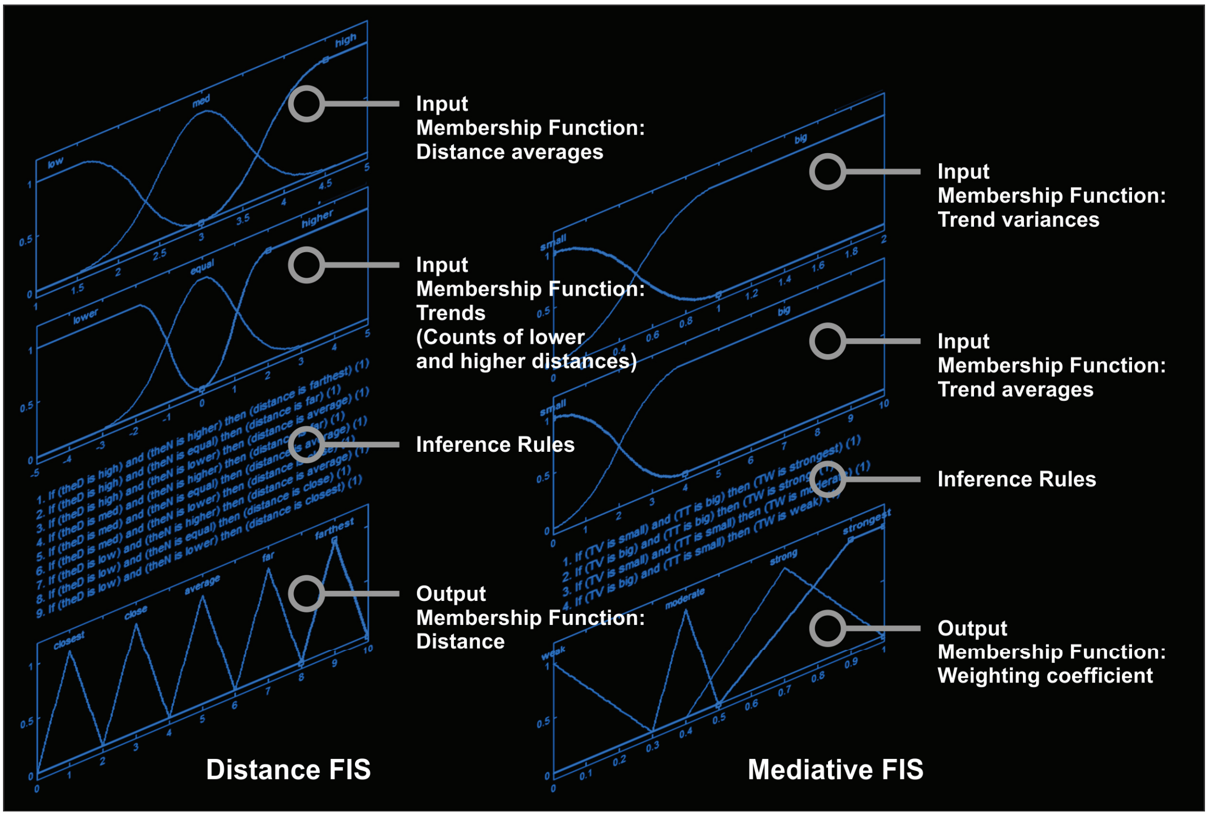

Fig. 8: Fuzzy Inference Systems.

4. THE RESULTS

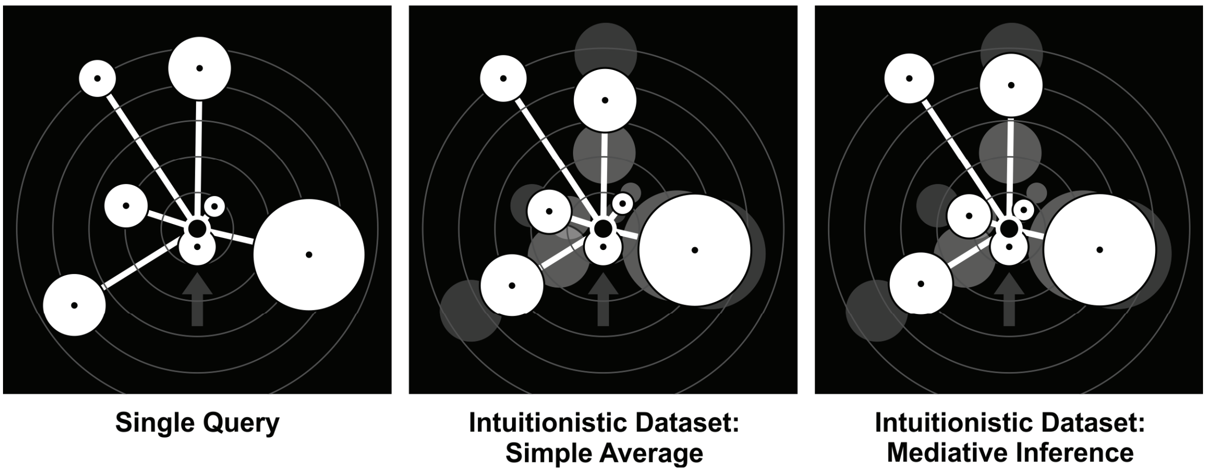

Fig. 9: Mapping of spatial relationships.

The analysis of spatial relationships was used to map the distances between the subject spaces through a central connecting node. Figure 9 illustrates solutions achieved through different methods. The single query is representative of the traditional approach. The mediative inference used the analysis of differences between the datasets to establish the mapping. It is noticeably different from the mapping achieved through simple averaging. Figure 10 overlays all the results to highlight the differences and the dynamic range of the intermediate solutions.

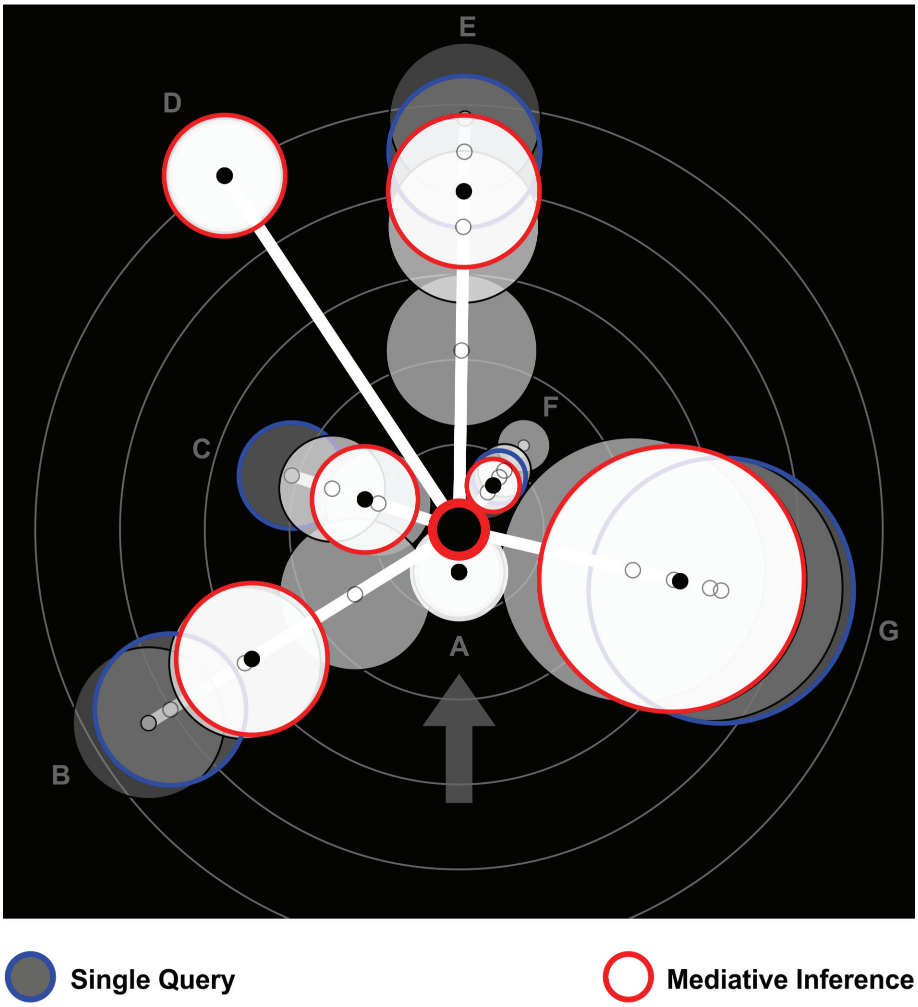

Fig. 10: Mapping of spatial relationships.

5. CLOSING REMARKS

This study proposes that the structure of an intuitionistic dataset is well suited for deriving parameters to be used in parametric CAD. The information processing flow, as shown in Figure 7, outputs the requirements as a 'mediated' solution derived from a range delimited by the intermediate results. Most importantly, the built-in mediative algorithm can be used for re-calculating the output whenever additional information becomes available. Such information may be a result of a design review (Figure 11). If so, interpreting of the design requirements can be seamlessly coordinated with design parameterization. Workflows based on intuitionistic approach would allow designers to capture and utilize a fuller extent of initial requirements. Furthermore, the captured information would be suitable for deriving multiple coexisting virtual scenarios to be accessible throughout the project thus eliminating the need for oversimplifying decisions during the initial stage. Such structured approach toward multilayered modeling of design requirements is a logical step in matching the adaptive performance of modern parametric CAD tools and in developing comprehensive BIM systems.

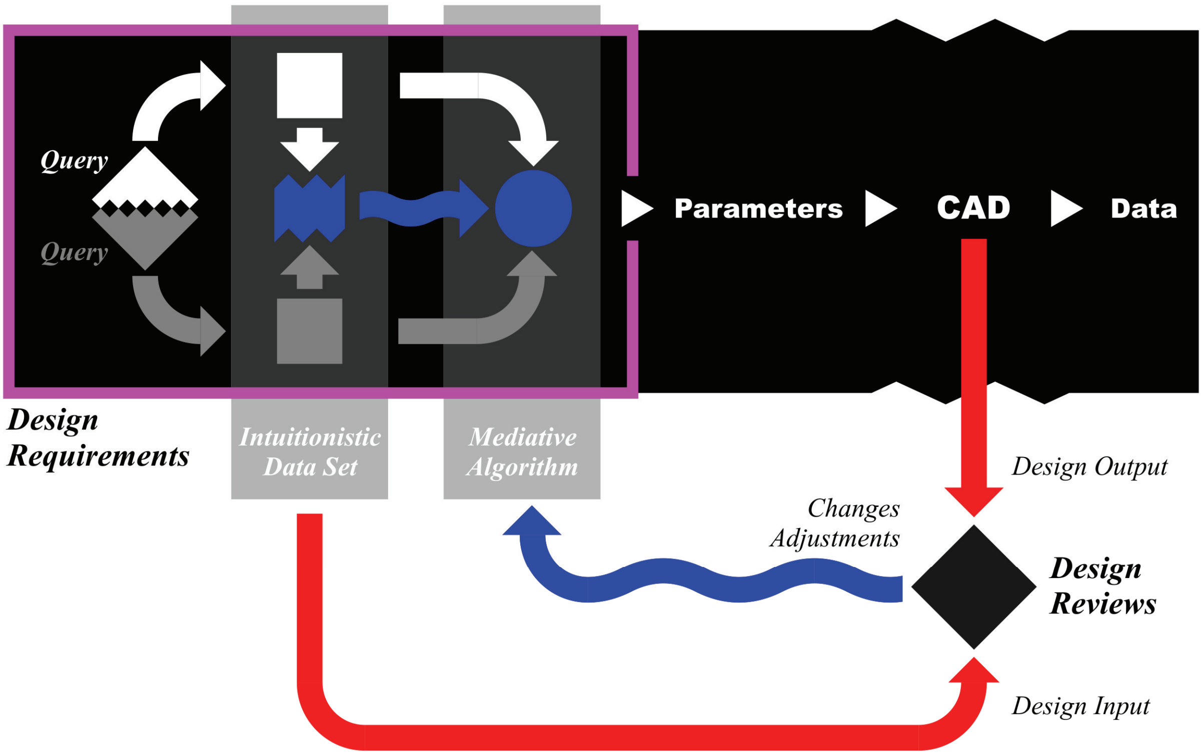

Fig. 11: Application of mediative inference during design review.

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COORDINATION AND VISUALIZATION OF DISTRIBUTED SCHEDULES IN THE CONSTRUCTION SUPPLY CHAIN: A POTENTIAL SOLUTION

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ABSTRACT: *The current construction supply chain is characterized by multiple subcontractors that perform most work on a construction project, provide their own resources, and coordinate between themselves under the general guidance of a main contractor. In such an environment, schedules are distributed and heterogeneous and as a result their coordination is a challenging task. Although schedules coordination is a crucial aspect, it has not attracted much attention from researchers and commercial software providers. This paper outlines the planned development of a tool for the coordination of schedules in the construction supply chain. While enabling coordination, the tool aims to put minimum constraints on planners, to accommodate planning information coming from different commercial planning tools, and to provide decision making capabilities. In addition, the tool is envisaged to be integrated within a 5D planning environment where schedules can be visualized and rehearsed.*

KEYWORDS*: Supply chain management, Construction supply chain, Supply system, Schedules coordination, 4D/5D planning.*

1. INTRODUCTION

Supply chain management is a relatively new concept within the construction industry. This concept imported from the manufacturing sector has been indicated as one of the ten key best practices that should deliver real added value to the construction industry and shape its direction in the near future (SECBE, 2006). A construction supply chain should be well thought-out networks of interrelated processes to satisfy end customer needs (Tommelein et al., 2003). Unlike the manufacturing sector, where high levels of integration are achievable, the construction industry is highly fragmented and characterized by poor communication, win-lose relationships and lack of commitment between trading partners and therefore, integration is far more challenging than in the manufacturing sector. In addition, due to the vast range of products and services involved within the construction industry, it would be impossible for any organization to manage all of its suppliers. For these reasons, leading organizations are currently organizing elements of the supply chain which are the most critical to their operation. One of these is the coordination and synchronization of multiple sub contractors and installers on site and the integration of key component suppliers. Existing research and available commercial tools either did not pay much attention to this aspect or tackled it within significant limitations and assumptions. Along with the problem of the coordination of multiple subcontractors on site, the construction supply chain requires an effective management of supply systems in order to achieve on-time completion of projects' milestones. Supply system management consists in the definition, design and implementation of temporary production systems that incorporate temporary flow of physical resources (e.g. labor, material, equipment) and information (Arbulu et al., 2003). The construction supply chain usually contains more than one supply system.

This research is concerned with both aspects: the synchronization of multiple subcontractors at the construction site and the management of the supply systems. This paper addresses the first aspect and outlines the current development of a module that allows the synchronization and coordination of the schedules of multiple subcontractors and the main contractor on the construction site. A further module, which aims at organizing the supply systems of the construction supply chain, will be developed and integrated with the current module. This research is currently being undertaken in collaboration between the Centre of Construction Innovation and Research (CCIR) and Deepdale Solutions Ltd in accordance with the research roadmap presented at CONVR 2008 (Table 1).

Table 1: Medium term multidimensional research roadmap at CCIR (Benghi and Dawood, 2008)

Stage	Function of current tools	Active research topics	Further development
Design			- Semi automated cost and plan generation
Planning	- Schedule rehearsal	- Cost Integration - Scenario evaluation - Integrated plan development	
Construction	- Schedule communication	- Programme control and adjustment	- Sub-contractors schedule synchronization
Operations			- H&S control and training

2. UNDERSTANDING THE CONSTRUCTION SUPPLY CHAIN COMPLEXITY

The construction supply chain is currently characterized by a high degree of fragmentation and specialization, which shape both the work on the construction site and the upstream supply systems of each participant on site. To exacerbate this situation, the attitude and mindsets of participants make it difficult to build a win-win situation and to accept new tools and processes. Table 2 presents a number of factors influencing each of the three problems in the construction supply chain (i.e. coordination of multiple participants, management of supply systems, attitude and mindsets) and the research areas tackling each problem.

Table 2: Factors affecting the construction supply chain

	Factors	Research areas/Initiatives
Coordination of multiple participants	- Fragmentation and specialization - High number of participants - Lack of formal processes for coordination - Lack of IT tools and integration solution (interoperability difficulties) - Change factors (schedule and scope changes, weather, party wall, etc.) - Dependent on multiple supply systems - Communication	- 4D and 5D planning and visualization tools - Web based tools (e.g. constraint checking, information sharing) - Schedule mappings - Negotiation-based planning and control systems - Database synchronization technology
Management of supply systems	- Low reliability of suppliers (poor OTIF performance) - Demand variability, non-matching demand-supply - Lead times of engineered to order products and design changes - Communication	- Web-based tool (e.g. based on last planners for information sharing) - Service-oriented approach - Construction project extranets (CPE) - ERPs
Attitude and mindsets	- Win-lose relationships - Resistance to change in adopting new tools and processes - Temporary nature of construction	- Partnering initiatives - Early involvement - Management of change

2.1 An example

Nowadays, major construction contractors have become aware of the cost savings and benefits that can result from better supply chain practices. One of the policies they are implementing is to reduce the number of companies in their supply chain and only use those capable of integrating with their scheduling systems and managing the lower part of the supply chains efficiently. This is along with other requirements that sub-contractors should adopt such as the capability of increasing their off-site production.

Deepdale Solutions Ltd (DSL), a sub-contractor involved in the building envelope industry as a designer, manufacturer and installer, is taking part to and funding this research. It aims to take advantage of these developments by enhancing its coordination and supply chain management activities. The delivery and fitting of DSL's products are on the critical path for weather-proofing of buildings. Therefore, the need to develop better site coordination and supply chain management capabilities is crucial for companies involved in the façade industry like DSL. A typical arrangement of the construction supply chain is shown in figure 1, which shows the dependency between multiple participants working on site and their distributed schedules. It also clarifies how the supply chain can be formed by a number of supply systems (three supply systems are shown in figure 1). The following tiers can be identified:

- Tier 1: Composed of subcontractors that are directly appointed by the general contractor to deliver works on site;
- Tier 2: Formed of manufacturers/suppliers that supply the main elements making up a building (e.g. building envelope elements, precast concrete elements);
- Tier 3: Formed of manufacturers/suppliers of components and materials (e.g. aluminium profiles, cement) used in the manufacturing of the main element. Third-tier occupiers can, in turn, have their own suppliers (tier 4: e.g. metal forming companies that carry out operations such as aluminium casting and extrusion for third-tier aluminium profile suppliers).

In most cases, in accordance with the supply chain trends mentioned above, a single company/trade occupies the first and second tier simultaneously (e.g. DSL as a manufacturer - second tier and as an installer - first tier).

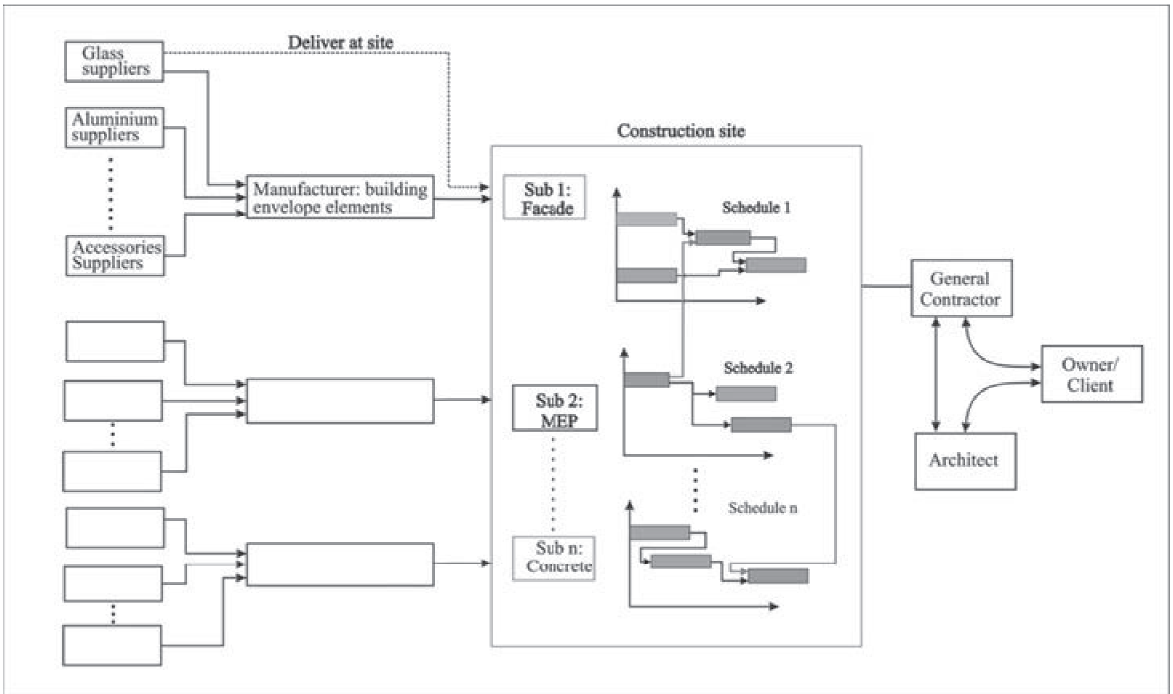

Fig. 1: Typical arrangement of a construction supply chain

To explain the difficulties of the construction industry in meeting site target dates, the following two facts are highlighted:

- In a typical project, the third-tier suppliers can be numerous. On one project, DSL has more than 20 suppliers, who can deliver either to the manufacturer premises (tier 2) or directly to the site (tier 1) (figure 1). DSL's processes on site cannot start until all materials from suppliers are available. If there are 15 suppliers with a probability of 90% of on-time delivery (high performance), then DSL's probability of meeting the site target date is: $0.90^{15} = 20\%$. Therefore, even with a reliable supply system, DSL only has a 20% chance of meeting its target date. A fishbone diagram of the main causes that can make DSL miss its site target dates is illustrated in figure 2.

- Likewise DSL, all other subcontractors have their own supply systems and similar causes of delays as the ones depicted in figure 2. As there is a dependency and interaction between first tier (figure 1) occupants, the supply system of each participant disturbs the supply system of other participant. This results in a combination of causes of delay that decrease substantially the chance of on-time delivery of a construction project.

If what have been said so far is true, readers may wonder how many construction projects are being delivered on time. This is obviously solved by building up a large buffer of finished products along the supply systems and on site. The consequences for actors like DSL are poor cash flow (they are paid for what has been successfully installed), higher storage costs, reduced quality and safety due to damage of stored materials, and stored material being at risk of design revisions and programme changes.

The above example gave a clear explanation as to why this project is tackling both the coordination of multiple participants on site and the management of the supply system. Both areas can be seen in figure 3. This paper is concerned only with coordination of multiple participants and a review of previous relevant work is presented in the next section.

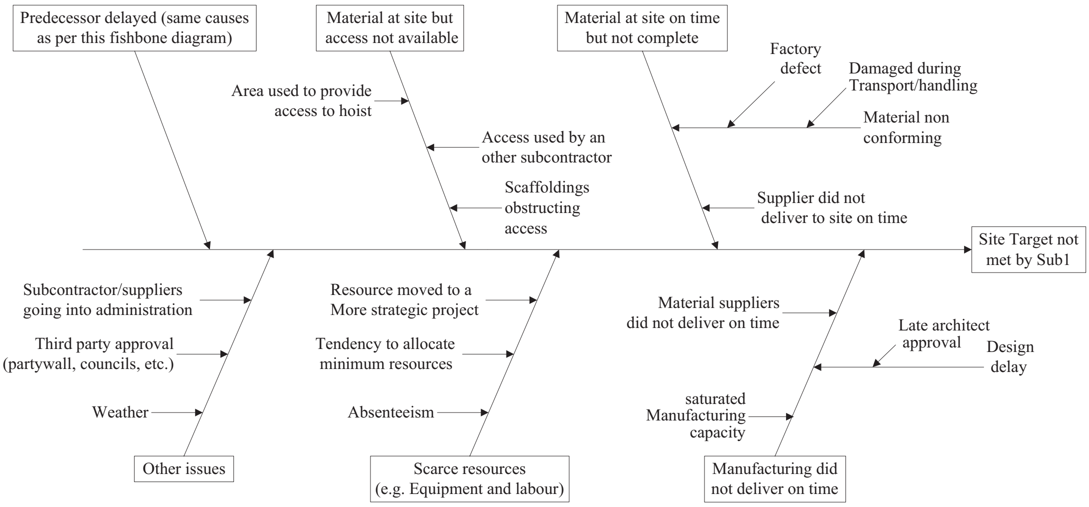

Fig. 2: Typical arrangement of a construction supply chain

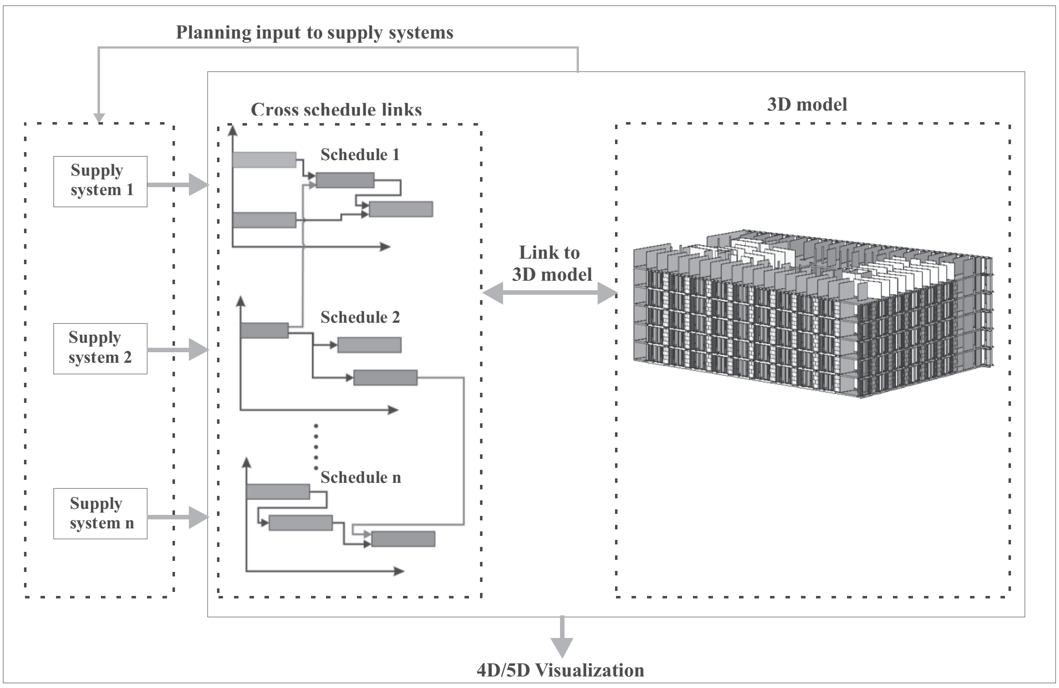

Fig. 3: Visual tool for the construction supply chain management

2.2 Related literature

The current construction industry entails more than ever quick, large, complex and uncertain projects with a high degree of specialization. As a result, subcontracting has become a way of life today. Subcontractors perform most of the work on a project and provide their own resources and often, subcontractors working on the same project have different project management objectives with different Work Breakdown Structures (WBS) and level of details. Scheduling capabilities vary among subcontractors as well as the planning applications used.

Two leading UK main contractors interviewed by the authors stated that they currently give sub-contractors site target dates or interface schedules (spreadsheets) and overview the process through weekly progress meetings on site. These site target dates are derived from three month look-ahead schedules that contain the main elements of subcontractors' WBSs. Subcontractors with formal scheduling capabilities have detailed schedules for these elements of the WBSs, and they may use spreadsheets or any of the commercial planning applications (e.g. Primavera, MS Project, Asta Powerproject) to produce such plans. Some subcontractors load the resources within their schedules, while others manage the resource separately (e.g. using spreadsheets with the number of operatives required daily) and they use the schedules just to express the logical sequence and the start and finish dates of tasks. Within such an environment, schedules are distributed and heterogeneous and their coordination is an extremely challenging task. Consequently, conflicts are very difficult to detect and resolve. They could be the result of either temporal conflicts or overallocated shared resources such as labor, equipments and working space with limited access capability.

Although the coordination of distributed schedules in the construction supply chain is a crucial aspect, it has not attracted much attention from researchers and commercial tools providers:

Kim et al. (2001) presented an Agent-Based Compensatory Negotiation (ABCN) methodology and developed a Distributed Subcontractor Agent System (DSAS), where agents (subcontractors) negotiate among themselves to reach a workable solution. The main objective of the negotiation is to minimize a utility function, which is the sum of subcontractors' costs associated with their resource constraints when a change occurs. However, this method has important limitations, as resources are not the only constraints in a project and it requires a high level of sophistication on the part of the participants involved, where computer programs (agents) represent the interests of each subcontractor. In addition, as subcontractors are reluctant to show information about their resources costs even in 'live negotiation', they are unlikely to do so with the DSAS.

Choo (2003) developed a synchronized database for multi-project schedule coordination. The rationale behind the method is to combine information about participants in one place on the WEB (data repository and sharing) where a checklist of constraints (contract, drawings, labor, equipment and pre-requisite site conditions) is entered by different participants on the project. Using this information, the project coordinator can release a work package only if all constraints are satisfied. However, this system has no link with the master schedule or the schedules of multiple participants and it is developed without any regard for scheduling software tools.

Siddiqui (2008) presented a method for the coordination of distributed schedules. This method aims to identify temporal conflicts using schedules mapping, where a group of tasks from one schedule can be linked to a group of tasks from another schedule. Although this method recognizes the 'distributed' nature of schedules, it only detects the temporal conflicts and requires a complex analysis of the schedules to obtain the mapping. The current incarnation of the tools to support this methodology deal with MS project schedules only; and more importantly, the schedule mapping approach introduces new constructs and terminology which are not familiar to planners and project managers.

Sriprasert and Dawood (2003) developed a system for multi-constraint information management and visualization, which is used in collaborative planning and control in construction. Information such as drawings, specifications, method statements, resources information are integrated into a central database named as Lean Enterprise Web-based Information System (LEWIS). The system also generates 4D constraints-based models by linking CAD objects (PBS) with schedules (WBS) using Uniclass standards and by associating other types of constraints within the LEWIS. Although this solution filled many existing gaps and represented an advancement of existing solutions, it requires that all subcontractor schedules exist at a predetermined level of detail and are closely tied to the general contractor schedule. So, it considers one schedule only rather than a number of distributed schedules. Finally, it constrains planners and designers to use Uniclass standard codes which are not of easy interpretation.

From this review, it can be concluded that existing methods have addressed the problem of the coordination of distributed schedules within the following significant limitations:

- Based on assumptions (e.g. willingness to cooperate between participants, availability of detailed information) that are unlikely to be satisfied in the construction environment;
- Developed for one specific software tool (e.g. MS project), while in the construction industry, numerous planning applications are used;
- Constrain planners of different participants to use some standard codes (e.g. Uniclass) for their tasks or to use new constructs and terminology which are not familiar with.

This paper presents the outlined developments of a potential solution for the coordination of multiple schedules in the construction supply chain. The authors believe that any solution must be able to integrate data from different planning applications and should place few if any constraints on planners or the project coordinator. In addition, potential solutions should have the capability to provide 4D/5D visualization of the construction process and generate useful inputs for the management of the supply systems making part of the supply chain.

3. MULTIPLE SCHEDULES COORDINATION: OUTLINE OF THE DEVELOPMENTS

The tool under development aims at helping multiple participants to plan and coordinate their supply chain activities. As stated earlier, this involves schedules coordination, site visualization and the management of the supply chain (supply systems). The outlined developments in this paper are mainly concerned with schedules coordination with some insights into the site visualization. After analyzing the existing research and reviewing real world practices, the authors suggest that in order to achieve these objectives, the tool should:

- Have the ability to accommodate the schedules of multiple subcontractors, which are created with different scheduling software tools (e.g. MS project, Primavera, Asta Power Project) and the schedules of the entire supply chain of a single company;
- Link or create cross-schedule relationships;
- Provide either the ability to create tasks or edit task attributes (SD, FD, relationships) within its environment (i.e. used as standalone software) or be synchronised on input and export with the most common scheduling software tools;
- Analyse the effects of delays of one schedule on other schedules and provide some decision making capabilities;
- Be capable of linking schedules' tasks to 3D models and provide 4D/5D visualisation.

The two leading commercial applications (i.e. Navisworks and Synchro) and the ndCCIR, which is a 5D planning application developed by the Centre for Construction and Innovation Research (CCIR), were reviewed as to these requirements. Such a review is summarised in Table 2.

It is important to highlight that this comparison did not consider the server-based version of these commercial tools, which allow all parties to share data within a central integrated database. This is because these applications are still limited to a very small number of major projects and are still unable to reconcile and contain the multiple views and needs of all participants (Amor and Farag, 2001; Turk, 2001; Zamanian et al, 1999). O'Brien et al. (2008) have further argued that whatever the advances of industry standards, semantic heterogeneity is likely to remain a significant barrier to integration (O'Brien et al., 2008). From the comparison in Table 2, it can be concluded that the ndCCIR, with the outlined developments (boxes shaded with grey), would represent a solution for the supply chain schedules coordination and visualization. These developments are being written in C# taking advantage of a Rapid Application Development (RAD) such as Microsoft Visual Studio 2008.

Table 2: Review of software tools with regards to the requirements of supply chain management

	Navisworks Manage (2010)	**Synchro professional (2010)**	**ndCCIR**
MS project	Import and export in XML	Import and export in XML	Import and export in XML
Primavera	Import with synchronisation, export	Import with synchronisation, export with synchronisation	Import with synchronisation, export
Asta Powerproject	Import with synchronisation, export	Import with synchronisation, export with synchronisation	-

Change task attributes (SD, FD and relationships)	Not required as schedule are synchronised with their native software	Not required as schedules are synchronised with their native software	Yes
Import multiple separate schedules	Yes	-	Yes
Create Cross schedule links	No – (can be linked without real dependencies, used just for the sequence of visualisation)	No	Yes
Conflict management of cross linked schedules	Only visual	Only visual	Initial detection of conflicts (temporal conflicts) based on a logic and then visually
Schedule crashing	No	No	Yes
Cost visualisation	No	No	Yes

3.1 Cross-schedule links

The ndCCIR tool currently can import the multiple schedules of different participants. However, it does not provide a way of creating cross-schedule links. With the outlined development of a module called 'ndCCIRLink', the software would become capable of creating these cross-schedule links. This will be enabled in two ways:

3.1.1 Graphically

The tool allows the linking of one or more tasks from one schedule to one or more tasks from another schedule. To graphically link one task from one schedule to one task (one to one) or more tasks (one to many) from another schedule , it is necessary to select a task bar in the first schedule and then, while keeping the shift button pressed, select one or more task bars from the other schedule. When the shift button is released, a window will pop up with the name of the tasks selected from both schedules (figure 4). Figure 5 shows the windows for the many to one relationship. Cross schedule links can be created for two schedules at a time. Using the windows in figure 4 and 5, it is possible to edit the selected tasks, if there were some mistakes in the graphical selection and to define other attributes such as the precedence relationship and lag time. Temporal conflicts among schedules are detected and checked at this stage, based on the real work logic (logical relationship) dictated by the planner. For example, if, based on the logical dependency (e.g. 'install window and doors' is a predecessor to 'plaster'), the planner is linking task 1 (i.e. install window and doors) to task 2 (i.e. plaster) in a 'finish to start relationship' and the start date of task 2 (plaster) is before the finish date of task 1 (install doors and windows), a pop up window will warn the planner about this conflict. Then, the planner can undertake the corresponding actions (e.g. delay the start date of task 2) and resolve eventual other conflicts arising within the schedule affected by the change.

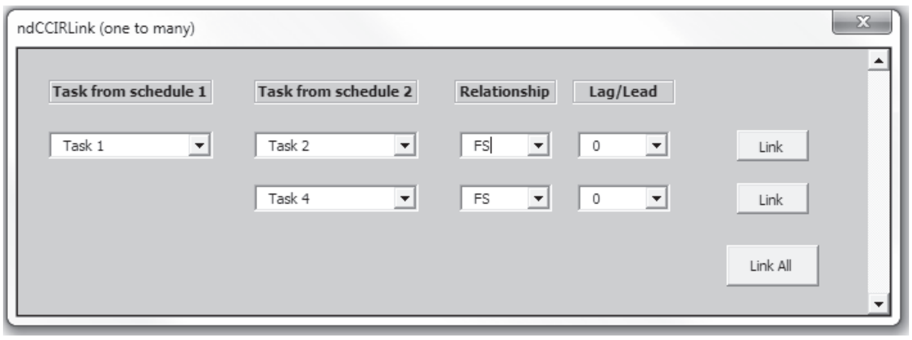

Fig. 4: One to one and one to many cross schedule linking window

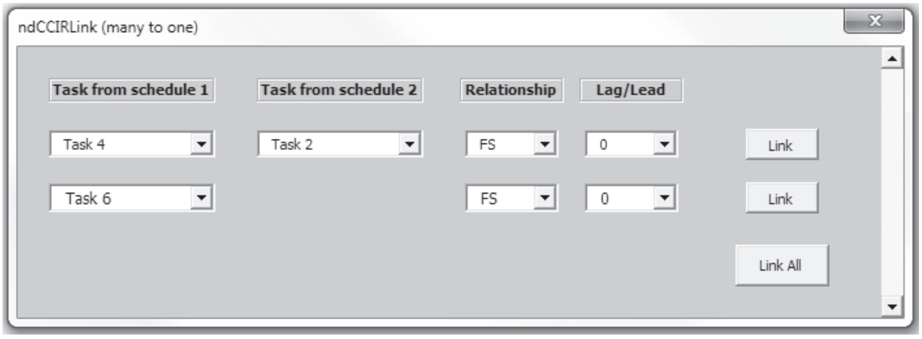

Fig. 5: Many to one cross-schedule linking window

Once the tasks are selected and the relationships are defined, by clicking "link", the schedules are updated by taking into account these new relationships. This can be done either every time a cross-schedule link is established (clicking "link" line by line) or after all cross-schedule links are established (clicking "link all"). It is recommended to carry out the cross-linking line by line, as it is easier to sort out eventual schedule conflicts once at a time.

3.1.2 Through a user interface

The graphical way of linking may become cumbersome and time-consuming if schedules have a large number of tasks. For this reason, a user-friendly interface can be used to create cross schedule links (figure 6). By using this user interface, tasks can be linked from two schedules at a time. Firstly, the two schedules have to be selected. Once the type of link is selected (e.g. one to many), the user interface displays a suitable number of lines for such a relationship. To speed up the selection of tasks, the field "task tag" should be selected first: this allows the displaying of only the relevant tasks under task field name. The list of attributes for the field 'task tag' is reported in table 3. These tags will not only speed up the process of linking but will also help identifying the tasks that conflict with others on shared key resources. The linking can be made line by line at a time or for all lines together by clicking 'link all'. Temporal conflicts are also detected at this stage as explained earlier.

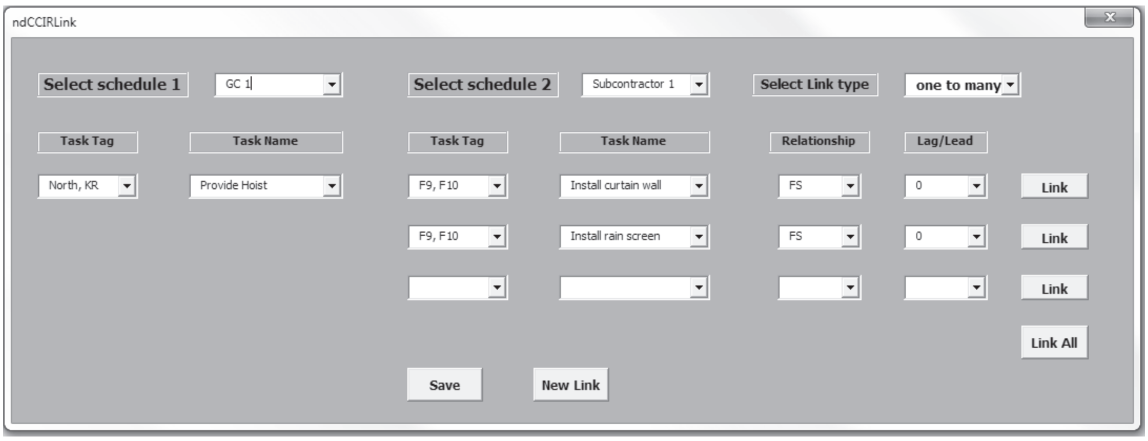

Fig. 6: One to many cross schedule linking window

Table 3: Attributes of tasks' tags

Field	Attribute	Explanation	Attribute	Explanation
Task Tag	KR	Key resources	D	Design
	F	Foundation	P	Procure
	GF	Ground floor	M	Manufacture
	F1, F2, .., Fn	Floor 1, Floor 2, .., Floor n	I	Install
	Pe	Penthouse	North, East, South, West	Reference to the elevation or scope of work

3.1.3 Analysis

An analysis interface (figure 7) allows a range of analysis that includes the following:

- *Data summary:* gives a summary of all cross-linked activities, the name of the schedules they belong to and the type of precedence relationships they are involved in;
- *Dates after linking*: once the cross-schedule linking has been established, the ndCCIRlink allows the comparison of start and finish dates for each subcontractor schedule before and after the linking (figure 8). By clicking on 'show details', the activities that have had some changes after the linking are listed for each sub-contractor and activities attributes (SD, FD and duration) are compared before and after the linking. The important tasks (e.g. tasks with deadlines) that are delayed after their key dates are also highlighted and reported separately in the report generated;
- *Updates*: once the cross-schedule linking has been established, new changes to task attributes (e.g. start date delayed) automatically affect other schedules' tasks. The cells of the tasks that are impacted by these updates get highlighted in light green. A summary of the impacts of the updates on different subcontractors is useful to generate as they might be used for the negotiation between subcontractors and the general contractor. This summary report can be obtained by clicking on 'update' (figure 7). Important tasks (i.e. task with deadlines, must finish on, milestones) are also highlighted as explained earlier;
- *Schedules crashing:* the tool displays all critical activities in a table where the planner can enter the allowable crash days for each activity. Then, the tool automatically calculates the crash cost for each activity and the new project duration resulting after the crashing of each activity on the critical path. The crashing process enabled is limited to the original critical path. Therefore, the tool has the ability to check if the number of crash days entered causes another path to become critical and warns the planner whenever this occurs. Once allowable crash days are entered and crash ratio (cost/day) is calculated for each activity on the critical path; based on the amount of time to recover (i.e. delay, reduction in project duration), the tool automatically selects the list of critical path activities that produce this reduction in project duration for the lowest cost;
- *Reports:* each of the results explained at the previous points can be saved as a report with a suitable name.

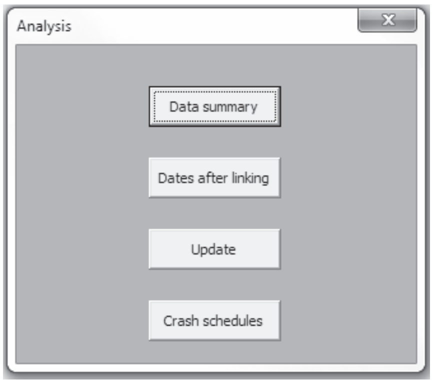

Fig. 7: Summary of the analysis

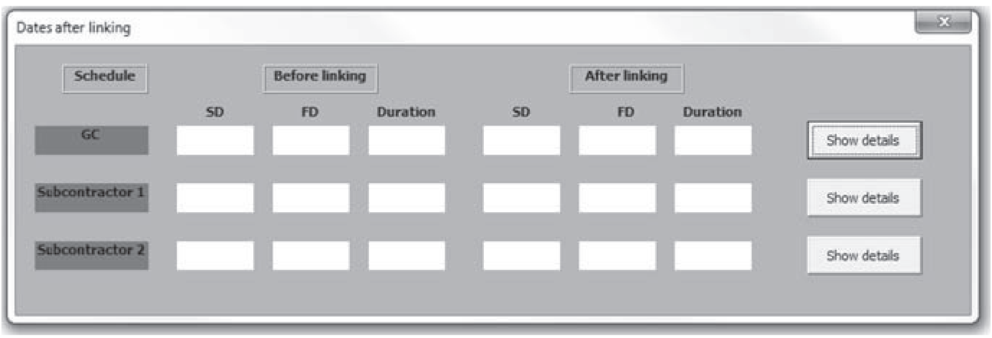

Fig. 8: Summary of the supply chain's programmes after linking

4. CONCLUSIONS

Supply chain management is a relatively new and still somewhat an uninvestigated concept within the construction industry and a clear roadmap for conducting the research within this area is still missing. Firstly, this paper aimed at explaining the different facets of the problem using a real example. This has led to the conclusion that the research in the construction supply chain management should be focused on two main areas: the coordination of the multiple participants on site and the management of the upstream supply systems forming the supply chain. Secondly, this paper presented a requirements specification for the coordination of multiple participants. These specifications are under development and would allow the coordination of multiple schedules. Unlike existing research, the proposed solution does not introduce new constructs and terminology and does not place any constraints on planners. Schedules involved can also be linked to a 3D model where 4D and 5D visualization is enabled. This visualization represents a second stage of the coordination process which can validate the initial coordination of the schedules and offer new capabilities (e.g. 4D/5D visualization, H&S issues, etc.). Future work will aim to develop a coordination module for one supply system (i.e. façade industry) in order to generate useful planning inputs for the supply system in terms of material delivery to the site.

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Development of Construction Planning Tool by Integration of Application Data

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ABSTRACT: *This paper reports the implementation of a system that visualizes the construction-planning process using 3D modeling data and schedule data to analyze construction planning. In the past, studies have reported the benefits of visual 4D planning in which the 3D modeling data combined with process schedule data for work progress control. The proposed methodology offers rapid visualization of the work performance with scheduled activity and simplifies the construction planning and schedule inspection. Consequently, it is expected to increase productivity and reduce the need for reworking the plan. However, even an innovative construction company will not readily adopt the new methodology unless the benefits outweigh the cost and effort. There are case examples that use 4D simulation or animation to show how a building looks or show the progress of the construction. A new model or even a new data structure might be required for the 4D demonstration. We aim to develop a system that integrates several types of data and enables simulation of the construction progress by displaying 3D models according to the activity schedule. The system has the following requirements: it must 1) import and display 3D modeling data, 2) import the project schedule, 3) link each model and activity, 4) give material data for each object to enhance the realism, and 5) show the cost accumulation. These functions should use previously reserved resources. Thus, the system should be able to import DXF-format files for 3D modeling data, and access MDB-format database for the project schedule and the costs. These data format are apparently the most widely used in this context.*

KEYWORDS*: construction planning, 4D CAD, virtual reality, data integration, congestion control*

1. INTRODUCTION

This paper presents the implementation of a construction-planning tool using 3D modeling data and schedule data as an application of ICT technology in the field of construction. In recent times, the construction industry has attempted to improve its production system by integrating procedures ranging from design to construction and therefore promoting the use of 3D CAD systems (Nagao et al. 2005). The aim of the recent 3D CAD technology is to provide a platform to unify the data types shared by project members, including data related to design, construction, and facilities (Yabuki et al. 2004); earlier CAD technology could be used to obtain only data related to the intended design at an early planning stage or to obtain a consistent drawing at the final planning stage.

Technical issues at the construction stage are now considered from the early design stage. Combining design with production in such a manner, which is referred to as *production design*, allows the user to demonstrate at an early stage the estimated progress in the work as well as the amount of completed work. It is also possible to reduce the reworking and redesigning at the post-processing stage since visualization at an early stage helps to identify technical problems. This methodology requires various types of applications, including a CAD system, to design, plan, manufacture, and manage the process. However, it should be noted that the interchangeability of shared data between the software tools is not sufficiently high, and thus, the overall efficiency of the project is not improved considerably. The product model is being developed as a solution that allows interoperation among different systems (Yabuki et al. 2005a, 2005b; Kawanai 2005). The product model is a generalized data model that expresses 3D shapes, and it provides information about the attributes of each element in a structure. The data set

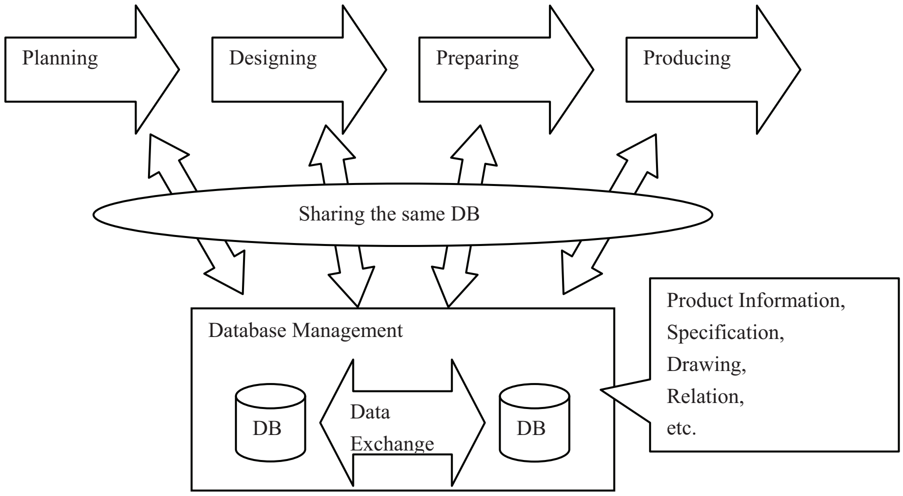

Fig. 1 Data Sharing Using Product Model.

can be shared by various systems or applications if the data set is created as a product model, as shown in Fig. 1.

Previous studies have reported the advantages of architectural methodologies that use 4D data to associate 3D modeling data with the schedule data for the construction. Despite the advantages of this method, even major construction companies do not use it. In fact, 2D drawings are still widely used for design and construction planning. Although a 2D drawing is sufficient for a designer, it is difficult for less-experienced people to visualize the 3D aspects using 2D drawing, and the problems cannot be simulated or analyzed on a PC. However, the conventional methods will not change unless the new approach can be clearly shown to offers benefits that outweigh the cost and effort involved. Considerable cost is involved in using the new methodology to produce a new set of data structures such as the product model, simulate the assembly process on an advanced CAD system, or animate the arrangement of objects in a high-performance 3D graphic designer. Even though each software tool provides multiple functionalities, the applications currently in use are all independent and specific, such as CAD for the design of 3D models and a project manager for the scheduling. The product model is very promising solution but developing a large amount of reusable data is essential otherwise specific data structure will have to be developed for each project all the time. Therefore, a system that integrates the outputs from each application is required for the implementation of the new methodology before the use of the product model.

Methods involving several applications have been introduced (Dawood et al. 2001, 2002, 2005, 2006; Sriprasert et al. 2003; Vries et al. 2007; Kang et al. 2006; Kano et al. 2002, 2003). Some require the original data structure and others simulate a specific project (http://www.bentley.co.jp/info/usercase/nishimatsu.htm). In this study, a system that integrates the data from several applications is proposed, whereas in other studies, the integration of the applications themselves has been suggested. Our approach is generally applicable for any case since the system accepts the data files created by several types of applications. The main component of the system is the visualization of the process control using a 3D shape linked to the schedule. The visualization not only shows the state of construction but also simulates the entire construction field. This is done by simulating heavy machinery and material carriers along with their route and temporary storages in order to examine the entire construction plan in advance. Although the data are created by different applications, the proposed system can link data from each dataset. It thus provides the same advantages as 4D CAD without the need to create a product model or a new type of data structure. Therefore, users can work with generic applications such as CAD and Microsoft Project (MS-Project) in the usual manner.

In this paper, we describe the implementation of software that simulates the progress in the work by visualizing the given drawing data and linking them with the schedule data.

2. DESIGN OF THE CONSTRUCTION-VISUALIZING TOOL

2.1 Software specification

Some tools implement the animation in AutoCAD using VBA or AutoLisp and others implement it in an advanced CAD system. The suggested system enables importing the model data contrary since data exchange without an expensive CAD system is widely required. This design is advantageous to both users and developers. Users can handle any implemented data type, and it is easy to supply a function to import other data formats since the system is independent of specific applications. It is assumed that the system needs to perform the following functions, integrating the resources by linking related material:

1. Reading drawing data
2. Reading schedule data
3. Linking components and schedule
4. 3D visualizing
5. Displaying progress in the work at any given time
6. Displaying the cost accumulation
7. Setting the textures for the components
8. Saving/reading work

Functions 1 and 2 involve importing data created by other applications. The other functions involve the processing of imported data. Functions 5–8 are the original functions. They show the construction status, the accumulating cost at any specified time, or illustrate the status transformation over time after linking the different types of imported data which is modeling data and schedule data, and additionally material/texture data in order to enhancing the reality. “Work” in function 8 implies the work on the proposed system and not the work in a construction project. Function 8 is important because any information in a data file is quite large and the users’ work should be reproducible. The proposed system is expected to use both the drawing data created by AutoCAD and the schedule data created by MS-Project. The system should look like a general Windows application; further, users should be able to navigate the 3D scene using a mouse. The system overview is shown in Fig. 2.

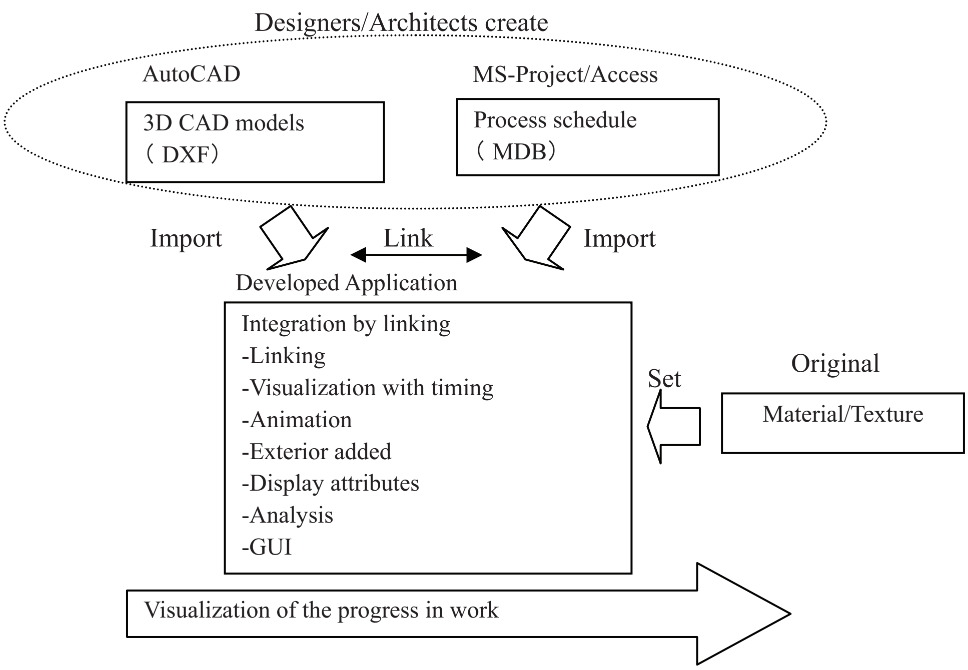

Fig. 2 System Overview.

2.2 Development Environment

The system is developed using Microsoft Visual C++ (hereafter VC) and DirectX SDK. Alternative languages include Visual Basic and Java, and alternative graphics engines include OpenGL and Java3D. Our choice was based on the need to handle huge data sets, and the fact that VC offers a Windows-like environment. The system is developed based on the FormView class so that additional functions can be represented by icons. It is also based on the Document-View architecture. The imported data are stored in the CDocument class and the CView class controls the visualization. Various data classes are defined for each data type and the system instantiates the appropriate data class in the CDocument class based on the type of the imported items. These data classes are referenced from the CView class and selectively rendered according to the time schedule. The relation among the classes is shown in Fig. 3. The principal functions are described in the following subsections.

2.3 Implementation

2.3.1 Importing the model data

AutoCAD creates two types of data: DWG and DXF. DWG is binary whereas DXF is text and therefore easier to handle. DXF is the drawing interchange file format; its specification has been published, and it is widely used for data exchange between applications that deal with models or drawings. The system must be able to process a DXF file.

Each DXF file consists of seven sections: HEADER, CLASSES, TABLES, BLOCKS, ENTITIES, OBJECTS, and THUMBNAILIMAGE. The ENTITIES section contains information about the shape. The data in this section are important for visualizing the model. There are entities that describe a specific figure such as a circle or a curve, with a layer name and the coordinates of the vertices. There are approximately 40 types of elements, as shown in Fig. 4. A preliminary survey indicates that the shapes defined in ENTITIES are usually one of four

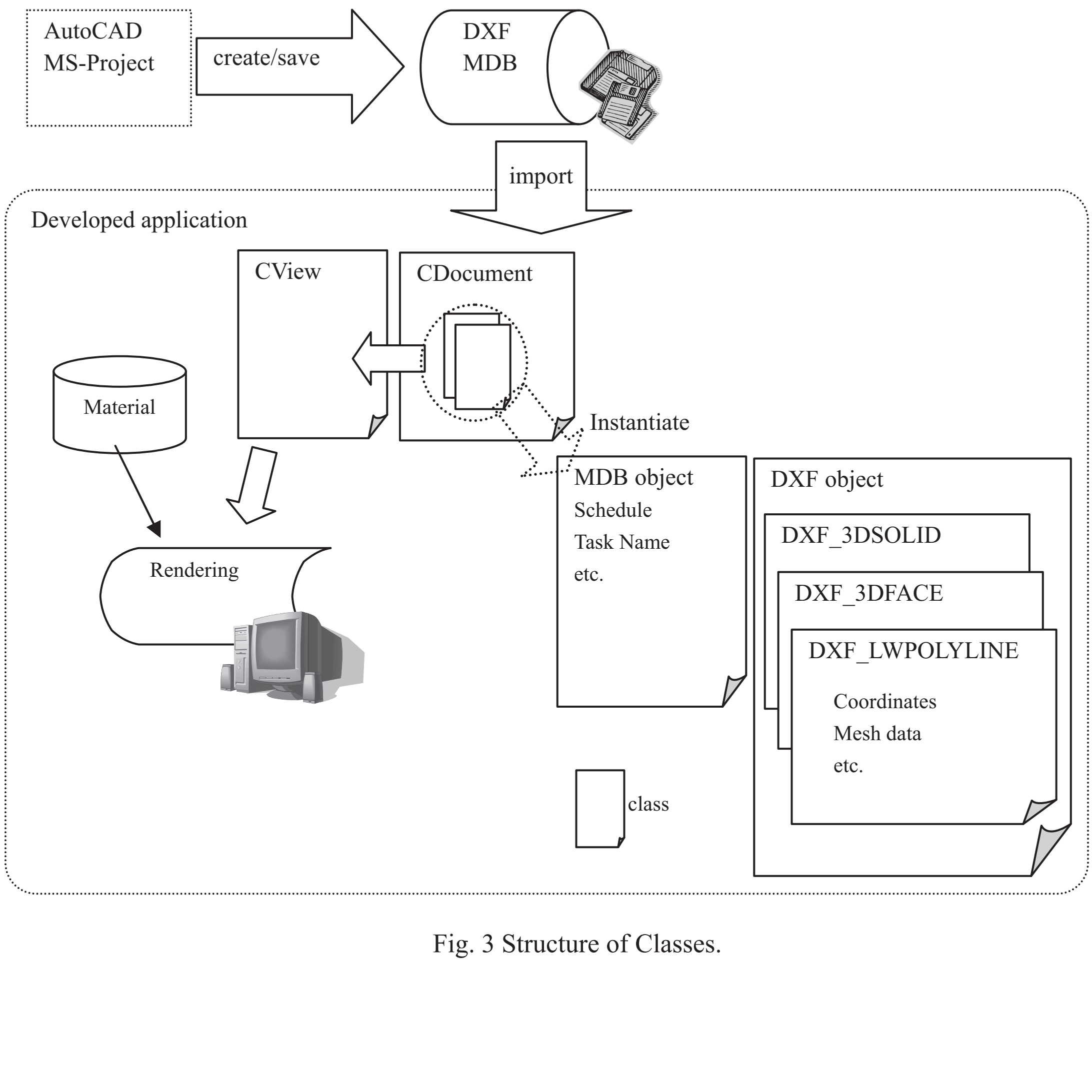

Fig. 3 Structure of Classes.

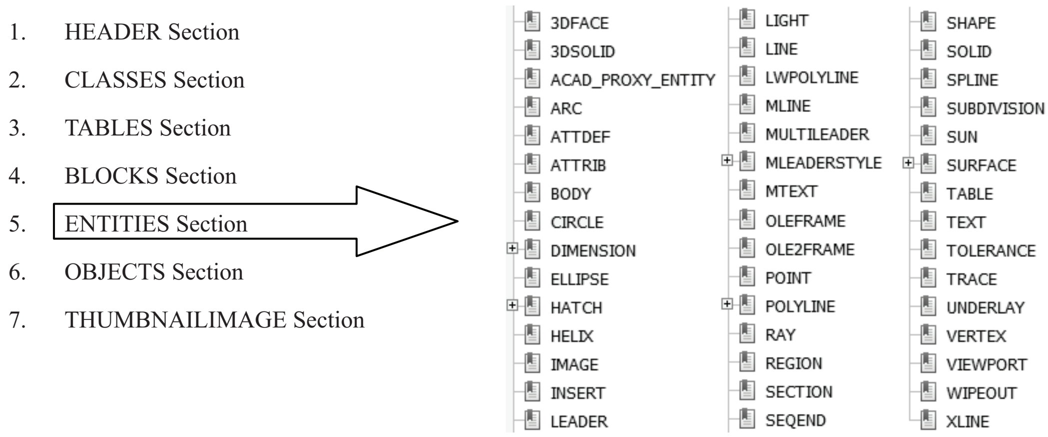

Fig. 4 Seven Sections in DXF File and Entity List in ENTITIES Section.

types: REGION, 3DFACE, 3DSOLID, and LWPOLYLINE; typically, the LWPOLYLINE shape is used. The processing of the drawing data is currently limited to these four shapes.

The system reads DXF files line by line and instantiates a class associated with each entity style when it finds the shape's definition within the ENTITIES section. Each class stores the coordinates, layer name, and so on. The imported shapes are rendered as a set of meshes obtained by defining these coordinates. The layer names are listed in an array (actually the vector class), and the classes are listed in an array together with the shapes, such as LWPOLYLINE or 3DSOLID. All the components belong to one of the layers. A set of components drawn on the same layer is considered to be the set needed by a particular construction process.

VPORT and LAYERS in the TABLE section are also essential. VPORT is used to determine the line of sight, and LAYERS is used to fetch the layer-name list for the shapes. All components of the structure belong to one of these layers. We assume that the component data that are related to a particular construction are drawn on a layer. When a layer is linked to a process in the construction plan, all the components drawn on the same layer are linked to that process. Therefore, an animation that changes process by process equivalently changes layer by layer.

2.3.2 Importing the schedule data

It is assumed that the process schedule is developed using MS-Project. The system currently requires a file exported by MS-Project that is in the Microsoft Access (MS-Access) format. The system accesses the elements stored in the database via an ODBC (open database connectivity) driver. The software is unable to access an MS-Project file directly since the relevant ODBC driver is not provided. The exported MS-Access file contains several databases, and one has a table that contains the process schedule. The table has fields that describe the task name, start date, finish date, and cost. The system can read them and modify them directly since it uses ODBC and can execute an SQL command. Screenshots of this operation are shown in Fig. 5.

2.3.3 Linking components and schedule

After the model data and schedule data are imported, the layer names and task names are listed. The component names are listed under their layer names. It is necessary to link task names in the schedule data and the modeling data. A task name should be reasonable since it is used for process management. Modeling data are created in the same layer for each process flow. The linking operation is as follows: choose one entry from the task-name list with a click and then one from the layer-name list, and then link them with a right-click. The layer that has to be scheduled, including the construction components, then appears under the process name. Fig. 6 shows this operation. This operation is carried out as many times as required by the process flow. A user should be able to save and reproduce these links because the number of processes is considerable when the structure to be built is large.

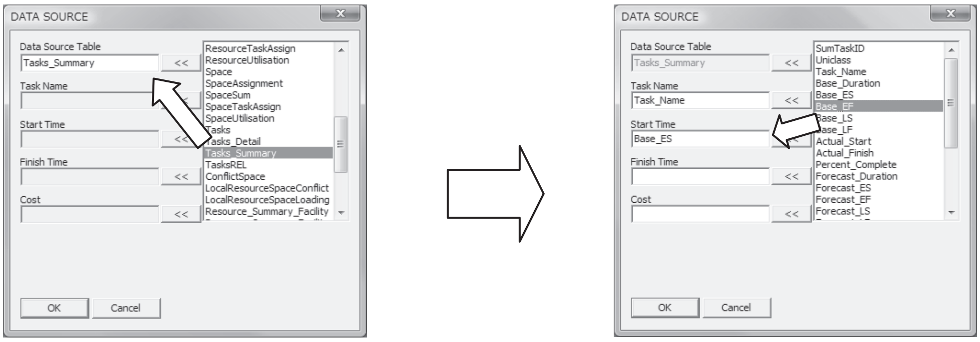

Fig. 5 Selection of Table (left) and Fields (right).

Fig. 6 Linking of Layer and Activity.

2.3.4 Visualization

When the system reads a DXF file, the coordinates are fetched for each component and constructed as a set of meshes. Each mesh is made up of triangles; hence, the displayed model is composed of a number of triangles because of the display mechanism of the hardware. A triangle mesh gives the best performance on the hardware used for the system.

The model displayed after the linking of layer and schedule shows the progress in the work at any given time. Some components are already constructed, others are in progress, and others are not yet started. They are distinguished by color. If a date is given by the user, the components that are not yet started on that date are not displayed, those under construction are displayed in red, and those completed are displayed in blue. The scene that displays the construction can be navigated by a mouse, and it is possible to examine the scene from any angle and any distance.

If the date is changed in a certain interval, the progress is animated as shown in Fig. 7. The resource list is shown on a tab. Clicking the other tabs shows other information such as the progress in the work, the cost, or the materials list, as shown in Fig. 8. The scene can be changed by changing either the display colors or the material attributes. When the tab is set to the materials list, the components and materials can be linked with the same operation as that used for linking components and tasks.

2.3.5 Setting the material for the components

DXF files have settings for colors, but they are not always used because they are not necessary at the design stage. Therefore, the system uses only mono color with gradation; however, the color differs according to the completion status. The displayed scene may be more realistic when each component has a material attribute. It is important to animate the design for process examination or analysis. If the system accomplished this, it would be a useful tool for the presentation of an area of interest. The DXF format does not support textures and material attributes so the material library must be stored in a different format.

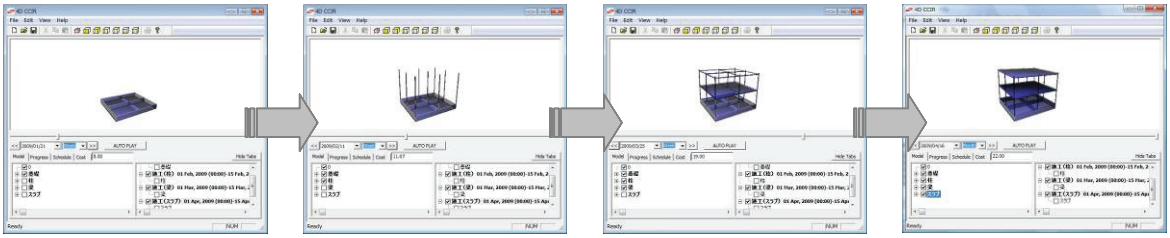

Fig. 7 Animation of Progress in Construction .

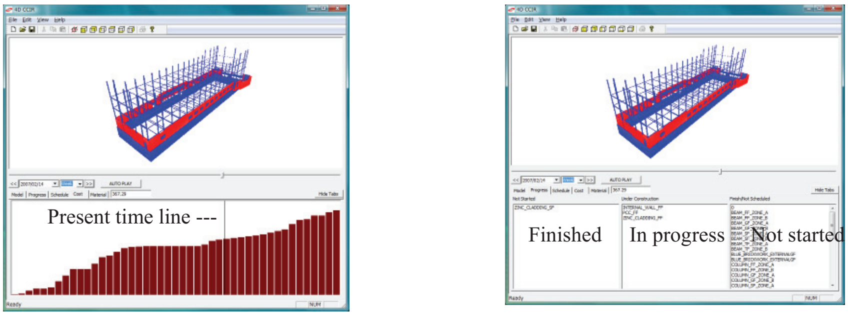

Fig. 8 Changing Tab to Show Cumulative Cost (left) and Progress in Work (right).

2.3.6 Saving and reading files

The system stores the source files, name of the database used, table names, field names, linkages of task names, and layer names in a text file. Each factor is separated by a text separator. When this file is read, the user changes are duplicated according to the information in the file. Currently, the text file lists each instruction performed by the user and the system carries out each of them.

3. DISCUSSION

The system can currently import model data and schedule data, visualize them, create an animation according to the process plan using materials/textures if the library is well organized, and display the cost accumulation. The construction status over time can be visually confirmed. All the construction processes can be displayed in the animation, and it is possible for the display to represent a specific time. The construction process plan can be examined and analyzed by performing simulations in advance. Smooth communication can be achieved among the designer, the purchaser, and the workers on the site. The display will be more realistic when the material of the components can be set.

The system can: 1) assess the completeness and accuracy of the plan, 2) communicate the progress, 3) visualize the progress, 4) visualize the direction of the work, and 5) identify conflicts (process and products). However, the biggest problem thus far is that the original processing of the model data cannot support all the elements that the DXF format defines. The system currently renders only a few shapes. Using a third-party SDK for DXF, e.g., Open Design Alliance's OpenDWG (http://www.opendwg.org/), is probably appropriate. A material library is also important to make the model realistic, but this would require considerable work.

4. CONCLUSION

This paper has presented the implementation of an application for construction sites. The application provides an interface to link 3D model data with the schedule data so as to visualize a construction scheme in 4D without a new data structure such as that of the product model.

In future, we plan to implement a function that can visualize temporarily used heavy vehicles. We will also incorporate background images and terrain data since the MS-Project data usually includes such information. We will examine the correspondence with the surroundings and simulate an overall architectural plan, including an examination of the delivery vehicles, installation positions, space for heavy equipment, temporary storage of materials, and placement of orders. We aim to derive the benefits of 4D CAD using the resource files that are generally available at production sites.

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4D WORKSPACE CONFLICT DETECTION AND ANALYSIS SYSTEM

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ABSTRACT: *Construction activities require a set of adequate workspaces to be executed in a safe and productive manner. This research classifies these required workspaces of activity into five categories: building component spaces, site layout spaces, people working spaces, equipment spaces and material spaces. All of these spaces change and move in three dimensions and across time throughout the construction process. Different activities may occasionally interfere with each another whilst working in the same space, causing space conflicts. In order to avoid the problem of space conflicts during the construction stage, this research develops a 4D workspace conflict detection and analysis system. Our system is implemented on top of Bentley MicroStation which supports both visualization of a 3D building model with capabilities for 3D object manipulation and information querying, and provides an API (Application Programming Interface) for functionality extensions. In this system, four types of space conflict are implemented: design conflict, safety conflict, damage conflict and congestion. Moreover, this system provides a visual environment, such as 3D visualization and 4D simulations, to present work space utilization of the ongoing project and the conflict status of activities with different colors. In this paper, the design and implementation of the 4D workspace conflict detection and analysis system is discussed and sample construction example is used to demonstrate the applicability of the system.*

KEYWORDS*: 4D, Conflict Detection, Conflict Analysis, Workspace, Construction Management*

1. INTRODUCTION

Space is regarded as a limited resource on construction sites. This becomes apparent when two or more trades are working in the same construction space, potentially interfering with each another, or when the workspace of on-site personnel conflict with material stacking space. These kinds of activity space conflicts occur frequently, severely affecting the process and efficiency of construction and resulting in productivity loss. Construction productivity is thus influenced by a variety of factors. Many researchers have studied the factors that cause loss of productivity in construction sites. Kaming et al. (1998) indicated that space conflicts have been identified as a one of the major causes of productivity loss in construction. Sanders et al. (1989) reported efficiency losses of up to 65% due to congested workspaces and losses up to 58% due to restricted access. Space conflicts can occur in many parts of the construction site and in various stages throughout the construction process. Inadequate workspace and interference during travel can result in access blockage, congestion, safety hazards, and heighten the risk of damaging the end product (Oglesby et al. 1989; Thabet 1992; Tommelein et al. 1992, 1993; Riley and Sanvido 1995; Akinci et al. 1998). Various approaches to ameliorate space conflict have been presented to address the above-mentioned issues. The approach taken in Guo (2002) focused on space availability due to time and scheduling, applying two typical tools, AutoCAD for space planning and MS Project for scheduling, to solve space conflicts. In the past decade, 4D simulation (or 4D CAD) technology, which bind 3D models with their corresponding construction schedules in their simplest form, has made rapid development in providing engineers with an effective tool to manage the coordination complexity of the site, especially in managing conflicts before actual construction commences. The rapid emergence of 4D simulation technology is not only driven by the rapid advancement of information technology, but also by increasing recognition from the construction industry of the benefits of using the 4D CAD applications to increase productivity, improve project coordination, and optimize on-site resources. 4D visualization has emerged as an interesting 4D space planning and visualization tool. 4D space planning specification and construction work development have been investigated by Riley (1998). Akinci et al. (2002a, 2002b, 2002c) also executed similar research which reduces non-value-adding activities due to time-space conflicts. A time-space conflict analysis based on a 4D production model was then proposed. Mallasi's research developed an innovative computer-based tool dubbed PECASO (Patterns Execution and Critical Analysis of Site-space Organization). There is potential for this system to assist site managers in the assignment and identification of workspace conflicts (Mallasi 2004; Dawood and Mallasi 2006). Though much of the research has targeted the space scheduling problem, much less literature is concerned with workspaces for dynamic working objects on construction sites, such as labor and equipment. This is further complicated by the variable requirements of different activities and the change in the location and size of the workspace over time. This study considered the space availability of construction sites in relation to scheduling, productivity loss due to path interference, and space constraints. This research has developed a conflict detection and analysis module based on a 4D CAD system to solve space conflict issues for various working objects in a construction site.

Section 2 seeks to define workspace and analyzes the types of workspace conflicts. Section 3 discusses the design and implementation of the conflict detection and analysis module. Section 4 demonstrates the applicability of the 4D workspace Conflict Detection and Analysis System with a construction example. Finally, Section 5 draws our conclusions from the study.

2. DEFINITION OF WORKSPACE CONFLICT

A concept diagram of this research is shown below in Fig. 1. The most important impact factors for this research are the requisite workspace for activities during construction, the method of workspace aggregation and the various types of workspace conflict. These will be discussed as follows.

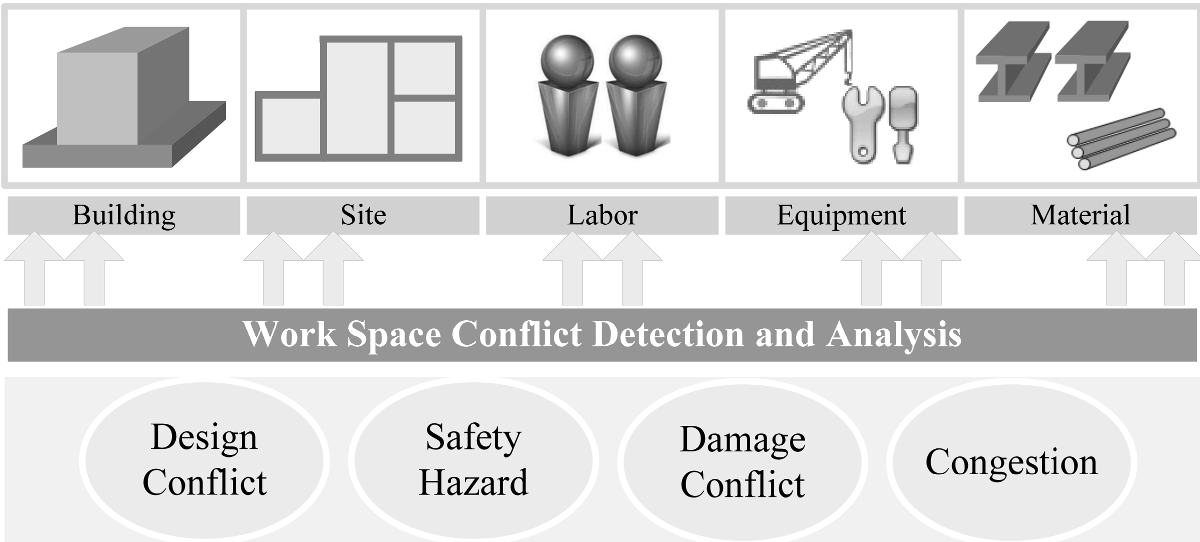


Fig. 1: A concept diagram of this research.

2.1 Workspace

Space is a resource that may cause crucial problems during construction. The construction workspace is a combination of resources, including building component spaces, site layout spaces, human workspaces, equipment spaces and material spaces.

- Building component: Building component means a specific design or structural element. Each building component, such as a column, beam or wall, is assigned a workspace. The space assigned is the physical space taken up by the building component, as well as providing a buffer required to keep a safe distance around them.

- Site layout: Construction engineers have to properly allocate construction spaces, such as material storage, the construction site, construction roads and the site office, to minimize the cost of labor and material travel such that the operation is accomplished quickly and efficiently, whilst ensuring the safety of both labor and equipment.

- Labor: Labor crews need a set of workspaces for constructing building components safely and productively. That is why construction sites need to provide enough space for working and safety, in order to reduce productivity loss and minimize accidents.

- Equipment: Constructions site need to provide enough operation room for equipment to maneuver safely.

In this manner, the workspace assignment for equipment must consider operation clearance and hazards. Examples of common equipment are cranes, pumps, temporary facilities, and so on.

- Material: Construction sites need to provide adequate room to store materials properly and allow safe access to them. This kind of workspace assignment must consider protected areas for materials to ensure that they will not be destroyed.

Workspace as defined by this research is shown in formula 1. Each object in the model (building component, site layout, labor, equipment and material) has its own space, as well as space needed for operation and safety. This research will calculate how much workspace each object needs and assigns it to them for workspace conflict detection and analysis.

$$\text{Workspace} = \text{Space}_{object} + \text{Space}_{operation} + \text{Space}_{safety} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

2.2 Workspace aggregation

Construction activities need a set of work spaces to be executed in a safe and productive manner. An example of this would be the pouring of concrete into pad foundation which requires a concrete mixer and a concrete vibrator to accomplish the task. Sufficient workspace needs to be provided for these two pieces of equipment to be able to maneuver safely. Therefore, we must consider workspace aggregation to calculate numerous workspaces at the same time to accurately detect and analyze workspace conflict. In this research, workspaces are created using Constructive Solid Geometry (CSG), a technique used in solid modeling. CSG allows a user to create a complex surface or object by using Boolean operators. The simplest cuboids are used in this research to represent workspaces. We classify workspace aggregation into two ways, with the first being the direct combination of workspaces. For example, since labor objects and equipment objects need independent spaces to operate and for a safety buffer, we can therefore directly combine their workspace cuboids into compound objects using operations such as the merger as shown in Fig. 2. Another aggregation is the combination of working objects. For example, building components and material objects require no space between each other so we can merge two of these objects when they have been installed or assembled, with the workspace for the combined object then recalculated and new workspace cuboids created as shown in Fig. 3.

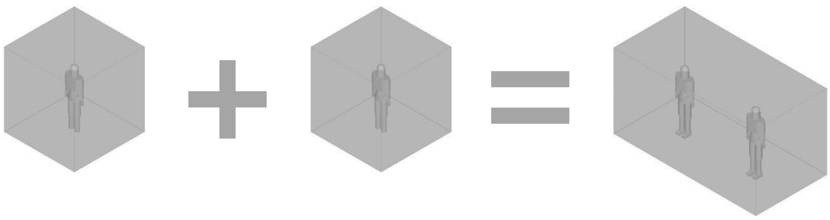


Fig. 2: Direct combination of workspace cuboids.

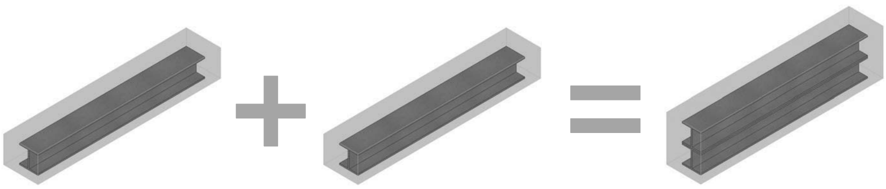


Fig. 3: Combination of working objects.

2.3 Conflict types

Project managers need to understand the different types of workspace conflict to develop customized solutions for managing them. According to the literature review, we introduced four major types of conflicts into our system as follows.

2.3.1 Design conflict

Current construction projects are more complex and have more participants involved. When different participants design their own separate parts of the building, design conflicts may occur. We can say that a design conflict occurs when a building component conflicts with another. Lack of space and pipeline overlap, for example, may arise from conflict between inappropriate electrical equipment design and HVAC pipe design. The causes of these conflicts are not construction related, but rather, design related.

2.3.2 Safety Hazard

The leading safety hazards on construction sites include being struck by falling objects, motor vehicle crashes, excavation accidents and electrical hazards. A safety hazard conflict occurs when a hazard space generated by an activity conflicts with a labor crew space required by another activity. People are not allowed to pass or stand underneath any loading or digging equipment. Labor crews are to remain at a safe distance from all equipment while it is in operation. When a hazard space conflicts with a labor crew space, it creates a safety hazard situation for the labor crew.

2.3.3 Damage conflict

In order to complete a particular activity, damage to the object or component that is completed in the previous activity may be sustained. A damage conflict occurs when a labor crew space, equipment space, or hazard space required by an activity conflicts with the protected space required by another activity. An example of this is if a worker wants to set up equipment in the correct position and the exit is too narrow or small, they must then remove the door for handling equipment.

2.3.4 Congestion

A congestion conflict occurs when a labor crew and a piece of equipment or material required by an activity needs the same space at same time causing a lack of space or space overlap. Examples of this are when storage space is too small caused by material stacking and overlap, where too many workers are working on the same building component causing congestion or when a large number of construction vehicles are entering or leaving the construction site at the same time causing congestion.

3. CONFLICTS DETECTION AND ANALYSIS MECHANISMS

The implementation of our 4D workspace detection and analysis system was carried out in Microsoft's VB.NET environment. During the simulation, the 3D objects in the construction site model are highlighted in different colors depending on their conflict types.

3.1 Workspace Data Model

A data model is an abstract model that describes how data is represented and accessed. This research proposed a workspace data model for data definition and storage. This data model includes six main classes, each with their own sub-classes and attributes for detecting and analyzing workspace conflicts as shown in Fig. 4.

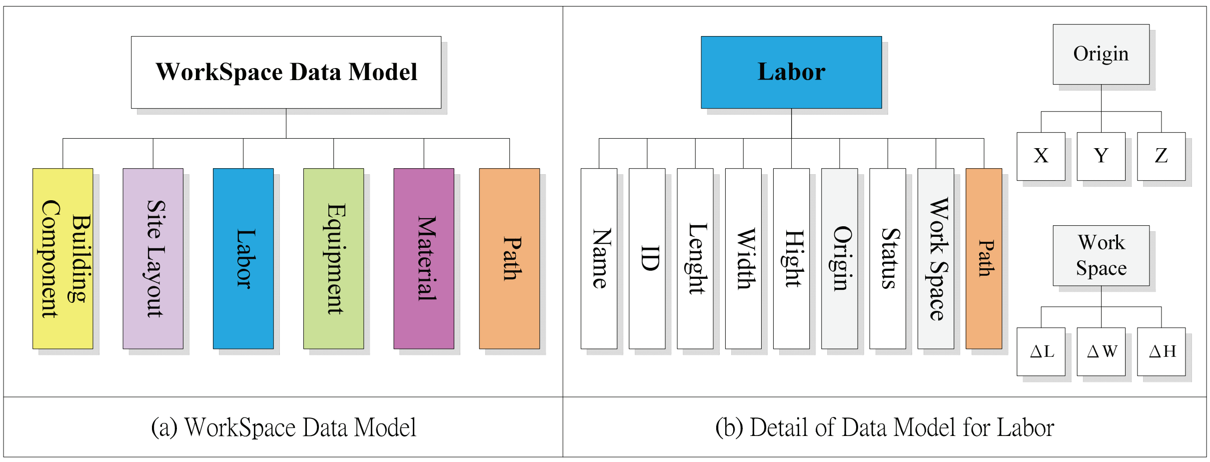


Fig. 4: Workspace data model.

3.2 Conflict Detection and Analysis Module

This research divided working objects into two categories according to their status: static working objects and dynamic working objects. Static working objects include building components, gatherings of people, parked equipment and materials stacks. Dynamic working objects include working people and equipment in operation or transportation. The simulation and visualization of the different working objects is discussed in the following sections.

3.2.1 Color Schema

We defined four colors to visualize the workspace conflicts in 3D environment. Table 1 shows the color scheme implemented with examples of the kind of working objects that will raise the specific conflict.

Table 1: Color schema for workspace conflicts.

Color	Conflict Type	Static vs. Static	Dynamic vs. Static	Dynamic vs. Dynamic
Purple	Design Conflict	Design Interference	None	None
Red	Safety Hazard	None	None	Equipment vs. Labor
Yellow	Damage Conflict	None	Equipment vs. Building	None
Green	Congestion	Material vs. Material	Labor vs. Material	Equipment vs. Equipment

3.2.2 4D Visualization

This research provides tools for defining the relationships between the objects in the 3D model and time schedule. The system will detect and analyze workspace conflicts between various working objects during 4D visualization.

- Static working object vs. Static working object

  Design or congestion conflicts may occur between two static working objects as shown in Fig. 5. For example, design interference between subcontracter and material.

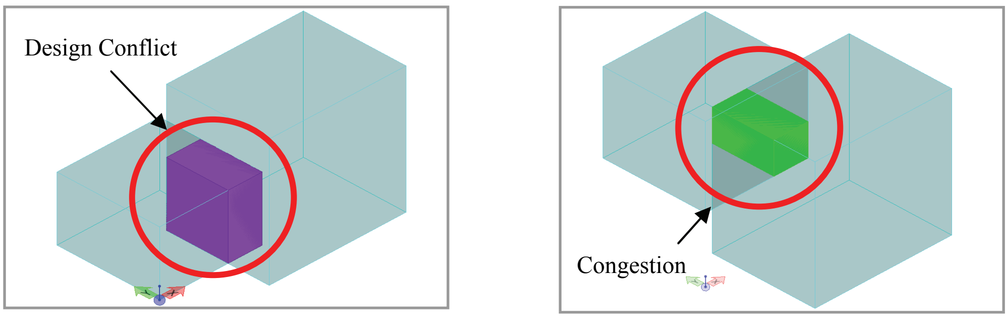


Fig. 5: Conflict visualization between two static working objects.

- Static working object vs. Dynamic working object

  Damage conflict or congestion conflict may arise from interaction between a static working object and a dynamic working object. Fig. 6 shows a simple case of equipment being driven to the building component. Assuming construction sites are unable to provide enough path space, damage conflict will occur.

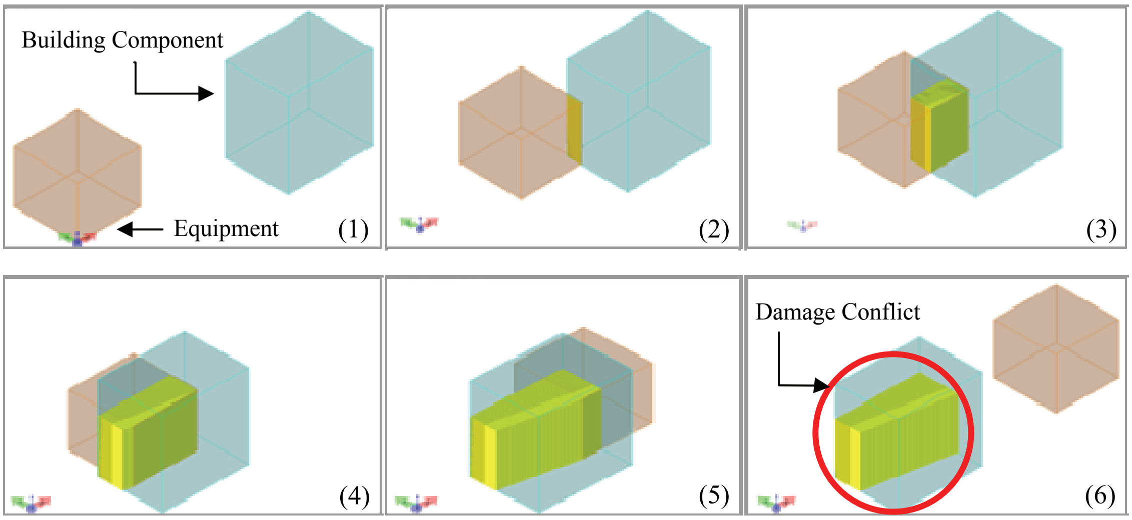


Fig. 6: Conflict visualization between a static working object and a dynamic working object.

- Dynamic working object vs. Dynamic working object

  Construction sites need to provide enough space for all laborers and equipment as well as for material transportation. For example, where many trucks want to move from the entrance to each working area at same time, congestion conflicts will occur. Fig. 7 is a schematic simulation of labor and equipment. As they move along their own path, a safety hazard conflict occurs.

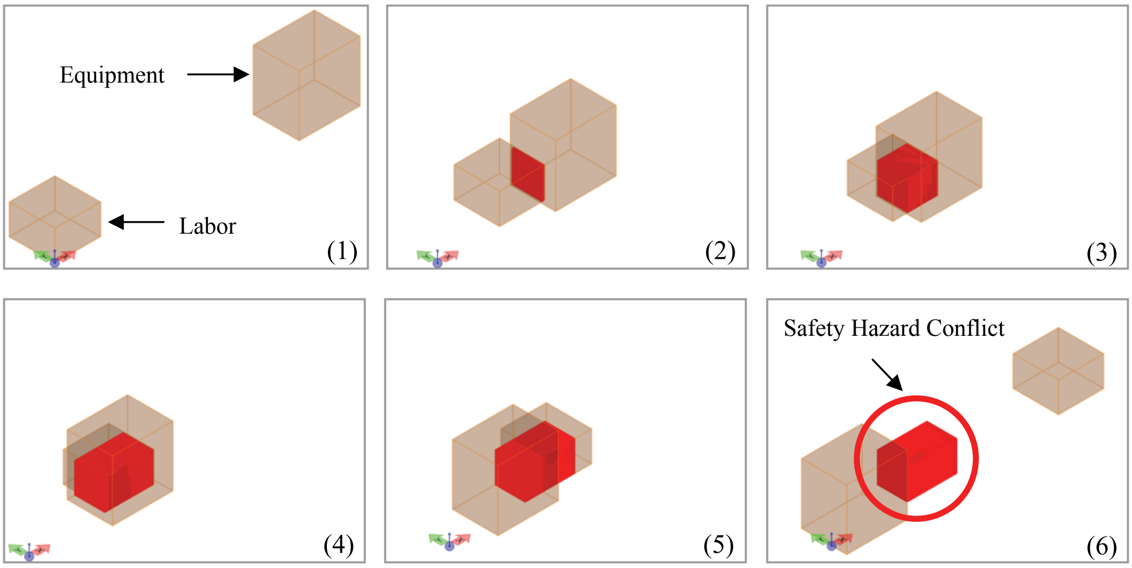


Fig. 7: Conflict visualization between two dynamic working objects.

4. DEMONSTRATION

A simple construction site was used as an example to test and demonstrate the functionality of our 4D workspace conflict detection and analysis system, as shown in Fig. 8. Users can create 3D models of working objects (building component, site layout, labor, equipment and material) within the system, which will then calculate and assign the required workspaces for these objects. In this case, the system will only analyze conflicts that deal with labor and equipment for calculatiion efficiently. As labor and equipment moves along a specified path the system will automatically detect and analyze workspace conflicts.

Fig. 9 shows the 4D visualization workspace conflicts detection and analysis. In our system, users can observe the whole process simulation. Dynamic working objects, labor and equipment are represented by orange boxes, while the location and size of safety hazard conflicts are depicted by red boxes.

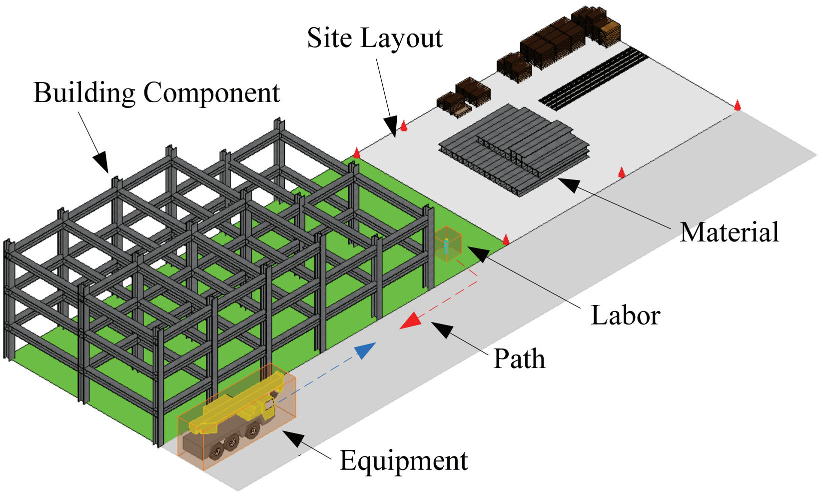
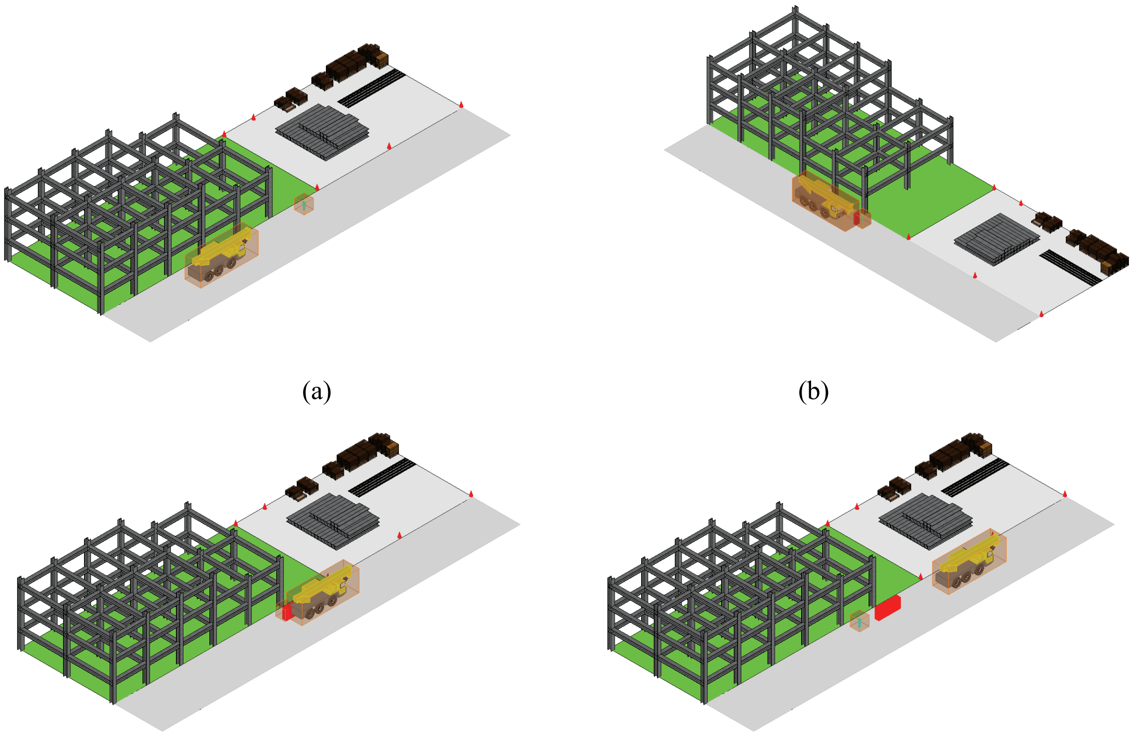


Fig. 8: A simple construction site example.



(a) (b)

(c) (d)

Fig. 9: 4D visualization of conflict detection and analysis.

5. CONCLUSIONS

Large numbers of building components, workers, equipment as well as materials share limited space during construction. Since space constraints may affect the moving path of resources and productivity, it is essential to detect and analyze workspace conflicts in advance, such that the available space can be used more efficiently. For this reason, this research develops a 4D workspace conflict detection and analysis system for solving space issues in construction sites. In this paper, the 3D CAD system, Bentley MicroStation, was integrated with schedule information for the dynamic identification of space conflicts and 4D visualization. The system can simultaneously detect and analyze workspace conflicts with various working objects, as well as visually representing the location, size, scope and type of workspace conflicts. This will assist project managers in quickly grasping the status of an ongoing project, in order to make decisions. In addition, a simple construction project example was used in this research to demonstrate the functionality and applicability of the 4D workspace conflict detection and analysis system. The workspace conflict that this research focuses on is a common issue in space management. In future, a numerical model and optimization theory will be introduced into our system for space and path planning optimization.

6. ACKNOWLEDGMENTS

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DEALING WITH BIASED RELIABILITY OF ON SITE DATA FOR THE SIMULATION OF CIVIL ENGINEERING PROCESSES

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ABSTRACT: *Researchers at the Bauhaus University Weimar have been working intensely on the process-oriented, constraint-based simulation of construction processes. One objective is to optimize the real process according to various criteria, such as scheduling, site congestion and cost items.*
Constraint-based simulation as a method to better manage construction processes will be used both, for optimization in the planning phase as well as for process monitoring and steering during execution.
This leads to a thorough front-end analysis, how to describe possible constraints and disturbances during the construction process. Their level of detail has to cope with the granularity of the simulation model in order to get reliable results. Since the implementation of the process data for unique types of construction is still very elaborative, this is a difficult balance between efforts and benefits.
Various bridge projects in reinforced and pre-stressed concrete have been monitored by the authors during construction in order to gain more data about special processes as well as data for typical disturbances, breakdowns, interruptions and other constraints during the construction process. All steps around the process including preparation activities as well as after treatment have been precisely documented. It is shown, how processes are composed by different sub-processes, what the individual logical links are and what the determining resources are for each process. Additionally it is documented, what types of interferences can interrupt the different processes. All information has been visualized by mapping in an event-oriented process chain.
By referring to the AHP-method (analytical hierarchy process), a special approach was developed to be able to classify the qualitative terms of the data. Processes, which are identified as being particularly susceptible to interferences, require special monitoring. In a simulation model, which is developed for optimization and monitoring during the construction phase, the setting of certain checkpoints should be focused on these processes.

KEYWORDS: *Simulation, optimization, process monitoring, construction process, day-to-day data*

1. INTRODUCTION

Process optimization by using simulation tools, which is state of the art in stationary industry becomes more and more important in construction industry. It is already used in some fields of applications. In use are discrete event-based simulation models for production and logistic planning in order to optimize the deadline controlling and resource management. The simulation of building processes allows a detailed and more realistic process scheduling and optimization. More robust prognoses can be made.

Furthermore, more and more complex processes are optimized by simulation. Researchers at the Bauhaus-University Weimar developed a constraint based simulation concept for construction applications in order to optimize scheduling. (König, 2007) (Beißert, 2008)

Up to now, those tools are predominantly been used in the start-up phase of a project. This predictive optimization strategy takes place only ahead of the project's execution phase. Thus changing boundary conditions and constraints are not considered, despite of the enormous relevance they have especially in construction processes.

The objective is to identify consistent schedules that solve the scheduling problem as optimal as possible. The main aspect, this paper focuses on, is, that due to dynamic and stochastic changes of boundary conditions and of planning environments' constraints, deviations between the process model and the reality increase more, the further the project progresses. This problem is much more crucial in construction than stationary industries. The consequence is that a previously optimal schedule may turn into a suboptimal or even unfeasible schedule during the progression of the project.

The Bauhaus-University Weimar is working on the implementation of a reactive process optimization designed for almost real time application. It will facilitate the simulation for ongoing optimization considering changing constraints. Thus, the critical path monitoring and the flexibility in case of changes will be improved immensely; long-term consequences can be spotted at earlier stages. For this reason the construction progress has to be determined in defined time intervals. Moreover the data processing has to be automated thus enabling a further process optimization considering current conditions. (Ailland, 2009) A concept, using “grid points”, was developed, that determines the construction progress as accurate as needed for simulation, while keeping the amount of data that have to be captured as low as possible. (Bargstädt, 2009)

The presented approach is based on a process model, which represents all constraints and boundary conditions of the process. The authors were interested in a highly realistic representation of the construction process. Therefore the model was established, based on the experiences and observations made in several field studies. This led to a thorough analysis, how to describe possible constraints and disturbances during the construction process. Using this model, studies were conducted to determine the appropriate level of detail. These considerations were necessary, because, with the periodic determination of the building progress and its boundary conditions, the effort on data evaluation increases enormously. Their level of detail has to cope with the granularity of the simulation model in order to get reliable results. Since the implementation of the process data for unique types of construction is still very elaborate, this is a difficult balance between efforts and benefits.

Another important aspect of this study considers the question: how can we record the necessary information with minimal effort? Therefore site documentes, that were tracked in the field studies, were analysed with respect to input data about the current construction progress.

Finally, the correctness of the input data from the construction sites documentations has been verified, facing, that optimization results can only be as reasonable as their data base.

2. CONSTRAINT-BASED SIMULATION

According to Sauer the following statements in terms of constraint based scheduling are given: constraint based schedule optimization considers the time allocation of activities to limited resources, while different constraints (hard and soft constraints) are taken into account and specific objectives have to be achieved or optimized. Important characteristics of real scheduling problems are the dynamics of the planning environment, i.e. scheduling must often react on unscheduled constraints and limitations that gave reason to deviate from the formerly optimized plan. This dynamics creates frequently new planning conditions. For solving the scheduling problem two main tasks must be observed. In the predictive scheduling, the plan is created in anticipation of a certain time period, assuming a static planning environment. In reactive scheduling the adoption of the scheduling plan to the new planning conditions (Figure 1) is the main focus in order to be able to create a valid updated one. (Sauer, 2004, p. 9)

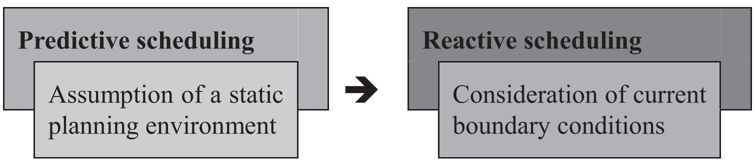


Fig. 1: From predictive to reactive scheduling

The information needs for catching up with the current situation to be described exactly in the process model.

3. PROCESS MODEL

For both predictive and reactive scheduling concepts, data are necessary to define precisely the construction process. These are data defining

- sub-processes, consisting of activities and events,
- durations of single activities,
- dependencies (constraints) of activities to each other,
- resource requirements of all activities, such as material and human resources and
- optimization concepts for the sub-processes and for the overall process.

For a real-time simulation data are additionally necessary that define the boundary conditions of the current process environment. This is information (actual data) about the current progress of construction and the construction sites conditions, such as material inventory as well as human and machine resources. These data should be recorded periodically, in short intervals, in adjustment to the particular sub process, and transferred to the simulation environment.

The registration of this information is important for the simulation model, because only by taking into account all relevant boundary conditions, reasonable optimization results will be achieved. However, both, the definition of the construction process data as well as the recording of the actual boundary conditions have proven to be difficult, because the detailed knowledge about different construction processes is merely found in the literature. In fact, these are present only in form of personal or corporate experiences of site managers or engineers from their former projects and not documented properly.

In order to gain access to this valuable information, several field studies on different construction sites were conducted. As a suitable research object a construction element was chosen, that meets the following criteria:

- The research results should be valid for a certain class of construction, i.e. deductions from the considered building process to other processes should be possible and results should be transferable.
- For the subsequent optimization, a high degree of repetition of the individual activities should be available. Therefore a line construction was searched.
- The construction element in consideration must be self contained at a maximum, in order to facilitate optimization experiments without the influence from other construction processes.
- The construction process should not be too complex, but a manageable number of activities, which can run in parallel, are necessary for a considerable potential for optimization.
- Materials with different requirements for the evaluation should be used to obtain a broad examination with good generalization potential. Bulk material must be monitored differently from single item goods. Thus because of these features, a typical component of a reinforced concrete structure should be chosen.

All these requirements are met with bridge curbs. Bridge curbs are self-contained components of reinforced concrete, which are built linear. They combine a number of very different sub-processes, such as the application of sealing layers, the construction of the formwork and formwork carriages and the concrete pouring process itself.

3.1 Field studies

The process identification can be done in various ways. The modeling was carried out using a bottom-up principle. (Buchhop, 2007) From a very detailed description of individual processes an idealized universal process is derived.

For the present study, the process identification started with a detailed documentation of real building projects, done by in-field research assistants. They were present on the construction site every day and documented all activities, events, boundary conditions and constraints. Furthermore, the duration of all activities, as well as the exact need for material, machines, and manpower was monitored. With regard to the information needed for the reactive scheduling all documents of the site management were filed and analyzed in terms of actual information they yield.

Three bridge sites in Germany have been documented, two highway bridges and one railway bridge.

The first bridge is a 12-span pre-stressed concrete bridge with a total length of 422 m and two separate bridge decks. It spans a valley with two service roads, an important double-track railway line, a federal road and the river Hörsel. This site was particularly suited for the research project because due to the railway line a large number of constraints had to be considered, which had great influence on the construction process and the optimization potential.

The second highway bridge is a three-span bridge with 200 m length. The composite steel bridge crosses a valley with a brook and a federal road. In contrast to the first bridge the construction process was hardly influenced by special limitations. Thus, an almost uninterrupted construction process was documented.

The third bridge is the largest of the bridges and one of the flagship projects of the German Railway Company Deutsche Bahn AG. With a length of 1681 m and a pillar height of up to 37,5 m the arch bride belongs to a series of spectacular pre-stressed concrete bridges, which are built for a new high speed line from Leipzig via Erfurt to Nuremberg.

Right from the beginning of the execution the construction sequence deviated and had to be constantly rescheduled by the site manager. The ongoing direction of the construction progress was based solely on the site manager's competence. He was acting on a day-to-day basis. A thorough consideration of long-term consequences was almost impossible.

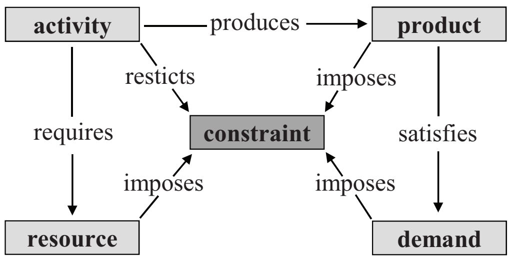
Within the monitoring of the real process, all interferences and the following deviations as well as the corrective activities were documented in order to use them for the presented approach as well as for future simulation scenarios.

3.2 Process modeling

Based on the field studies several models have been developed that represent project specific construction processes of bridge curb building. Hence a generalized process model representing all process components in parameterized form was derived. A generally applicable model that is transferable to other projects was established. The observed deviations were processed separately for future optimization approaches in order to reflect compensation strategies applied in practice.

For predictive as well as for reactive optimization modeling, the needed data, that describe the construction process as accurately as needed for the simulation have to be defined. Additionally information about the current construction progress has to be described for the reactive optimization model. Hereafter this information is referred to as states.

Smith and Becker (Smith, 2004) developed at Carnegie Mellon University an ontology (Figure 2) for a constraint-based scheduling. In this context *„Scheduling is defined as a process of feasibly synchronizing the use of resources by activities to satisfy demands over time, and application problems are described in terms of this abstract domain model."* (Smith, 2004, p. 37) This approach focuses the activities in the center of the analysis.



According to Smith (2004), Buchhop (2007) and Sauer (2004) the collected data were structured in main and sub processes, activities and events. Activities can have the states "not started", "in progress" and "completed". The conclusion, whether a process is in progress or is completed, can be determined on the basis of the activities, which are associated with the process. Events can have the state not occurred or occurred.

main process mp state: waiting, progressing, completed

It combines several sub processes, that stay in logical connection, for example as work sections. There may be sequence variations.

sub process sp state: waiting, progressing, completed

Sub processes do not necessarily consist of only one activity and one event. But no sequence variations are allowed.

activity a state: waiting, progressing, completed

An activity is an integral part of a process and causes a transformation. Activities have a defined **duration**.

event e state: not occurred, occurred

An event is an integral part of a process as well, but it does not transform. It indicates the occurrence of a state. An event can be input or output of a process (Figure 3). An event has **no duration**.

<table>
<tr><th colspan="10">process</th></tr>
<tr><th colspan="4">main process</th><th colspan="6">mp</th></tr>
<tr><th colspan="2">sub process</th><th colspan="2">sp</th><th colspan="2">sp</th><th colspan="2">sp</th><th colspan="2">sp</th></tr>
<tr><th>activity</th><th>event</th><th>a</th><th>e</th><th>a</th><th>e</th><th>a</th><th>e</th><th>a</th><th>e</th></tr>
</table>

Fig. 3: Structure of the process components

The interrelations between the different levels of activities and thus the possible construction processes result from the constraints. The result is a sequence of activities respecting the boundary conditions of the construction process. By the consideration of different types of constraints several possible schedules can be identified.

In addition to the description of all activities for the building process, the detection and accurate description of constraints for the constraint-based simulation is of particular importance. These are limitations to the solution space for possible sequence variations. All of the activities constraints have to be met before the activity can start. Constraints are divided into hard and soft constraints.

hard constraints **hc** **state: not met, met**

Hard constraints describe a set of constraints that have strictly to be met to run a respective activity.
(Sauer, 2004, p. 51)

soft constraints **sc** **state: not met, met**

Soft constraints define a set of constraints that should be respected in the planning or the planning result, but can be neglected to some extent, e.g. compliance with deadlines or good utilization of resources. Soft constraints reflect predominantly planning objectives. (Sauer, 2004)

For each activity a number of constraints have to be met depending on the optimization objective. Below these are summarized as input. Each activity produces an output by transformation. As shown in Figure 4 the output can be the input for the next activity and thus the next process. (Buchhop, 2007, p. 6)

input **ip** **state: not met, met**

The input summarizes all constraints that have to be met.

output **op** **state: not met, met**

The result of the transformation is the output. (Buchhop, 2007, p. 7)

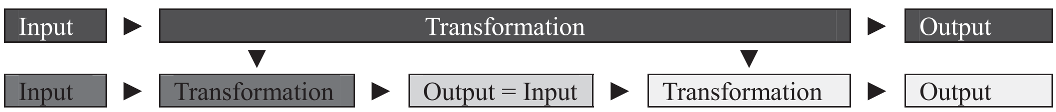


Fig. 4: Process input and output (Buchhop, 2007, p. 7)

evaluation function **ef** **state: not satisfied, satisfied**

The compliance of soft constraints can be quantified by objective or evaluation functions. An evaluation function evaluates a schedule and makes schedules comparable. (Sauer, 2004, p. 52)

Constraints result for example from the resources and capacities, which must be available in a sufficient number to start an activity. Other than in Sauer, the term "resources" in this context is used for material, as items that are transformed. "Capacity" means machinery and staff that do the transformation.

resources **r** **state: quantity not available, available**

Resources are materials that are used and transformed during the construction process.

capacities **c** **state: qualification and quantity not available, available**

The term capacity subsumes staff and machines, which can have the status not available or available. Furthermore data that define the qualification and the available quantity are needed. They are characterized by their availability. Capacities are also characterized by the fact, that an activity can be accelerated by the quantity, that is used. Availability of capacity and resources is important and therefore a hard constraint.

Challenging is the capturing and description of unscheduled constraints and limitations, that give reason to deviate from the formerly optimized plan. These events are the reason for the need of a reactive optimization. These unscheduled events occur, where hard constraints cannot be met.

unscheduled events **ue** **state: occurred**

Unscheduled events require changes in the planning environment. Therefore the current, formally consistent schedule becomes inconsistent and needs to be adapted to the changed situation needs. (Sauer, 2004)

3.3 Process model

The generalized construction process of bridges curbs was structured in the previously described process elements and visualized as event driven process chain. Using this structure, all the hard constrains and possible unscheduled events were defined (Table 1). Thus, a structure of all data has been established, which must be gathered to create a reactive optimization.

Table 1: Structuring of the construction process

	title	process		hard constraints			unscheduled events
		sub	main	input activities	capacities	resources	
a_1	curb survey	sp_x	mp_1 surveys	-	2 surveyors 1 tachymeter	-	surveyors not avail. tachymeter not avail. heavy weather
e_1	curb survey completed			-	-	-	-
a_2	construction survey			-	2 surveyors 1 tachymeter	-	surveyors not avail. tachymeter not avail. heavy weather
e_2	construction survey completed			-	-	-	-
⋮							
a_{x+1}	shot blasting	sp_{x+1}	mp_x surface preparation	a_x	2 caulkers	Shot blast material	caulkers not avail. material not avail. heavy weather
e_{x+1}	shot blasting completed			-	-	-	-
a_{x+2}	determination of adhesive tensile strength	sp_{x+2}		a_{x+1}	1 caulker	Test equipment	caulker not available equipment not avail. heavy weather
e_{x+2}	determination passed			-	-	-	-
a_{x+3}	determination surface roughness	sp_{x+3}		a_{x+2}	1 caulker	Test equipment	caulker not available equipment not avail. heavy weather
e_{x+3}	determination passed			-	-	-	-

4. PROCESS DETAILLING

The building process as shown in table 1 is structured in activities and hence highly detailed. Thus the effort of data capturing is far too high. Therefore, a methodical approach for a systematic determination of the needed detailing has been developed. It avoids the need to capture completely all activities, the process consists of.

The identification of the most significant activities is important. Activities are called significant, if they have a high failure or controlling potential. Processes including significant activities are called key processes. The AHP (Analytic Hierarchy Process) method is used to rank the activities by criteria order to identify key processes, which are of particular importance for the ongoing optimization. Later these processes are identified by significant events in the construction process. Sensitivity analysis is implemented to check the plausibility of the criteria and their emphasis in the AHP.

A rating scheme for the identification of important activities within the processes, the so called key processes, was developed. The rating scheme is based on the idea, that main processes with a high controlling or failure potential are subject of special interest. Thus those processes, the especially critical activities, must be captured in more detail than processes without this risk potential. Processes that only consist of activities with almost no failure risk and no controlling potential will be summarized in a less detailed way.

Criteria were defined to assess the failure potential of activities, e.g. the failure potential by weather conditions, number of dependent activities (Some activities must be completed before the following activity can start. If an activity is the input for a high number of other activities, the consequences of a failure will be higher.) or buffer time (It is expected that construction processes with a high buffer time are less sensitive to interferences, because the total construction time will only be extended, if the interruption due to the failure will take longer than the buffer time.).

Criteria were defined to assess the controlling potential of activities, e.g. the acceleration potential by increasing the number of workers, prefabrication, using more or other types of equipment, using material with other behavior patterns or switching to shift or night work.

For these criteria their limiting characteristics were defined, and the criteria were weighted to each other. Using them, all activities were evaluated in terms of their controlling respectively failure potentials. Finally processes that consist of activities with less potential were summarized and thus the very detailed process model significantly simplified and hence the data acquisition reduced.

For verification, the process model has been implemented for analysis by the simulation, modelling different levels of detail. Using these simulation models of different granularity, the construction process has been thoroughly analysed and its optimization potential has been determined. As an additional result some generalised recommendations for the detailing of simulation models in bridge construction could be derived and will be presented.

Thus it was determined, that in comparison concrete pouring is an error prone process. In contrast the preparation of reinforcement has a low failure potential.

The selection of grid points that is data, which must necessarily be captured, has been based on this assessment.

5. PROCESS ORIENTED DATA EVALUATION

Based on the structured process model the building progress is captured in order to identify the significant events or activities. A simulation model in real time requires the acquisition and processing of many data in short intervals and a short time. Additionally the various activities course different requirements to the data capturing and evaluating instruments. The state of the art shows that most research projects, which deal with the identification of a daily accurate building progress, concentrate on a geometric evaluation. They use image- or laser data. But the analysis is complex and time consuming and the high accuracy of the data cannot be exploited in this research approach. Other research projects deal with RFID-technologies or bar codes. But those data primarily cover the boundary conditions of the construction site and the material and resources passing certain control gates. So far a thorough progress description by using RFID or barcodes has not yet be shown.

With regard to the objective to optimize time and resources, a concept was developed, that describes the progress of construction projects less complex, but sufficiently precise for the desired objective. This approach is based on so called grid points.

This term is adopted in analogy to analytical algebra. Using this approach, a curve's shape can be defined, if a sufficient number of discrete points and the type of curve are known. The idea in structuring the building process is to identify these specific grid points. A sufficient amount of reliable process information will be used to define the actual status of work. This information will be taken as grid points for the indication of the actual state of construction progress. Grid points are set up as control gates, from which signal information can be generated or taken. They clearly, or at least with sufficient certainty, indicate, which events have taken place and which activities are in progress. Therefore, the kind and density of required information has to be determined.

As already mentioned each process starts with an activity and reaches the following event. These events have to be identified and described as grid points. Appropriate grid points are, for example, events required, before a certain procedure can start (material delivery), events assigned to the completion of a procedure (milestone), easy-to-describe intermediate states (finishing of sealing or acceptance of reinforcement), and placement of certain types of rebar and installation units. Grid points are comparable to a less stringent type of milestones in time schedules. (Bargstädt, 2009)

5.1 Documents as information source

The approach to the designing of an efficient and realistic controlling tool starts with the identification of documents and other information sources that are widely used on most construction sites. Documents like construction records, minutes of meetings, or delivery notes are associated with the everyday life on most construction sites. Up to this point, however, they have rarely been evaluated in terms of capturing accurate information about the daily construction progress. These documents are analyzed with reference to the information they yield with respect to the degree of completion or material deliveries. (Bargstädt, 2009)

Thus it was determined; whether it is possible to reproduce the construction progress based only on information taken from the construction sites documents. It was studied, how the construction process can sufficiently be simulated on the basis of the distinguished data, where data gaps remain and the time delay between reality and information supply must be quantified.

To address the question, how accurate the current building progress can be determined by the available data, an example process was implemented in a simulation environment. Thus it was tested, what the influence was from avoidable and non avoidable data modifications on the simulation results.

This approach was preceded by field studies in order to determine, which documents have to be conducted as obliged by regulations and other provisions. In order to generalize the findings of the field studies, a survey was conducted among construction companies. It was asked, which of the required and the "state-of-the-art "related documents are maintained in reality. It was also asked, in which time intervals the necessary documents were recorded, and how the reliability of these data was judged by the site personnel themselves. It gave a reliable picture of what to expect from the onsite documentation, its contents, the recording intervals and the scope of the content.

Finally the content of the documents from the authors' field studies was compared with the content, that had to be expected based on the survey and the content due to the regulations. It became obvious, that in all field studies "highly variable" construction data are documented, which provide a very diverse base for current process models.

5.2 Data continuity and reliability

The following significant, but for practitioners not entirely surprising findings to the stringency and coherence of data in documents from constructions sites were ascertained.

Significant data gaps and deviations from own observations of the construction process conclude that the documentation is classified often as a tedious extra work, which is only done, "if there is time for extra work".

Furthermore significant "data adoptions" were detected, which are of non negligible relevance for a real time simulation model.

The weak points of the documents are therefore the reliability and the currency. A comparison with the reality clarified, that quite a few documents were "adjusted". For example in construction records, which have to be accepted and signed by the building owner, information with an high relevance to the description of the current building progress and a high relevance to the contractual execution of the project have been optimized in an opportunistic way, which means, that they were distorted or remained unmentioned.

The alignment of the real construction process with the process model of the construction process, which has be developed based on the construction documents, revealed, that a lot of documents don't fulfill the necessary requirements for a real time data acquisition. Many construction documents are recorded with a significant time delay that varies from some hours to several weeks. The delay depends on the type of document. Important test reports are normally written on the same day as well as most of the delivery notes. But even the daily construction records or special minutes of meetings are usually written with considerable time delay, sometimes even at the end of the week, when the contents depend merely on the site manager's good memory. Even the handover of the documents, passing them to the owner, the contractor or to other partners, is so irregular, that they arrive far too late for a real-time simulation.

This will lead to a false model of the current construction progress. For example, test processes, which should be at the end of a construction process, then occur earlier than the manufacturing process itself, because the manufacturing was still documented as ongoing in the later on written construction record. One of the process models, that was created based on these field studies, showed a delay of up to two weeks in comparison to the real progress. Furthermore the process sequence had to be corrected afterwards.

In this study all available data were included, regardless whether they were recorded and forwarded by hand, partially automated or fully automatically recorded. At all projects it turned out, that the construction site documentation is still predominantly done by hand and it's usually done in formats, that cannot be evaluated automatically. Digital construction records and other recording tools, that are evaluated and communicated digitally, are still very rarely used and even then not without media breaks. This situation must be changed, if a better control and optimization of ongoing construction processes shall become reality not only on some exemplary research-accompanied construction sites.

5.3 Improvement of data quality

The evaluation of site documents revealed, that the construction progress can be reproduced in a simulation model by using the information of the site documents. But the reproduction is still incomplete and blurred. Thus data quality and density have to be improved considerably. Moreover the evaluation intervals should be shorter and the reliability has to be enhanced. The data processing without a high degree of automation in order to speed is limiting a daily, reactive optimization.

This led to the question of how these requirements can be implemented. An important starting point is the precise specification of the data that need to be captured. The basis was already provided by structuring the construction process and introducing grid points. Thus the site management needs exact specifications about the data, the evaluation intervals and the data formats, that have to be recorded. However, in order to keep the efforts of data processing to a minimum, a stronger digitalization is necessary. A lot of appropriate digital tools (as digital construction records) are already available. But so far their application on construction sites is very limited. One reason is, that despite high investment cost contractors expect only a limited potential of improvement by changing to digital documentation. However, as soon as a direct benefit can be derived, the willingness to change will increase. Furthermore the documentation will be more valuable for the site management, and based on the simulations model a direct feedback can be given. Thus it is expected, that less "data adoptions" will be made, since such adjustments are immediately verifiable.

Another important aspect in the introductions of a digital data processing is the match between the data input and the required information. The data documented must be adapted to the requirements of the process model for further processing. Beside of the improvement of the data reliability, the data density can also be enhanced by digital documentation tools, because data capturing and processing will be much less lengthy. Thus the correlation between the current construction progress and the process model will be more accurate. However, the study revealed, that still not all relevant information can be captured with a justifiable expense. This, further automatic or semi-automatic evaluation instruments were considered. The expanded use of automated and modern evaluation techniques is therefore essential. Based on the previously mentioned, detailed description of the required information, additional data that need to be captured by evaluation instruments were defined. However, the various states of the process components (see chapter 3.2) require different performance characteristics of the evaluation instruments. Thus a preselection of instruments, which were suitable due to their performance characteristics were examined. The examination included current technical instruments as RFID, Photo evaluation, Laser scanning and Bar codes. The task was to identify the relevant evaluation instruments and register and analyze them with regard to their ability to record real-time data. This comprises speed, data volume, precision, and automation of data. It leads to the question of which instruments are appropriate to recognize the described parameters that are relevant for the building progress. Constraints and requirements needed for the application of different instruments were considered.

The examination concluded that a mix of evaluation instruments and an advanced automation of the constructions sites documentation provide a sufficiently accurate data about the construction progress. Thus the boundary conditions can sufficiently be captured by RFID. This technique can be applied more comprehensively than Barcodes for example. But for example the evaluation of geometric data has proved too time consuming. The integration in the constructions sites daily business would be more difficult. Thus it would require a separate and independent data evaluation strategy.

The study also concluded that the construction progress should be recorded using a digital construction diary whose contents precisely matches to the previously developed process structure. This approach assumes an exact specification of the needed information, the data format and the acquisition date.

6. CONCLUSION

The study concludes that ongoing construction processes can be captured for a constraint based optimization using a process oriented data evaluation. However, an improved data evaluation that is adjusted to the requirements of constraint based simulation is needed for a performance-based reactive optimization. An exact definition of the required data, data formats and capturing intervals is needed. Based on several field studies the authors presented how a construction process can be structured in order to define the required information and evaluation intervals.

Furthermore the study concluded that parts of the required data can be taken from the constructions sites documentation, if the automation and reliability of the documentation are improved. As the amount of information is not yet as dense as needed for reactive simulation, data must be captured by the use of additional evaluation technologies. The corresponding tools are already available on the market, but not yet sufficiently coordinated and installed at a minimum degree on the average construction site. Moreover, by using modern evaluation instrument, the plausibility of the captured data must be consolidated in order to create a reliable database for the process model.

At the Chair of construction engineering and management at the Bauhaus-University Weimar simulation models are currently developed that are used for the optimization of construction schedules and logistics processes. These models are carefully expanded in their application spectrum to test and develop further methods and basics for a reactive simulation approach.

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CONSTRUCTION LOGISTICS PLANNING BY SIMULATION

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ABSTRACT: *Good construction logistics on building sites saves time and costs. Several parallel and independent supply chains cross on site and interact with each other. To plan construction logistics, numerous interferences between the configuration of construction site and construction works have to be considered additionally. To find a useable solution requires the investigation of quite a number of alternatives with the variation of many factors. In particular in outfitting processes, their countless possible work sequences and many involved companies govern production logistics. This complex system can be analyzed by simulation.*

Nevertheless logistic systems on site are influenced by various factors, so that the determination of an optimal network configuration and organizational structure becomes not trivial. To find a useable solution requires countless simulation runs with many factor variations.

This paper presents a constrained-based simulation model, which integrates detailed logistic activities for construction sites considering a high number of influence factors and their variability. The identification of typical qualified factor combinations, derived from special combinations of construction processes and building attributes, is essential to secure optimization potential and quick accessibility. The elimination of less relevant factors is also advantageous to minimize the experimental and the number of simulation runs and to accelerate the logistics planning.

KEYWORDS*: construction logistics, construction logistics planning, process simulation, planning by simulation.*

1. INTROCUCTION

Construction logistics comprises planning, application, coordination and supervision of material flow to, within and from construction sites as a self-contained management function (Portatius, 1997). Several parallel and independently existing supply chains cross on site and interact. The higher-level planning and coordination is a difficult challenge, because companies are only interested in their own supply chain on the site.

Superordinated control and optimization are not considered, which might take advantage of positive interdependencies between several supply chains. Traditionally in most companies, construction logistics tasks are performed by several different persons, of whom only a few are also occupied by the construction process itself. Insufficiently planned and not at all coordinated logistic processes are the consequences and reasons for the high amount of non-productive actions and consequently disturbed work flow on construction sites. In consequence disorganized material storage causes extra time for congested work areas, for the search of material and to rearrange storage areas.

Several studies on German construction sites pointed out, that approximately one third of the total execution time is consumed by logistic processes in any aspect (Guntermann, 1997). Boenert and Blömeke (2006) estimate the deducible optimization potential by well-planned and coordinated construction logistics up to 10 percent of construction time, or 4 percent of building costs in outfitting processes.

To consider all logistic network elements (e.g. loading zones, builder's hoist, storage areas) and processes (e.g. store, transport, handle) on site and their influencing factors as a superior logistic network is a necessary challenge.

2. LOGISTIC NETWORK FOR CONSTRUCTION SITES

Logistic management in construction industries was not considered very deeply in the past. One reason is, that the planning and the construction processes are attached to several contractual partners. Only in the planning of site facilities detailed logistics aspects are considered. This is not sufficient for the thinking in an overall logistic system.

To globally optimize the construction site logistic, it is essential to consider all individual in-house supply chains and to combine them to a single global network. Thus elements of single supply chains become network elements. This enables to analyze all influencing factors and their effects on the logistic network configuration and the logistic organization structure (Voigtmann and Bargstädt, 2008).

Company-wide approach generates far more optimization potential, but it is increasing the complexity of the system. To find a feasible network configuration and an appropriate organizational structure, it is necessary to collect all relevant logistic factors. Not the peculiarities of in-house supply chains, but also interferences between individual logistic chains and between logistics and the construction processes have to be considered. All factors are highly variable in regard to type, time and spatial aspects (table 1).

Table 1: variability of logistic influence factors (Bargstädt and Voigtmann, 2010)

variability	In-house factory by company	Factors between companies.
by type	company-owned site equipment, e.g. specific transport equipment	commonly used site equipment, e.g. storage areas, transportation equipment
	type of construction work and resulting logistic material and process characteristics	type and site location and resulting logistic influences
	size and profile of working gang	organization form and responsibilities for logistic activities
temporal	utilization periods of company-owned site equipment	utilization periods of commonly used site equipment
	construction time and scope of work	gang sequences, construction sequence, temporal convergence
	material delivery dates	
spatial	placement of company-owned site equipment	placement of commonly used site equipment
	work sequences and working direction	gang sequences, construction sequence, spatial convergence

Types of construction requirements for outfitting processes vary mainly in regard to vertical and horizontal material transport. For vertical transport, cranes are predominant. Elevators, lifting platforms and high lift trucks are also alternatives to be considered. Horizontal transport can be facilitated by forklifts and transport containers on wheels. Pumping allows for both, horizontal and vertical transport. Manual transport, especially at small scale, is also common for outfitting processes and currently counts for quite a big portion of overall working time.

Spatial variability is indicated by alternative positions of construction requirements. In comparison to structural work, the working areas during outfitting processes are literally scattered all over the building, because innumerable working positions are feasible. Furthermore, and especially in outfitting, the rescheduling of storage areas, the rearrangement of means of transportation and other major changes in layout are daily business. Often even the access to the site is changed frequently. These changes are mainly caused by the work process itself. For example an unfinished room is first used for material storage, but then has to be made free for outfitting processes, which shall start in this room. A stairway is temporarily blocked, because of ongoing finishing works.

Temporarily limited storage areas and positions of construction equipment indicate the necessary variability of the logistic system. It is mainly caused by the working process itself. Sometimes the use of lifts and other means of transportation are restricted. For example, after finishing the façade elements, outdoor elevators are dismantled, and all remaining transports have to be shifted to an inside elevator (Voigtmann et al, 2008).

In summery logistic systems on site are influenced by innumerably various and variable factors, so that the determination of an optimal network configuration and organizational structure becomes not trivial. Such a complex system can be analyzed by simulation. The amount of influence factors requires countless simulation runs with many factor variations to find a feasible solution. However the identification of qualified factor combinations depending on several process or building attributes and the elimination of irrelevant factors accelerate logistic planning.

3. SIMULATION OF CONSTRUCTION LOGISITGS

3.1 Demands on the simulation model

To analyze practicable logistic network configurations, the simulation model must respect the specialties of construction processes and their logistic activities. In comparison to stationary industry, work on site is typical for its non permanent working areas. Therefore the exact location of working areas has to be taken into account, when modeling logistic activities with sufficient accuracy. The chosen model enables in an easy way to simulate construction, especially outfitting processes with several different characteristics. The adaptation of the model to a special construction site should be possible without programming (Voigtmann and Bargstädt, 2008). The dimensioning of the site equipment elements and the structuring of the logistic organization are done in a simple way. Table 2 shows the most important input data (characteristics of construction processes, site, material and logistic strategies and organizational structure) to simulate logistic activities on site.

Table 2: important input data

Input data for	Examples
assembly	point of assembly, dimensions, workers (number and qualification), assembly duration
work order (constraints)	order of work steps (on material basis or on basis of structural components), order of assembly of structural components (needed predecessors)
process	work area, safety zone, accessibility after work (area blocked completely, closed for storage, etc.), etc.
personnel	performance characteristics (number, working hours, qualification)
equipment	type (number, location, working hours, relevant technical data for construction, requirement elements)
material	transport characteristics (dimensions, weights, stackability, delivery characteristics)
organizational structure	responsibilities (for several logistic activities, priorities)
logistic strategies	delivery (number, date of delivery, transportation device, dimensions, kind of material)
	storage (number, use period, location, accepted user)
	disposal (disposal rhythm, capacity)
	transports (responsibilities, capacities, priorities, channelization)

To evaluate a chosen network configuration, the recording of several data of the construction process is required. This includes the total construction time, working time and further time slices of workers. In particular the recording of time slices caused by logistic activities (for material transport, clean up, hauling time, ways between work areas) will allow the identification of bottlenecks and other surplus items.

3.2 Simulation model

The presented approach starts out from a simulation model, which is used to display construction processes, especially outfitting processes. The used simulation model is a constraint-based model, which has been developed by König et al to analyze construction processes and work orders (König et al., 2007a, König et al., 2007b). The fundamental idea is, that work steps can only start, when certain necessary constraints are fulfilled. This model is implemented by the Simulation Toolkit Shipbuilding (STS) of the SimCoMar community (SimCoMar, 2010), (Steinhauer, 2007) and uses the discrete-event simulation program Plant Simulation (Siemens PLM, 2010).

Users are enabled to model and simulate several outfitting processes and basic logistic activities using the included

STS simulation framework. Several STS-components are available. For example the assembly control component distributes, assigns and releases work steps, and the transport control manages transport activities. All STS-components are interlocked and simulate work steps and additional activities to perform the construction work to finish construction work in order to the user's guidelines (König et al., 2007a). To integrate detailed logistic activities for construction sites, a logistic control component is developed.

The new component manages all logistic activities in interaction with the other components for the construction process. It considers relevant site, process and material characteristics, logistic strategies and organizational structures. For example, important input data to simulate logistic activities on site are process data (work area, safety zone, accessibility after work), workers performance (number, working hours, qualification), type of site equipment (number, location, working hours, relevant technical data for construction), material data (dimensions, weights, stackability, delivery characteristics), responsibilities for several logistic activities and logistic strategies (for delivery, storage, disposal, transport) (Bargstädt and Voigtmann, 2010).

The choice of an organizational structure for several logistic subsystems is provided on the logistic control panel, a component for the user interface. For each subsystem some predefined logistic strategies are available, e.g. material delivery strategies (delivery of all material at the beginning, by schedule, on call etc.) and storage strategies (central storage area, storage close to work areas etc.). The dimensioning of the site equipment (e.g. localization, capacity of builder's hoists) is similarly done by user interfaces for site elements, which are represented in the standard program or as special STS elements. The adaptation of the model to a special construction site and its characteristics of all available resources and the logistic structure is possible without programming. This is essential to improve acceptance of simulation models and their execution in construction industry.

During the simulation the data are recorded. All standard program and STS-elements record their working hours, offtime (break, blockades, interrupts) and utilization levels. To analyze the effects of logistic network alternatives, the logistic control component records detailed workers` occupancy (work activities, material hauling, unloading/loading, restoring and clean up). Recorded vehicle data are the arrival on construction site, the beginning and ending of unloading. Analysis of vehicles' waiting time and therefore evaluation of required unloading areas is now possible. Additional number of non-accomplishable store activities, in case the storage area is crowded, is recorded. This is helpful to dimension the storage areas. (Voigtmann and Bargstädt, 2008)

All logistic activities are automatically started by the logistic control component. The generation of rearrangement activities is exemplarily shown in Figure 1.

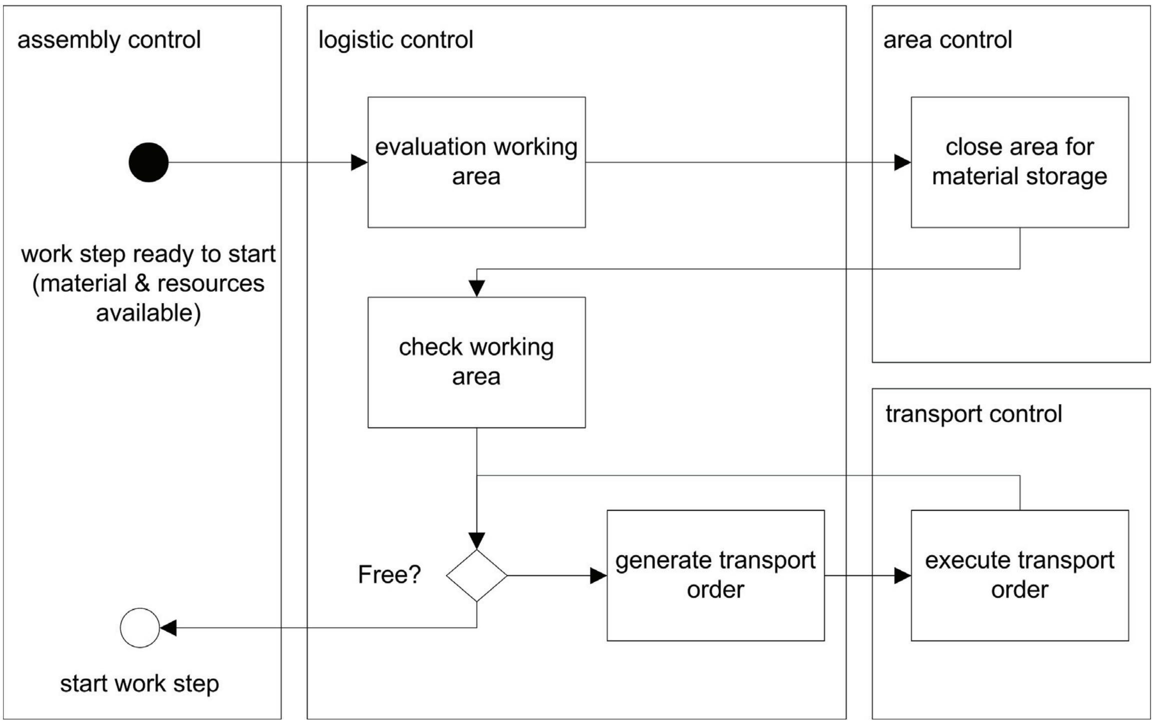

Fig. 1: Interaction between components (Bargstädt and Voigtmann, 2010)

3.3 Application possibilities and limitations

The simulation model has two main fields of application: the dimensioning of construction site elements and the selection of usable logistic strategies and organizational structures considering a high number of influence factors and their variability without each time having to do special programming or restructuring of the model.

Construction site elements are variable by number, location, capacities and other relevant technical data. Especially for storage areas, the period of use and the user group are selectable. Logistic activities are ordered according to user-given priority. Several logistic strategies for delivery, storage, disposal and transport are predefined. The different strategies can be attached to different work gangs. This leads to a large variety of parameters and options to configure the logistic network with its elements and organizational structure. Analysing of recorded time slices caused by logistic activities (for material transport, clean up, rearrangement, ways between work areas) will allow the identification of usable network configuration, bottlenecks and other surplus items.

By defining different systematic work orders their effects on logistic activities can be analyzed. Evaluation criteria can be the total construction time, minimal placement requirements and a constant resource efficiency. The identification of typical qualified factor combinations, derived from a special combination of construction process and building attributes, constrains the search-space for similar projects. That development allows to minimize experimental scheduling and the number of simulation runs, and it accelerates the logistics planning.

Costs can also be allocated to time, storage and efficiency parameters. The strength of a certain network configuration or logistic strategy is only evaluable by comparing several settings. Information about the suitability of work sequences cannot be given directly, because the work sequence in this case is part of the input data (defined by the technical constraints).

The model can be used to generate delivery schedules, overview tables of storage areas and operation schedules for personnel and site equipment. An analysis of vehicles´ waiting time and therefore evaluation of required unloading areas is possible, too. Additional applications in training sessions and for analyzing what-if-scenarios are also possible.

4. EXAMPLE

4.1 Model application

The example shows a standard office building with eight floors and 16 sections (two on each floor). All tasks have to be performed in all 16 sections. The overall work sequence is: first floor left, first floor right, second floor left, second floor right, and so on. All work sequences within these sections are free, but they are due to the availability of material in the work areas, and also the constraints for transport sequence and accessibility of work areas must be respected.

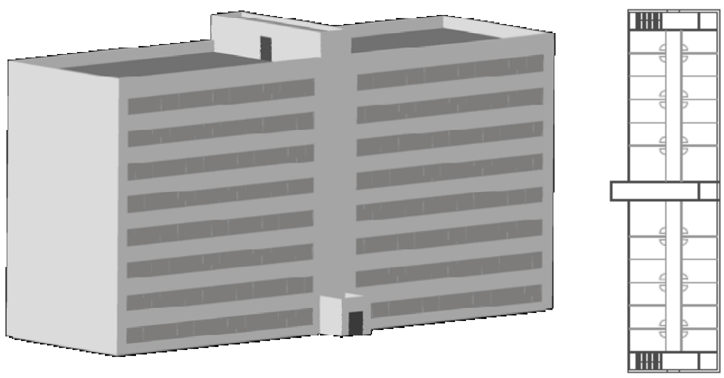

Fig. 2: Simulated administration building (left: view, right: ground floor plan)

All floors can be reached by stairs at the ends of the building and by an elevator in the middle of the building. Access to the building on first floor is next to the stairs as well as an additional entry in the middle of the building. Vertical material transport is only possible by elevator, whereas the personnel can use stairs or elevator to reach the floors. The decision is taken on the basis of the distance to stairs or elevator and by accessibility.

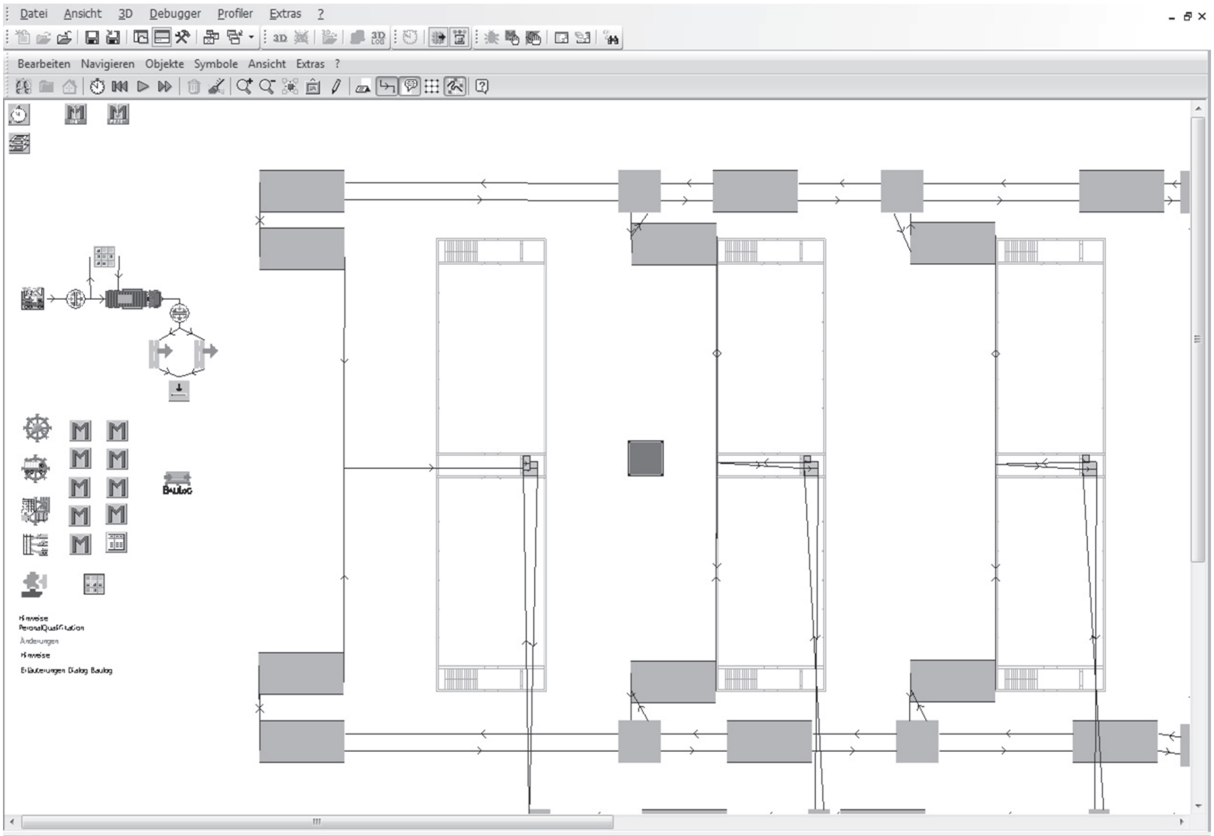

Fig. 3: Simulation model (screenshot)

To pinpoint the effects of changing configurations, the analysis is limited to one outfitting task (drywall construction or flooring) for each simulation run.

4.2 Network configuration and scope of research

In the examined example all material is delivered at the start of construction (delivery strategy). There a two unloading areas in front of the building near to the main entrance. After unloading, the material is transported to the floors (decentralized storage strategy). Storage areas are located next to the lift on each floor. The transport to the installation areas starts as soon as the corresponding work step is ready to start (all other constraints are fulfilled, the work area is free of other materials). If necessary, the material is transported close to installation point.

All logistic activities are done by workers themselves. The activities are priorised as following (higher priority = favored execution): construction task (1), material transport to storage/installation area (2), clean up and rearrangement (3) and unload (4). Low priority in construction results from less urgency of logistic activities. If work areas or material are not available, they constrain the construction processes.

Using the example of drywall construction, the effects of diversified equipment (experiment nr. 2-4) and organizational structure (experiment nr. 5, 6) can be demonstrated. Table 3 shows modified parameters.

Table 3: experiment overview

experiment no.	modified parameter
1	none (basic network configuration)
2	lift speed increased to 1 m/s
3	lifting capacity increased to 500 kg
4	lifting position modified (shifted to left end of building)
5	responsibility modified (unload, storage, clean up done by logistician)
6	responsibility modified (all logistic activities done by logistician)

To evaluate the applicability of the results to other maintenance groups, all six experiments were repeated with another construction task: flooring (experiment no. 7 – 12). The network configuration, organizational structure and the simulated building and its ground floor plan remained unmodified.

4.3 Data interpretation

The effects of modification in the network configuration, respectively modified site element parameters, are analyzed with regard to the required logistic time and construction time. All results are noted as percentage improvement to the basic network configuration. Table 4 subsumes all results.

Table 4: experiment results overview

drywall construction			flooring		
experiment no.	deviation in logistic time [%]	deviation in construction time [%]	experiment no.	deviation in logistic time [%]	deviation in construction time [%]
1	-	-	7	-	-
2	- 45,3 %	- 2,3 %	8	- 50,1 %	- 11,4 %
3	+ 0,1 %	+/- 0 %	9	+ 1,8 %	+ 0,6 %
4	- 3,2 %	- 0,2 %	10	+ 5,1 %	- 3,3 %
5	- 3,1 %	- 1,7 %	11	- 6,6 %	- 7,8 %
6	- 5,2 %	- 3,4 %	12	+ 8,4 %	- 10,7 %

The example shows, that there is no obvious correlation between spent logistic time and necessary construction time. A high deviation in logistic time (experiment 2) not always causes a high deviation in construction time. A reason for higher logistic activities in case of increased lift parameters (experiment 3 and 9) is, that the material for both construction sections is stored in the same storage area. In this case material delivery on the floors ahead of time causes additional need for rearrangement.

Sometimes increased logistic time even causes a shorter construction time (experiments 10 and 12). The differences because of the unregulated work order within the construction sections are predominant. The work sequence, however, is according to the availability of material at the work areas. With better elevator characteristics, more material is available at the work areas. Especially in the flooring processes it is then possible, that rugs are installed first (e.g. on corridors), which then hinder work in downstream areas (rooms). In other cases additional waiting time and finally longer construction time would be the consequence (experiment 9).

Modified responsibilities for logistic activities actually don`t reduce logistic time. But workers' concentration on construction work reduces ways between the unloading area, storage areas and work places, and finally reduces logistic time. Logistic and working activities in parallel decrease construction time (experiments 5, 6 and 12). The increased logistic time in experiment 11 is caused by a faster material delivery on the floors and by therefore additional need for rearrangement.

Hence two important facts are distinguishable: good logistics respectively well planned network configurations cannot improve unfavorably chosen work sequences. For example installing rugs in corridors before installing them in the rooms leads to congestion. If only one network element is improved, e.g. site equipment, without the consideration of other logistic elements, it might even act against productivity.

A number of more than 150 experiments based on the basic configurations 1 to 6 with modified floor numbers and process times show similar effects, but in different intensity. On top of these effects, another result is evident: the higher the share of logistic activities is in construction time (less floors or shorter process time), the higher is its optimization potential. But not all construction types (combination of number of floors and process time) profit from the optimization (modified network configuration) at the same rate. Especially in the simulation of drywalls the effects are obvious. The cycle time of an elevator has a very obvious influence, whereas the position of the elevator with respect to the floor areas had a neglectable consequence (figure 4).

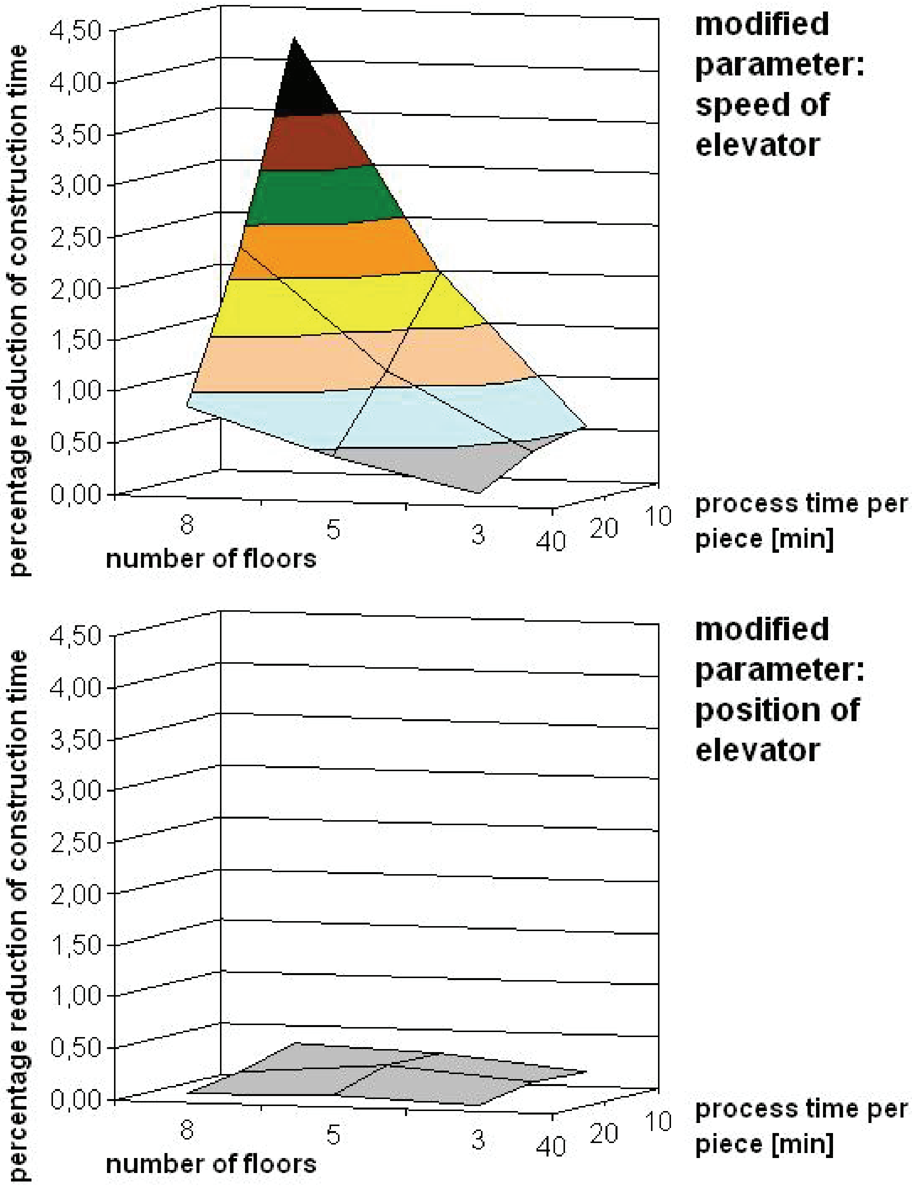

Fig. 4: Dependency of construction time reduction on floor numbers and process time per piece

To generalize these results the experimental schedule is to expand. Not until other outfitting tasks show similar effects, a single factor or factor combination can be neglected in the further analysis. Influences of other boundary conditions, e. g. kind of outfitting task (horizontal or vertical oriented) or deployment and the workers to logisticians ratio, have to be considered. Furthermore reduction of construction time is not the only benchmark. Feasibility and cost-value ratio are also to observe.

5. Discussion and Conclusion

Optimization of construction site logistics cannot be achieved by a straight forward simulation. To improve an initial logistics configuration of a construction site, several simulation runs with various factor adjustments have to be executed. Therefore an initial feasible solution and the knowledge about the major factors of influence are advantageous.

First simulation experiments based on a given site configuration point out, that several factors influence the percentage of logistic activities and finally the productivity on site in different orders of magnitude. To accelerate logistics planning, the elimination of irrelevant factors will be advantageous. It minimizes experimental scheduling and the number of simulation runs. The identification of typical qualified factor combinations, which depend on several processes and building attributes, secures optimisation potential and makes it quickly accessible.

It is obvious, that reducing logistic activities does not always result in reduced construction time. An insufficiently planned work order cannot be improved by a purely logistic planning.

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DEVELOPING 5D SYSTEM CONNECTING COST, SCHEDULE AND 3D MODEL

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ABSTRACT: *A recent topic, BIM could be considered as an effort to integrate all the information. So far, the integration of cost and schedule data has been done successfully as there is a good case of EVMS in order to synthesize those data. There have been many efforts to develop a 5D system that integrates cost, schedule data and a 3D model, but its technology is so difficult that few have succeeded. The 5D system will have many advantages once it is made: The visualization of schedule data and verification of cost in real time are possible and the future cost and schedule can be expected accurately. Especially, in case of an atypical structure the clash of members and errors of drawings which are hard to find in 2D drawings can be detected and corrected in a 3D model. This paper presents the methodology and results to develop a 5D system with the integrated cost and schedule data from EVMS, and a 3D model of the 2nd Geumgang Bridge within nD-CCIR, a 5D system developed in the UK.*

KEYWORDS*: BIM (Building Information Modeling), 5D System, EVMS (Earned Value Management System), Cable-Stayed Bridge, 3D Modeling, WBS, CBS*

1. INTRODUCTION

BIM (Building Information Modeling) which many people say nowadays is linking 3D modeling with construction information such as schedule, cost data and etc, and it is managing various information through 3D modeling conventionally rather than new concept.

In short, BIM is the integration of information. Comparing the other industries, the construction industry has had many difficulties in being computerized, because its size is bigger than others and it has many uncertainties. It might be impossible before, but it becomes possible by drastically developed computer technology.

There has been a big stride in integration of information in many construction companies because they recognized its utility. *EVMS* (Earned Value Management System: cost and schedule management system in the firm), which *Daelim Industrial Co., Ltd.* (domestic construction company in Korea) developed as a tool of managing schedule and cost, enables us to know real-time schedule according to cost data and real-time cost according to schedule data by managing schedule and cost simultaneously. It is not conventional system managed with cost, but new system managed with cost and schedule. It is, however, difficult to understand the detailed schedule although it is well-explained, and moreover it takes much time for even workers concerned to know it, because it presents by only texts and tables. It has become necessary combining schedule, cost and 3D modeling so that anyone knows it easily with visual effect.

There is very few 5D simulation software such as Virtual Construction made by Vico Software in Finland because of difficulty in making program and the domestic structure of cost is different from foreign one, which makes us not be able to use it. Although commercialized foreign estimating system based on BIM is more efficient and accurate than domestic one based on 2D, it takes much time in order to calculate more exact quantities and make more exact 3D modeling, because our domestic bidding system needs exact quantities other than rough one, which makes the limit on utilizing it. Furthermore, currently, management is much more concerned about contract and cost rather than production at construction work face (SRIPRASERT E. and DAWOOD N.).

Therefore it was recognized the necessity of developing new system endowed with already existing EVMS and 3D modeling and the scheme was presented. For experimental study on integrated system prior to developing web-based system, stand-alone system has been made and 2nd Geumgang Bridge which is cable-stayed bridge was selected as target structure because it has asymmetric and round pylon.

2. 2ND GEUMGANG BRIDGE

The 2nd Geumgang Bridge is being under construction now, the construction period of which is from 2008 to 2011 and located at the multifunctional administrative city, i.e., Sejong city in the middle of South Korea. A total length is 880m and it has 6 lanes of both bound. It is composed of cable-stayed bridge section (main span 200m and side span 140m) with composite steel plate girder, the stiffening girder of which is I shaped edge steel girder with precast concrete deck, and the pylon of which is round, asymmetric and 100m high, and approaching section (540m) with composite narrow steel box girder as shown in Fig. 1.

2.1 Overview

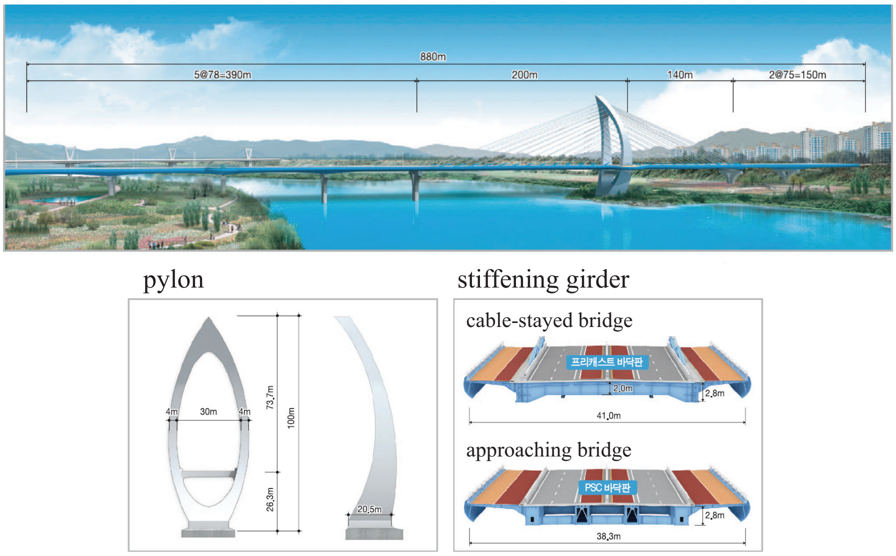

Fig. 1: Overview of 2nd Guemgang Bridge

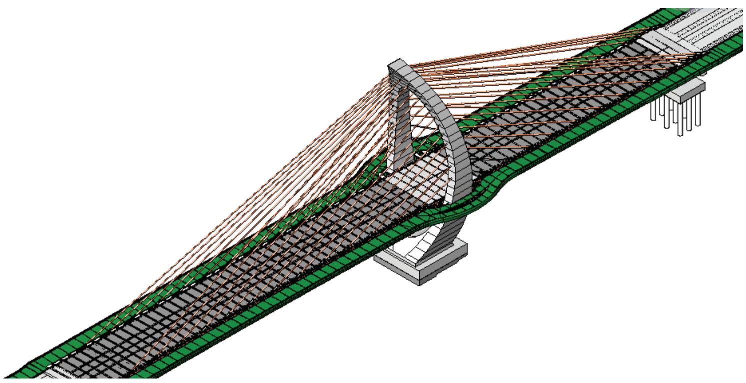

Fig. 2: 3D Modeling of 2nd Guemgang Bridge with Revit Structure 2009

2.2 3D Modeling

In Korea, unfortunately making 2D drawings is still conventional, which makes designer draw repeatedly in order to make 3D modeling. Once it is established, we can utilize it in various ways such as clash detection, planning simulation, decision-making, coordination support and so on. It is strongly insisted that drawing in 3D is settled in the near future in Korea. Making 3D modeling, which had been divided suitable for sub-activity in advance, was done with Revit Structure 2009 as shown in Fig. 2.

3D modeller had lots of difficulties in working because each member in 2D drawing did not include longitudinal slope and some errors such as clash between members were fixed. 3D modeling, or Revit file was transformed into IFC file which is an international standard of 3D modeling including information.

3. DESIGN OF 5D SYSTEM

3.1 EVMS

EVMS is the way of analyzing performance and expecting final project cost and schedule by managing schedule and cost of project and utilizing a structure of standard classifying based on schedule managing system.

EVMS is composed of WBS (Work Breakdown Structure) and CBS (Cost Breakdown Structure), and WBS at the level of sub-activity is connected with CBS at the 5th level of cost item. The 3D modeling is connected with WBS at the level of sub-activity and CBS is connected automatically with WBS by matching table as shown in Fig. 3. Therefore 3D modeling should be divided as to be adequate for sub-activity and WBS, CBS and matching table were extracted for linking with new system.

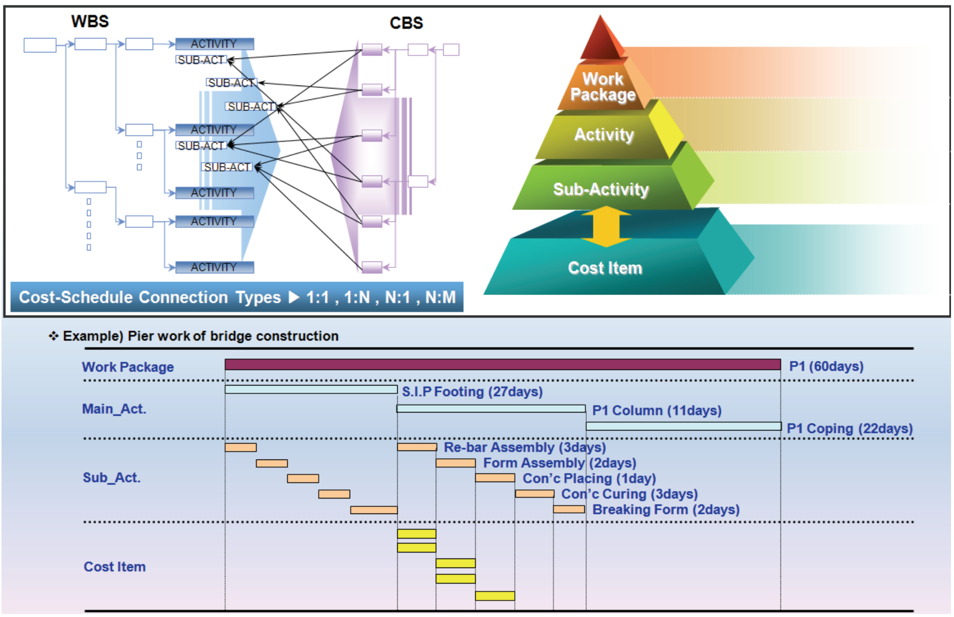

Fig. 3: Structure of EVMS

3.2 Customized nD-CCIR

The New system's name is so-called nD-CCIR which has been already developed by Prof. Nashwan Dawood and his team at Teesside University in Middlesbrough, UK and brief structure is as shown in Fig. 4 (BENGHI C. and DAWOOD N.).

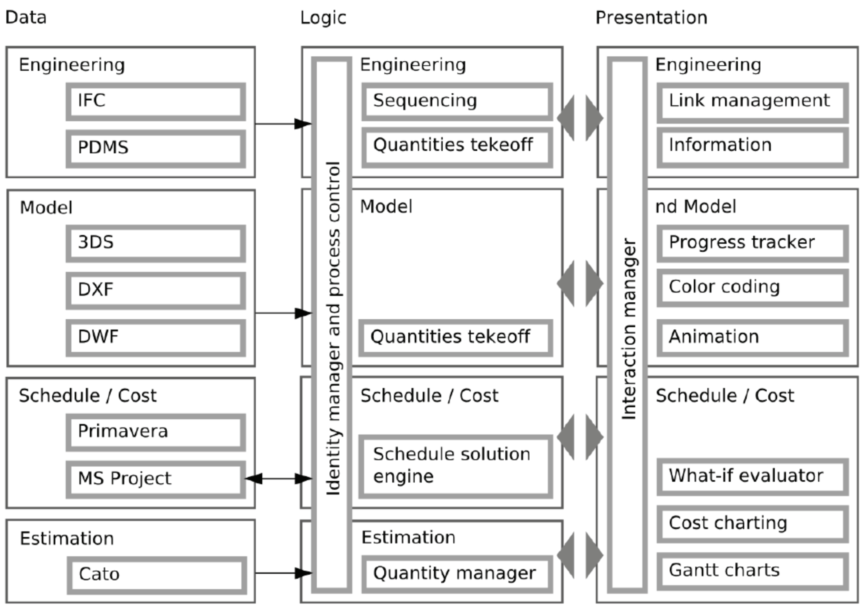

Fig. 4: Structure of nD-CCIR

Initially, because nD-CCIR took different input form and had nothing to do with EVMS, we felt the necessity of customizing it to our system environment including EVMS so that nD-CCIR, itself can download and manipulate EVMS data and 3D modeling. A program was developed with C# based on .NET framework and DirectX 9.0 was used as graphic engine. The data of cost and schedule in EVMS are downloaded once a month as form of XML which will be embedded ndp file, or nD-CCIR input file. Because data update is performed monthly, the data saved in local PC are shown before updating it. The 5D simulator embedded in program presents 3D modeling.

4. RESULTS FROM 5D SYSTEM

After completing 5D system, we obtained the system as shown in Fig. 6. When the program is launched for the first time, linking 3D modeling with EVMS data will be done automatically, once 3D modeling is loaded. Typically, the system has 5 parts which are 3D modeling window, model list window, information window, Gantt chart window and cost inspector window. Each window can be easily moved by drag-and-drop of mouse.

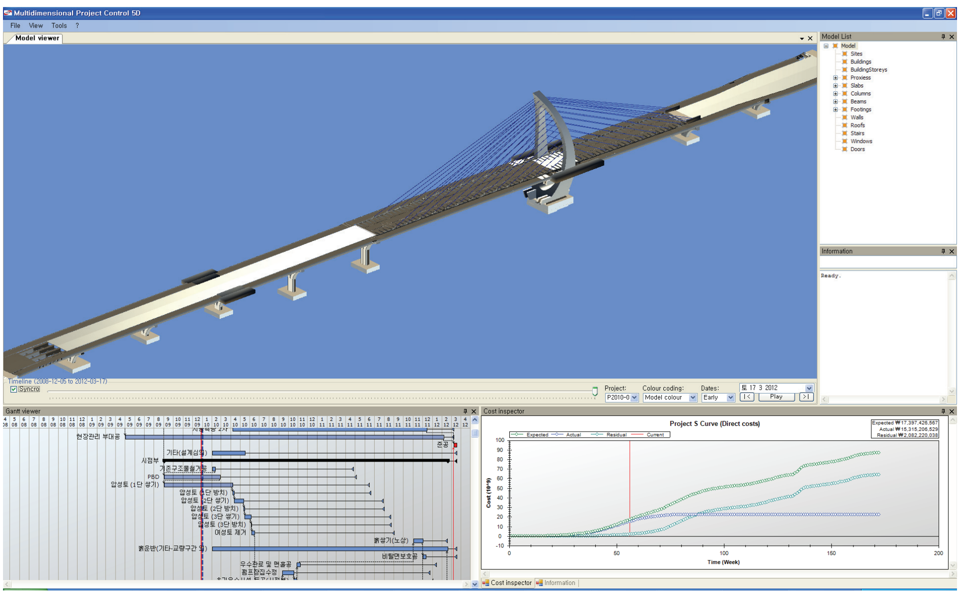

Fig. 6: nD-CCIR Endowed with EVMS Data

4.1 Managing Schedule and Cost with Visualization

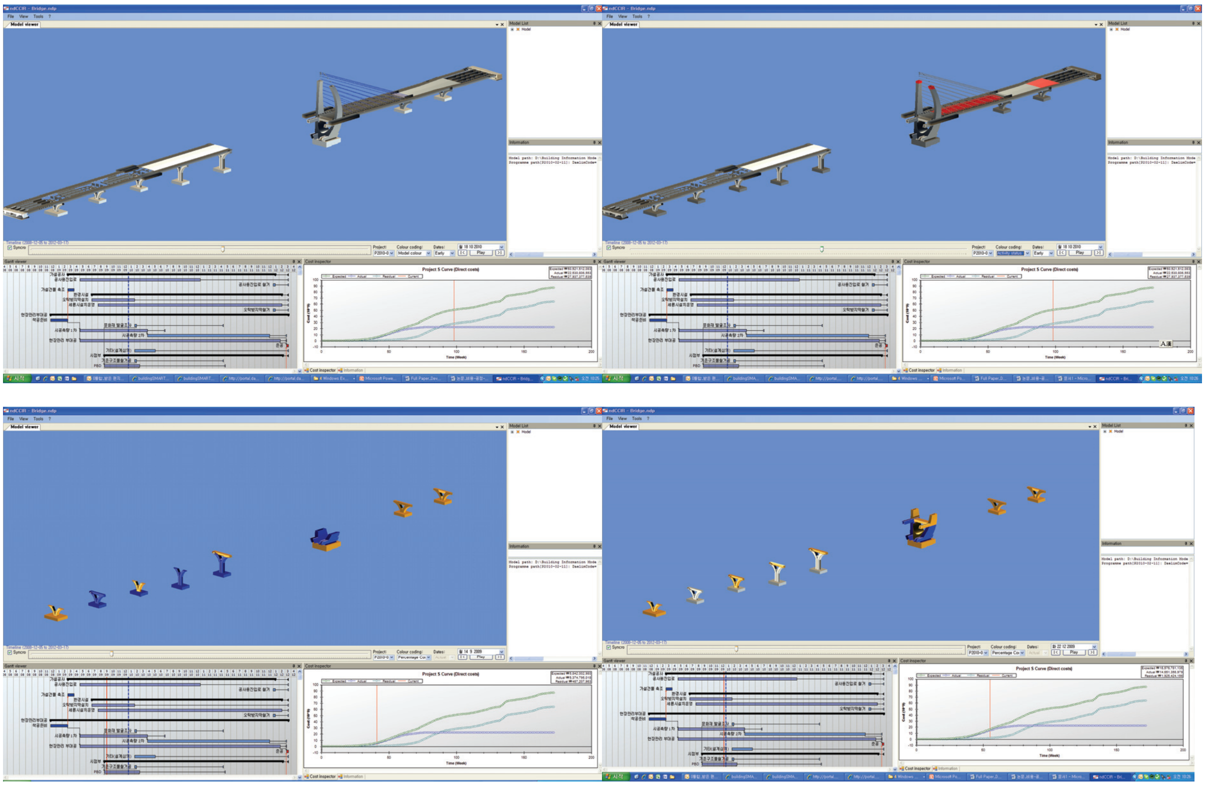

Fig. 7: Various Model Colours Representing Practical Status in Simulating Construction

The user is provided with various colours which can represent the practical status in simulating construction process as shown in Fig. 7. In model colour option, it is possible to simulate planned schedule with real colour. In activity status option, the colour of member related to running schedule turns red. In percentage control option, the member related to fast activity turns chrome if it finishes, the member related to delayed one turns red if it finishes, the member related to fast one turns blue if it is running, the member related to delayed one turns green if it is running, the member related to fast one turns bright orange if it does not start, and the member related to delayed one turns dark green if it does not start.

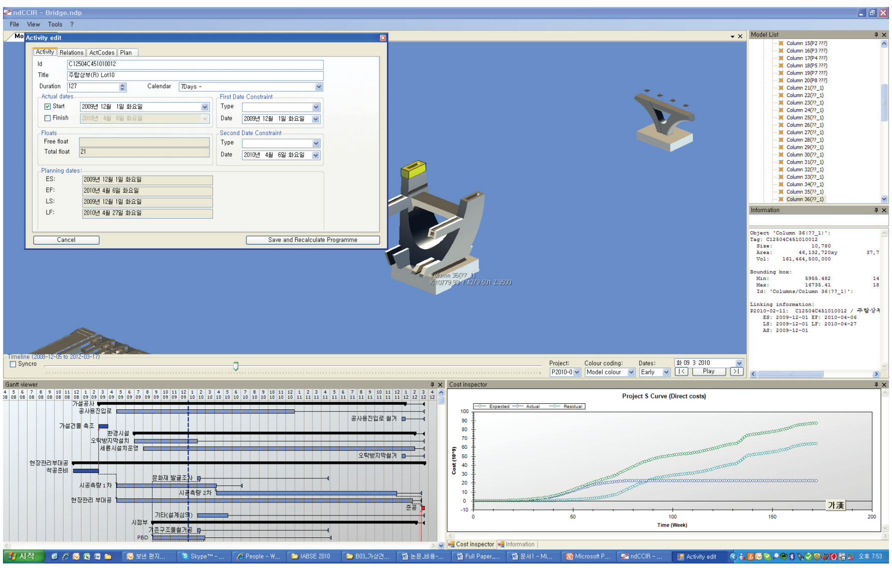

Fig. 8: Activity Edit Pop-Up Window

Also, the user can modify activity or relation about schedule in activity edit pop-up window, by selecting a specific member as shown in Fig. 8. It was very tiresome to modify an activity in Gantt chart because it is hard to search what they want to change, but by means of synchronized 3D modeling, it was totally solved.

The user can add another model viewer window up to 4, which allows them to compare different schedules. That makes it possible to save money or time by checking all possible procedures before constructing structure.

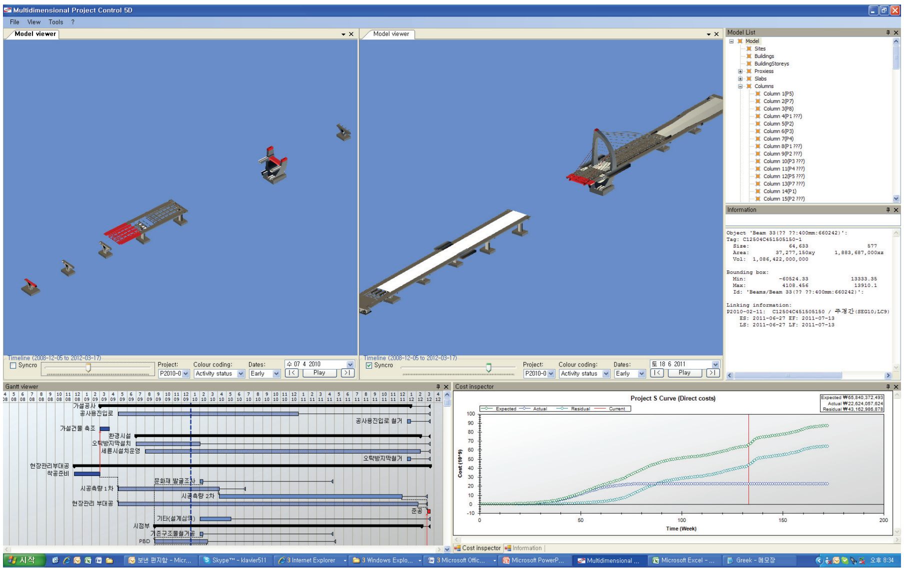

Fig. 9: Added 3D View for Comparing Different Schedules

4.2 Managing Information

The user can insert the information concerning specific member on product information window by right clicking it as shown in Fig. 10. The information can be all the valuable things such as manufacturer, material, strength and so on, that are the essential factor in BIM. The general properties such as dimension and schedule appear in information window, whenever the user selects a member. The categories of information can be expanded to anyone the user wants to include.

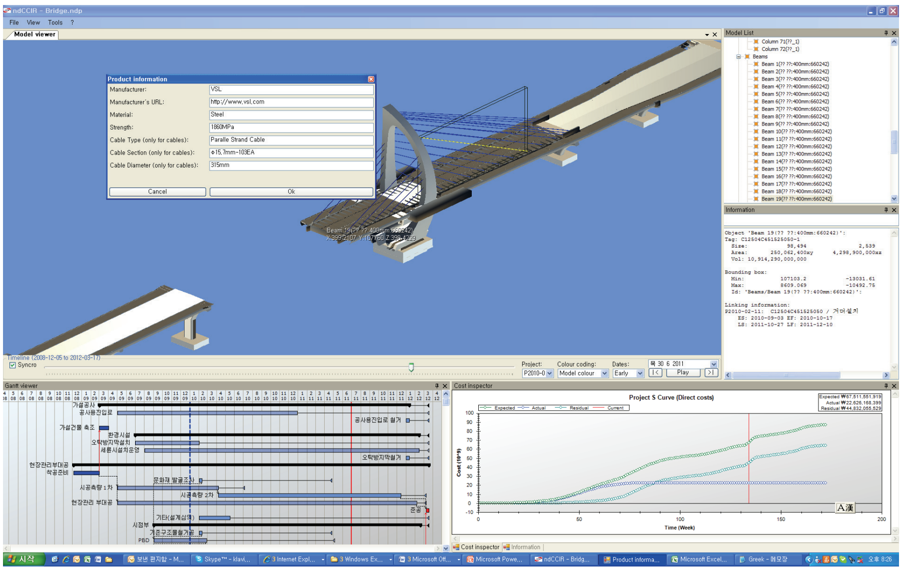

Fig. 10: Product Information Window and General Properties Information Window

Besides what were mentioned in this chapter, there are many beneficial aspects in nD-CCIR.

5. CONCLUSIONS

This study has presented the methodology and result of developing 5D system, or nD-CCIR, which was previously made by professor Dawood and his team in Teesside University, UK and customized by themselves according to Daelim company's EVMS environment. It links schedule and cost which come from EVMS with 3D modeling of 2nd Geumgang Bridge, and shows various valuable results such as managing cost and schedule with visualization, and managing information about specific member.

Generally speaking, all the information can be saved, but the problem is that it has been difficult to utilize it. In addition, unfortunately, managing information properly has been neglected in the most cases of construction in spite of brilliant evolution of information technology. The point is how it is saved, retrieved and managed and it can be more beneficial only if it is managed with systematic and consistent way with BIM.

This study also tells us that BIM shows one of the possibilities that the mixture of construction and computer technology can be more useful to any concerned construction party such as client, engineer, contractor and etc. Because this system's type is stand-alone, user has to install the program on each computer, so it is difficult to check the status of project without installation. If web-based system were developed, it would be solved directly and we could know it anywhere. Therefore, web-based system will be developed in order to fix these problems, next year.

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AUTOMATIC GENERATION OF WORKSPACE REQUIREMENTS USING QUALITATIVE AND QUANTITATIVE DESCRIPTION

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ABSTRACT: *Sophisticated methods of planning and analyzing the sequence of tasks within the breakdown structure for time scheduling have been developed. However, the work space generation problem has received little attention from researchers and practitioners. Moreover, few researchers have addressed this problem in combination with a scheduling process. This paper addresses the problem of the generation of the different types of workspace associated with different activities. However, assigning the space requirements to activities and manually updating this information as the design or the schedule changes, especially in large projects, can become cumbersome and practically prohibitive. In order to develop a sophisticated method for the generation of the different type workspaces, first, the important construction workspace requirements and their characteristics are derived. Secondly, the concept of the Plant Simulation software will be introduced and will be further studied. Finally we will implement the identified requirements of the workspace generation in Plant Simulation.*

KEYWORDS: *Simulation, Workspace.*

1. INTRODUCTION

The identification of construction tasks and their work space requirements is mostly dependent on the construction activities scheduled for a project. Once the construction activities are selected and the project schedule is developed, the tasks, that have to be performed in order to complete each construction activity, are, to a great extent, predictable. Observations of construction operations in progress have shown that work areas are required for intervals, which may vary from some minutes to several days or even weeks. Work space allocation is complicated by the need to include buffers that allow for uncertainties during execution. Smith concluded that the planning of the different types of space related to process activities in construction is difficult, as such activities are extremely dynamic and are not fixed in the same position for the duration of the activity (Smith, 1987). Research in site layout planning has been able to reason about the adjacencies of different work areas (Tommelein and Zouein, 1993, Yeh, 1995, Zouein and Tommelein, 1999); however, these approaches have not yet been able to describe the dynamic nature of the process areas in construction and to reference them with the building material.

2. OBJECTIVE

For defining space requirements, the level of detail has to be determined, in which the workspace is attached to the construction activities. Furthermore, to overcome the dynamic nature of work space, the generation of workspace should be related to the processes performed by the trades. This makes the model of such a dynamic process more accurate. The breakdown of the construction workspace requirements in the framework of this paper is performed at a relatively high level of detail, which is referred to as the *Work Step Process* (*WSP*). The generation of workspace for construction activities is based on worksteps (*WSP*). Each workstep requires a certain type of space and may cause a set of possible impacts. However, assigning the different space requirements to activities and manually updating this information as the design or the schedule changes, especially in large projects, can become cumbersome and practically prohibitive. Therefore this paper proposes to automatically generate and assign the different space types required for performing each activity. This paper starts by reviewing some important recent developments in construction work space generation before presenting the own concept. A state of art software, Plant Simulation, provides the context for the focus on main elements of the generation of work space.

3. LITERATURE REVIEW

Space is needed for executing tasks. Research has been conducted to figure out the amount of human operational workspace required by construction trades. The quality of literature that has attempted to determine the required area by human resources in construction operations has related the required workspace area to the performance of labor (Logcher and Collins, 1978, Smith, 1987, Thomas and Smith, 1992, Horner and Talhouni, 1993). These studies limited a certain average amount of required area for human resources allocated to an area at the same time for a certain period of time. This description represents the characterization of construction projects in a very broad way. The concept inherent in this description neither fulfills the requirement of the nature of work (different types of space for different activities) nor the determination of the impact of congestion in construction management. It ignores the congestion other than that of too many craftsmen. But what about cramped workspaces and stored materials that impede work?

Riley and Sanvido recognize that workspace is constricted by the actual work in place and the amount of space available. They developed a methodology for detailed daily activity planning on construction sites. Their methodology identifies required space, generates layouts, sequences activities and resolves conflicts. The output from each of these is graphically displayed (Riley and Sanvido, 1995, 1997). The major limitation in their work is that the importing of the schedule information as well as the product information are done manually. They also do not make a clear distinction in the source of the spatial information, either in terms of available space or in term of the amount of required space.

Thabet and Beliveau proposed a scheduling method for analyzing available space of repetitive work in multistory buildings. Their methodology divides the work floor into a number of zones and layer blocks. Each block represents a work area of the floor at a specific zone during a specific time period. The physical spaces available are utilized by a three-dimensional computer aided design model of the floor. Tasks are carried out manually (Thabet and Beliveau, 1994).

Another attempt to generate space has been developed by Winch and North, which allows the user to manually draw up the areas available for work packages to be executed. This methodology helps the construction planner to interactively “mark up” areas not occupied by either work in place or temporary work objects. Tasks and subsequently the space required by associated resources could then be assigned to these manually drawn areas (Winch and North, 2006). They focus on task execution spaces, as these are the critical ones for construction project planning.

Akinci et al. developed a methodology to model the construction activities in 4D CAD models by formalizing the general description of space requirement through a computer system. Space requirement involves three considerations: the spatial orientation with respect to a reference object, the reference itself and the specific volumetric parameters. The result is a “space-loaded production model.” By using 4D CAD a user can automatically generate the project-specific work spaces according to schedule information and represent the work spaces in four dimensions with their relationships to construction methods. This methodology provides understanding of the various types of spaces that are related to specific types of construction activities and potential conflicts (e.g., material space, labor space, building component space, etc.) (Akinci, Fischer and Kunz, 2002). However they ignore the relationship between the different work space types. They assumed that all micro level spaces are connected to the relevant sides of their reference objects.

On this basis, it may be concluded, that the different methodologies, which have been implemented in the generation of the dynamic work space, did not pay attention about adjacencies of the different types of space. On the other hand, site layout research reasons mostly about adjacencies of the different types of space. However, this did not yet pay attention to the dynamic nature of the construction process.

4. STATE OF ART IN PLANT SIMULATION

The Plant Simulation from Tecnomatix Technologies Ltd. is a discrete event simulation program. It has been widely used in the stationary industry in order to plan processes, allocate resources, and detect conflicts. The Flensburg Schiffbau-Gesellschaft mbH & Co. KG (The Flensburgers) cooperates with the Bauhaus University-Weimar represented by the Chair of Construction Engineering and Management. The common goal of the cooperation is the development of flexible and innovative approaches (simulation modules) to support construction progress planning. First the cooperation was on selected configurable simulation modules as sub-process, which can then be linked in addition and in compliance with a variety of boundary conditions, in a continuous simulation model. Within the cooperation the focus is on finishing processes, initially limited to drywall construction (König, Beißert and Bargstädt, 2007, König, Beißert, Steinhauer and Bargstädt, 2007). The associated trades are particularly suitable for a joint development of ship building and civil engineering construction. Figure 1 illustrates a state of the art Plant Simulation program. The user create six essential tables: *tasks:* the task table contains all activities, which are required to fulfill the final product. Tasks are broken down into different subtasks. A subtask (subtask 01) may consist of several objects to be created (drywall01, 02, ...), *worksteps templates:* the table specified for each object (drywall01) the required elements (plasterboard, U-channel), *assembling details:* described in the table is the assembly strategy process for the different elements (plasterboard, U-channel), *global constraints:* the table allows for the definition of processing sequences between different trades, *local constraints:* the table allows for the definition of the processing orders within one trade, and finally *date constraint:* allows the specification of the start dates of individual tasks (König, Beißert, Steinhauer and Bargstädt, 2007).

By uploading these tables, the Constraint Manger generates from this specified information the worksteps and their corresponding constraints. Worksteps, which have satisfied the constraints, are transferred to the next table for the executable steps table (see Figure1). The Constraint Manager generates a sequence of works, taking into account a variety of constraints. The Constraint Manager verifies during the simulation the compliance with the constraints.

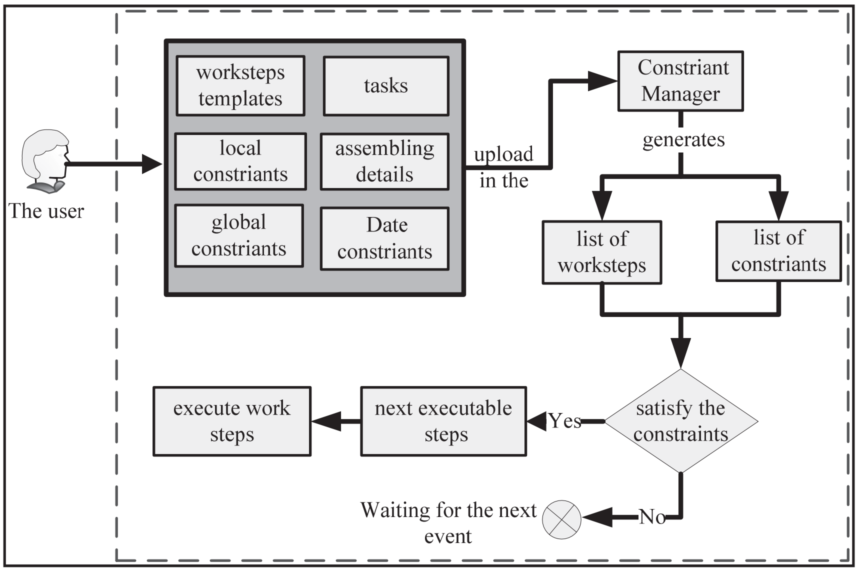

Fig. 1: State of Art of the Plant Simulation

This first concept developed at the Bauhaus-University Weimar is a constraint-based simulation. Thereby, the construction tasks and their constraints for production such as technological dependencies, availability and capacity can be specified and valid execution schedules can be generated (Beißert, König and Bargstädt, 2007, Beißert, König and Bargstädt, 2008a). However in this concept, the space required for good workmanship is not considered. To consider spatial aspects, we have to acknowledge the work space requirements and integrate these requirements as additional constraints. Then, the fulfillment of spatial constraints at the construction site can be checked and verified. In our proposal we are going to focus first on the generation of the different required types of work spaces. For reasons of simplicity in the model it is assumed, that all workspace requirements will be represented as occupying a specific number of rectangles in a grid frame.

To summarize the features of Plant Simulation, activities can be built within Plant Simulation in a hierarchical structure. The highest level of the activity description is the trade. The lowest level of the activity description is the element or section. For each element or section one or more worksteps may be defined. Workstep performance with-in one trade is restricted to the order of sequence, which is defined in a local constraint table. In addition to the order of sequence the user can define a temporal relationship between the worksteps. The sequence of work between the different trades is defined in the global constraint table. The Date Constraint allows the specification of start dates of individual tasks. Here can the user define for a specific object or its individual associated elements a specific starting date for execution.

5. INTERACTIVE SPACE GENERATION

Starting from the classification of the different types of space utilization (Bargstädt and Elmahdi, 2010), the types of activities in construction projects have to be analyzed. In our proposal we are going to focus on the process area (see Figure 2), as it is most intensely related to the production planning of multiple crews. According to Akinci's definition, the process area (Akinci calls it micro level space) is an amalgamation of the different types of spaces required within the proximity of the components being installed.

For the automatic generation of the work space for any given activity on a specific project site its quantitative and qualitative description must be given. The quantitative description includes the definition of the worksteps and the breakdown of the activity into work sections or elements in order to identify the required work space types and their attributes (length, width, area etc.). In Plant Simulation tasks are broken down into subtasks. The subtasks are further broken down further into objects. Each object is composed of different elements or sections. For each section or element one or more worksteps may has been defined. We define two levels to assign workspace types and their attributes to the previous hierarchical break down of the activity: *object level* and *workstep level*. Space required for equipment, material and hazard space are at the *object level,* since these spaces are going to be reserved for the entire duration of the work associated with an object e.g. drywall 01. The duration for this type may take from a few hours to several days. The second level is the *workstep level*, the work space for the laborer to perform one workstep. Since this level is very detailed, the duration for this type takes from several minutes to hours.

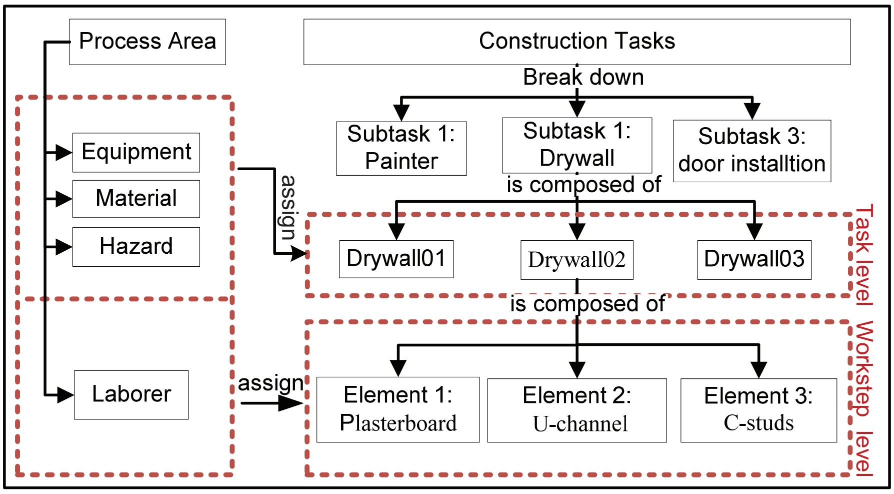

Fig. 2: Construction tasks breakdown and work space assign

The qualitative description of the workspace includes the definition of referencing and the orientation for the different required types of workspace. Referencing defines the relative placement of spatial objects (workspace). The goal of defining such referencing for the different types of workspace is to express the characteristics of configurations that are of interest in determining the required workspaces, and a flexible representation of the different types of work spaces for different trades. We define two kinds of referencing: *direct referencing* and *relative referencing*. Labourer workspace is directly referred to the element, e.g. plasterboard. The material and equipment, however, as well as possible hazard areas have a relative reference to the object, e.g. wall. Once the referencing is identified, the second part of the qualitative description is to interpret the orientation. In this research we identified and modeled four orientation descriptions for the different types of space: North, South, East and West.

6. DEVELOPMENT METHODOLOGY

For the generation of the workspace, we developed an additional network ”the spatial network.” This developed spatial network is embedded in Plant Simulation (see Figure 3). The network includes methods and tables. Tables are the input data for the generation of the work space. Methods are the impulse for the generation of the work spaces between the input data and the constraint manager.

Our aim here is to capture the essential characteristics of the different trades’ performances in a high level description; so that the relevant

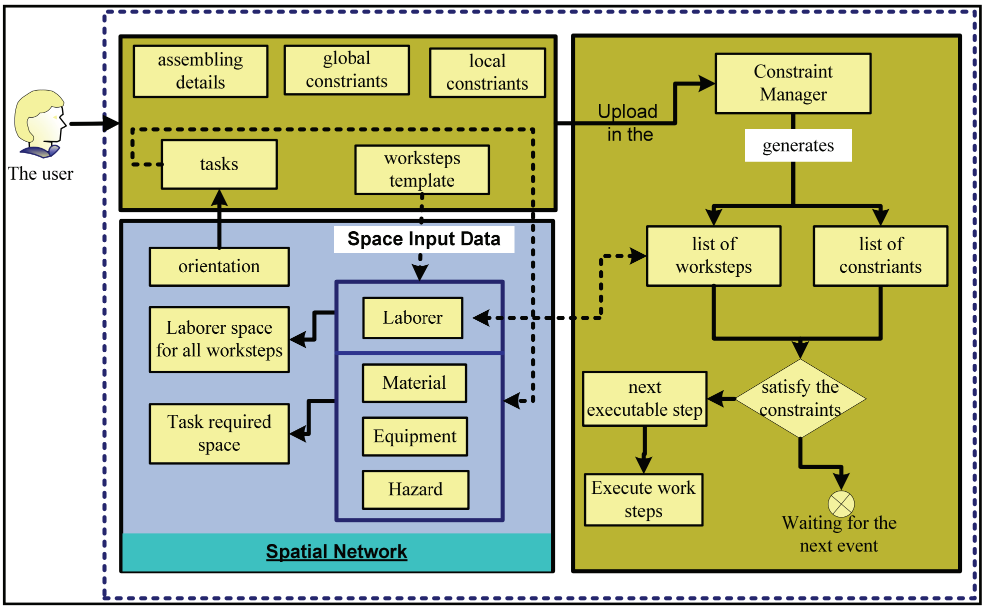

Fig. 3: State of art of the Plant Simulation and the new Spatial Network

conclusions can be drawn from it for the workspace generation. As the work progress on site, the position of performing works for individual trades changes continuously due to the dynamic nature of the overall construction process. In order to apply the qualitative and quantitative description in the generation of workspace in such a dynamic system, we need to rely on a sophisticated description of the construction process.

Through interviews with different laborers and observations from their performance on construction sites, we found out that the work performed by the trades is based on worksteps. Each trade performs a unique sequence of worksteps, which is repeated irrespectively of the position of the work location, in order to complete a task. The methodology proposed in this paper to base it on the description of the unique worksteps for different trades. Once the related worksteps are identified, the user has to create the relevant tables, each table representing work space types with their associated required space attributes (length, width, height) for the unique workstep, e.g. laborer. In addition to the geometrical attributes, the user can define the required processing time for a unique workstep. This additional attribute could also be defined in the worksteps templates table. Relying the qualitative and quantitative descriptions to the worksteps workspace can be generated through the following steps:

Step 1 unifies the coordination system: Objects such as drywall01are coordinated through a global constraints system (GCS). Elements associated to these specific objects are oriented through a local coordination system (LCS) for each object. Since we are generating work space for elements associated to different objects, it is important to unify the coordination system between the different objects and their associated elements. This deters conflicts, which could rise from using two different coordination systems.

Step 2 determines task orientation: As we have stated previously, we use a geographical orientation (North, East, South, and West). We have added a column in the task table "*Object_Orientation*". The user has to specify the orientation of the laborer to the object.

Step 3 reference Laborer space: The size of the spaces required is represented as a number of rectangular prisms. The reference point for this workspace is the center point of the element. The method calculates from this point the width of the required space by dividing the total width into two equal parts: left and right from the center point of the element. The length of this space is calculated from the center point back from the element to the total required length.

Step 4 reference other required workspaces: Based on the site observation and our personal experience, we have found out that the material and equipment space are placed on the area behind the laborer workspace. The user can specify an offset distance from the object through the object length (at the beginning, at the middle, etc.) associated with each required work space to an object in a table.

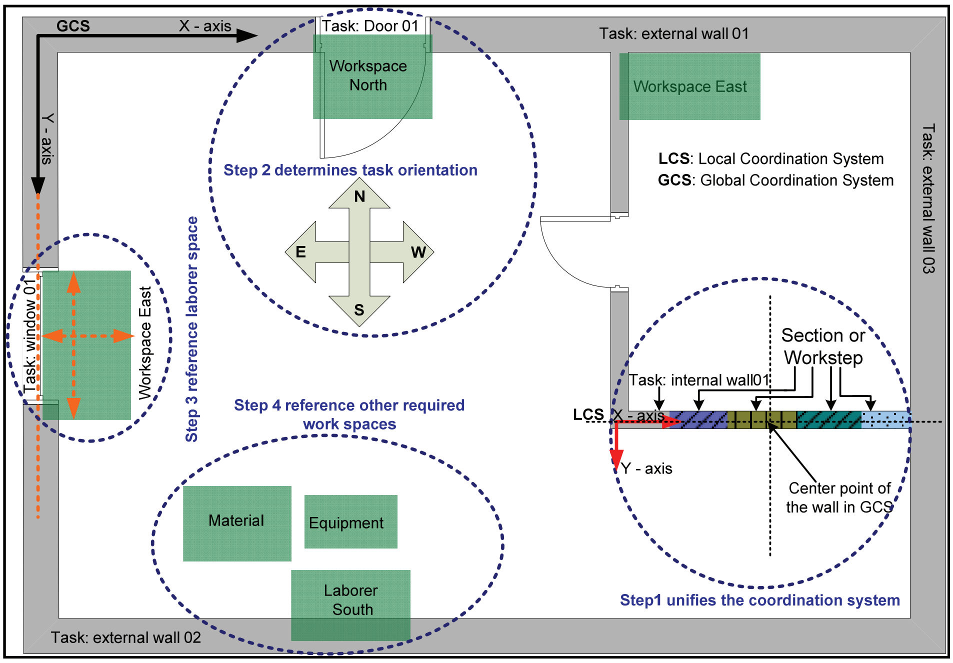

Fig. 4: Steps for generation of work spaces

The output of this mechanism is shown in two tables. Laborer work space contains all the worksteps with its associated work space attributes (length, width, etc.). The support table contains the required workspaces for a specific object with its associated attributes (length, width, reference)

7. CONCLUSION

The paper shows, how different space requirements and allocations can be combined within a scheduling process to a set of necessary space requirements for work in congested areas. Also methods are shown how to develop suitable space parameters and efficiency curves along the intensity of occupation of work space with different activities. With this tool a construction manager will be able to better plan and coordinate work of different trades within flexible, but highly congested work areas.

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Scene simulation of bridge collapse based on OpenSceneGraph and Finite Element Method

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ABSTRACT: *The scene simulations of bridge collapse of high quality require the realistic graphics and the scientific dynamic data. The scene simulations of bridge collapse based on graphics engine OSG (Open Scene Graph) are easy to realize the realistic effects, but they are not supported by scientific dynamic data. The dynamic simulations of bridge collapse based on FEM (Finite Element Method) are scientific and accurate, but they are abstract and unrealistic. So it is significant to combine scene simulation and FEM simulation for the scientific and realistic simulations of bridge collapse. This paper presents the methods about the modeling of bridge scene and the animation control of bridge collapse based on OSG and FEM software Marc. The dynamic simulation of bridge collapse is done by Marc firstly and the data of Marc is used for the scene simulation in OSG. To realize the consistent deformation with the simulation in Marc, the bridge model is created in OSG scene based on the model data of Marc and the process of bridge collapse in OSG scene is controlled by the scientific dynamic data of Marc. By comparing the animation of bridge collapse in OSG with the simulation of bridge collapse in Marc, the methods about the modeling of bridge scene and the animation control based on OSG and Marc prove to be operative. By this method, the scene simulation of bridge collapse will be more scientific in OSG. The work presented in this paper can be applied in the technical appraisal for bridge collapse accidents, providing a method to realize the scientific and realistic scene simulations of bridge collapse based on OSG and Marc.*

KEYWORDS: *Bridge collapse; Scene simulation; OSG; FEM; Marc*

1. INTRODUCTIONS

In recent years, some serious casualties and property losses for bridge collapse accidents appear repeatedly at home and abroad. For instance, Fenghuang Bridge collapsed when the scaffoldings of the bridge were being dismantled in August, 2007, in Hunan province of China. As a result, 64 people were killed and 22 people were injured in the accident. The direct economic losses hit 39.747 million Yuan (Chen, 2008). In America, the I-35W Mississippi River Bridge collapsed on August 1, 2007, killing 13 and injuring 121 others (Hojjat, 2009). Because of the seriousness of bridge collapse accidents, the technical appraisals for bridge collapse accidents arouse wide public concern. So the scientific, efficient and accurate technical appraisals for bridge collapse accidents are badly needed.

The technical appraisals for bridge collapse accidents need to replay the process of bridge collapse by computer simulation technology. As a scientific and accurate computational method, FEM (Finite Element Method) has been used in the dynamic simulation of bridge collapse (Sun et al., 2002; Liu and Gu, 2003; Lu et al., 2007). However, the simulations of FEM are abstract and unrealistic in contract to the scene simulation in graphic engine. So if two simulations can be combined, the simulation on bridge collapse will be scientific and realistic. The combined simulation will be better for serving the technical appraisals for bridge collapse accidents.

The scene simulation combined with FEM simulation is mainly applied in virtual manufacturing (Fritz and Andreas, 2004) and virtual surgery (Morten and Stephane, 2003). Wu peng et al. (2001) proposed an algorithm for deformable model based on finite element to make virtual surgery on deformable model more accurate. Igor et al. (2002) developed a prototype of a system for the simulation of elastic objects in virtual environments under real-time conditions and improved the render efficiency for FEM model with large number of nodes. In the field of civil engineering, Chen juntao et al. (2006) developed a 3D graphics system of finite elements for underground engineering by openGL. However, the scene simulation combined with FEM simulation is scarcely used in the bridge collapse.

In this paper, we realize the primary scene simulation of bridge collapse in graphic engine OSG (Open Scene Graph) based on the dynamic data of FEM software Marc. The dynamic process of bridge collapse is simulated in Marc. To make the scene simulation more accurate, the bridge model is created in OSG based on the model data of Marc and the process of bridge collapse in OSG scene is controlled by the scientific dynamic data of Marc. To make the scene simulation more realistic, the simple textures and walkthrough functions are applied in the scene simulation. The methods of bridge scene modeling and the animation control are discussed mainly, and a study case is presented in this paper.

2. PREPARATIONS

The dynamic simulation of bridge collapse by Marc is the preparation for the scene simulation in OSG. Marc is famous advanced nonlinear simulation software for finite element analysis, developed by MSC Software Corporation. In Marc, the bridge geometric model is divided into many small elements, including hexahedral element, polygon element and line element. In the process of simulation of bridge collapse, every element can appear deformation more or less and the deformation of the whole bridge is the accumulation of the deformations of all the elements. The method of killing or activating elements is adopted in FEM generally to simulate the discrete mechanic behaviors, for instance, scatter and fragmentation, because FEM is not good at simulating the discrete elements. So some elements will be killed in simulation due to large deformation.

The simulation in Marc shows the deformation of bridge and the process of bridge collapse. When the dynamic simulation is done, Marc can output 4 files for the scene simulation in OSG, as showed in table 1.In fact, the methods of the scene simulation in OSG also work without Marc, if other FEM software can output the 4 files as in table 1. Besides, the methods presented in this paper are not limited by bridge and can be applied in other structures, if FEM model only includes hexahedral element, polygon element and line element.

Table 1: Information of files provided by Marc

File Name	File Format	File Information
Node	txt	the 3D coordinates of all the vertex
Elem	txt	the type and the vertex ID numbers of all the elements
DispOut	txt	the displacements of all the vertex in every time step
DelElem	txt	the ID numbers of the killed elements in every time step

3. OVERVIEW

OSG is open source graphic engine based on openGL, with a complete API for C++. There is a hierarchy in scene management of OSG. The highest level is Group in OSG scene and Group can contain different kinds of Nodes. In Nodes, there is a special Node for the management of geometry elements, named Geode. In Geode, Geometry is used for drawing geometry elements and storing the property of geometry, for example, Vertex, Normal, Texture and so on, as specified in figure 1.

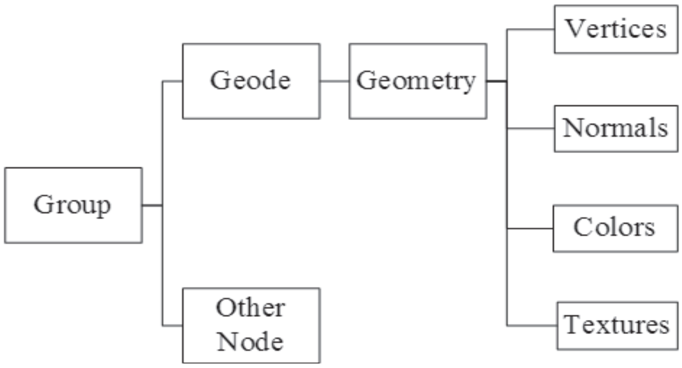

Fig. 1: Hierarchy of scene management in OSG

The scene simulation system of bridge collapse is designed to display the process of bridge collapse and provide some interactive functions for the technical appraisals for bridge collapse accidents. The animation of bridge collapse, the special effects on bridge collapse and the walkthrough for the whole virtual scene need to be developed in this system. Besides, this system is required to create the bridge scene model and the terrain model based on the corresponding files. The architecture of the system is showed in figure 2. To realize the scene simulation of bridge collapse based on OSG and Marc, the bridge scene model will be created in OSG by the Marc files firstly. Then, the animation of bridge collapse will be realized in control of the Marc files. Finally, the simple textures on bridge collapse and the primary walkthrough functions will be developed for a complete simulation. The animation of bridge collapse and the modeling of bridge scene are studied mainly in this paper, but the other work of the system requires further studies.

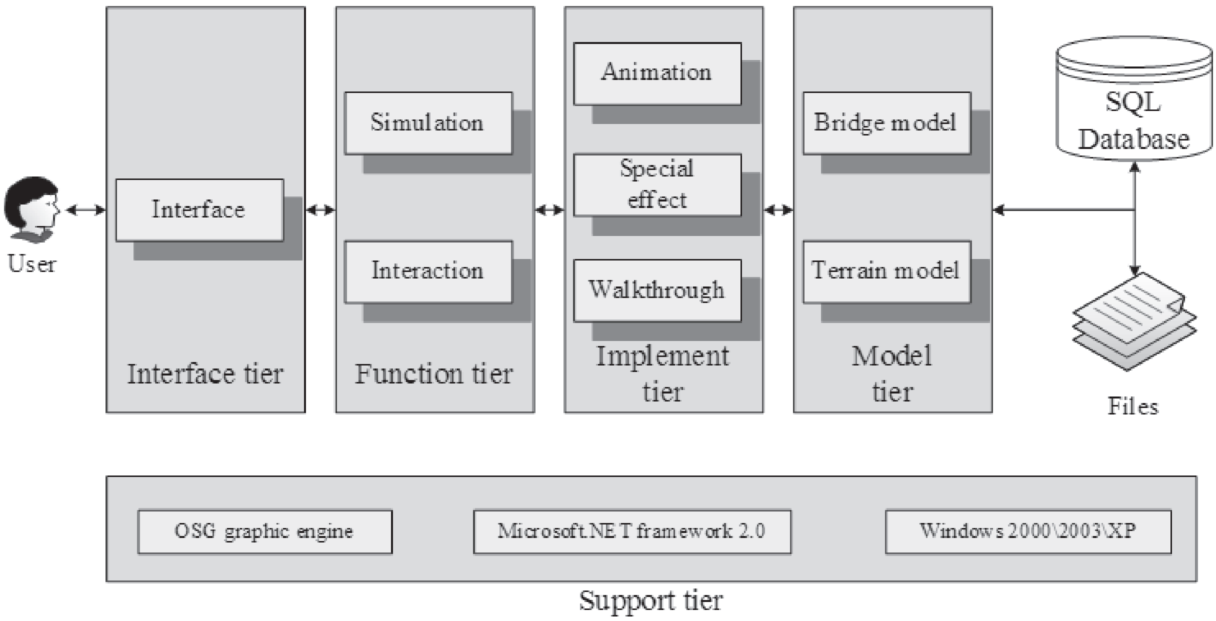

Fig. 2: Architecture of the scene simulation system of bridge collapse

4. IMPLEMENTATION

To replay the collapse simulation of Marc in OSG scene accurately, the bridge model of OSG will keep consistent with the FEM model in Marc and the animation of bridge collapse is controlled by the displacement data and the killing element data of Marc.

4.1 Bridge scene model

The bridge scene model is the basis of the animation control of bridge collapse, so the control method should be taken into account in bridge modeling.

4.1.1 Scene hierarchy

In simulation of bridge collapse, some FEM elements will be killed, so FEM elements need to be controlled in OSG. All FEM elements, including hexahedral element, polygon element and line element, should be stored in the corresponding Geometry in OSG. The whole bridge model should be stored in a Geode. In OSG, the pointer of Geometry can be gained by Geode.getDrawable(unsigned int i). The parameter i in function getDrawable(i) represents the i th Geometry in Geode and i is determined by the drawing order. So the drawing order of Geometry should be consistent with the ID numbers in Elem.txt file, for controlling all FEM elements in bridge model.

4.1.2 Drawing methods

In OSG, Vertices Array is needed for drawing geometry element. Firstly, the ID numbers of vertices of FEM elements are gained by Elem.txt file. Then the coordinates of vertices, used for making up of Vertices Array, are found in Node.txt file by the ID numbers of vertices. Finally, the FEM elements are drawn by function DrawArrays() in OSG. Vertices are not repeated in polygon element or line element, but there are many repeated vertices in hexahedral element. The six faces are drawn separately by DrawArray() and 24 vertices are needed, because DrawArrays() can not draw hexahedral element directly. In fact, there are only 8 independent vertices for the hexahedral element. For removing the repeated vertices and saving the memory, function DrawElementsUInt(), replacing Vertices Array with Index Array, is adopted for drawing hexahedral element. By Index Array, only 8 independent vertices are stored in hexahedral element. Furthermore, if one vertex moves, the corresponding polygons of hexahedral elements created by Index Array will be deformed with this vertex.

4.1.3 Render state

The Normals of all the face need to be calculated by the coordinates of vertices in OSG, because Marc can't provide Normal information. Although Normal can be worked out, the direction of Normal of polygon elements can not be determined by Marc data in the scene. As a result, some polygon elements whose Normals are unsuitable can't be seen in the scene, because of the Backface Culling in OSG. To make all the polygon elements visible, the render state set, named StateSet, should be gained from the polygon elements and the Backface Culling can be shut off in StateSet. Besides, light source for two sides of face should be open by function setTwoSided().

4.2 Bridge collapse animation

There are two important works for the animation of bridge collapse in OSG. One is to control the deformation of bridge in animation by DispOut.txt file; the other is to simulate the killed elements by DelElem.txt file.

4.2.1 Animation control

In OSG, Class Animation is designed for making animation. In Animation, there is a class for deformable models, named Morph Target Animation. However, Morph Target Animation is mainly used for the animation of human face and clothing, suitable for the model with no more than 9000 nodes (Wang and Qian, 2009), so it is not fit for the FEM model with large numbers of nodes. In this paper, the animation of bridge deformation is realized by CallBack method in OSG.

All the work in every frame is finished by CallBack in OSG. There are many kinds of CallBack in OSG, for instance, Node CallBack, Drawable CallBack, Camera CallBack and so on. DrawableUpdateCallback is one of Drawable CallBack and the function update() of DrawableUpdateCallback can be overloaded to update Geometry and realize deformation animation.

Firstly, Class DeformationUpdate is created inheriting Class DrawableUpdateCallback and the function update() of DeformationUpdate is overloaded to get the Vertices Array from Geometry in every frame by the function getVertexArray(). Then the Vertices Array is reset by the displacement data of vertices in DispOut.txt file. Finally, the Vertices Array is updated by the function dirty() in CallBack and the deformation of Geometry is realized.

To realize the deformation animation of the whole bridge, every Geometry should connect the overloaded update() by the function setUpdateCallback(). The pointer of Geometry can be gained by getDrawable() from Geode. In update(), the start time and the end time of the process of CallBack can be gained by osg::Timer::instance()->tick() to control animation time. The flow of animation control is showed in figure 3. Besides, the display mode of bridge should use the VBO (Vertex Buffer Object) for calling the memory of vertices dynamically.

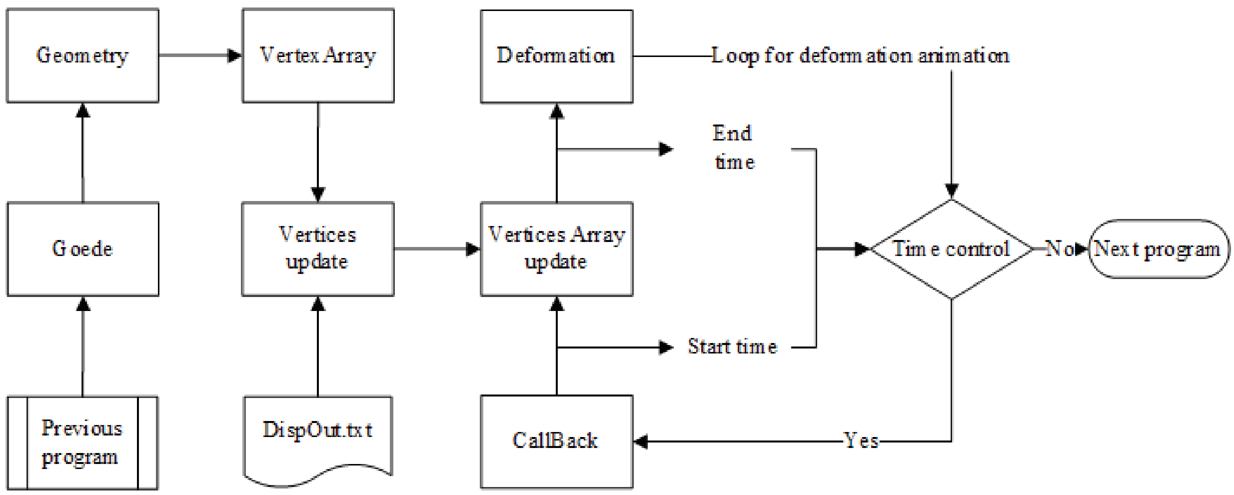

Fig. 3: Flow of the animation of bridge collapse in OSG

4.2.2 Simulation of killed elements

Some elements are killed due to large deformation in FEM simulation, so these killed elements should be invisible in the scene simulation. Geode provide the function removeDrawable() to remove elements in OSG. Once some elements are removed by removeDrawable(), the IDs of Geometry will be changed in Geode. As a result, the IDs of Geometry will not be consistent with the IDs of FEM element in Elem.txt file and Geometry will be out of control. So Switch Node of OSG is used for control the visual property to realize simulation of killed elements in this paper.

Switch can make some child nodes invisible and unused, some child nodes visible and working at the same time, like the concept of Layer (Xiao *et al,* 2010). In Node CallBack, the killed elements in every time step can be added to Switch by the function addChild(). Then the visual property of the killed elements can be set by the function setValue() in Switch, based on DelElem.txt file. The simulation of killed elements by Switch keeps the IDs of elements consistent between in scene and in Elem.txt file, and saves the computer resources, because the killed elements is unused in Switch.

5. APPLICATION

A highway bridge made of reinforced concrete is used as study case in this paper. This bridge is an arch bridge with concrete hybrid truss, whose whole length is 191.6 m and whose span is 138 m, as showed in figure 4.

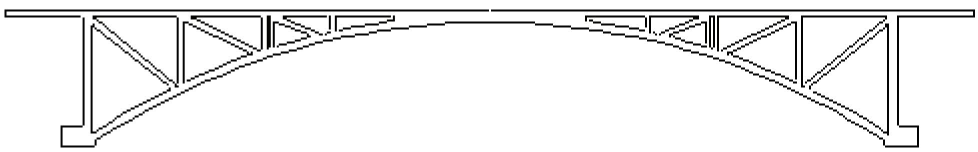

Fig. 4: Elevation of the bridge

The FEM model is created in Marc, including hexahedral element, polygon element and line element, and the total number of elements is more than 20 thousands. The dynamic simulation of bridge collapse as a result of over-loading trucks is done in Marc and the whole process of bridge collapse maintains 9.4 s. By the methods proposed by this paper, the bridge scene model is created and the animation of bridge collapse is realized in OSG. This paper compares the scene simulation in OSG with the dynamic simulation in Marc, as showed in figure 5 - figure 7.

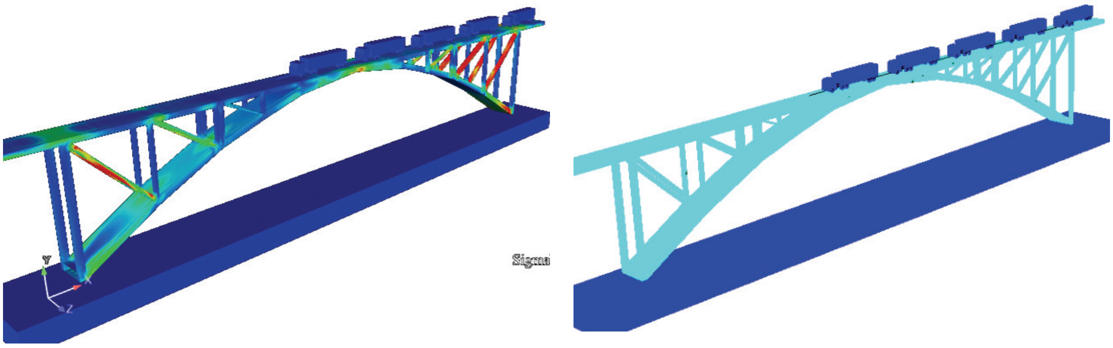

Fig. 5: The dynamic simulation in Marc and the scene simulation in OSG (2.3s)

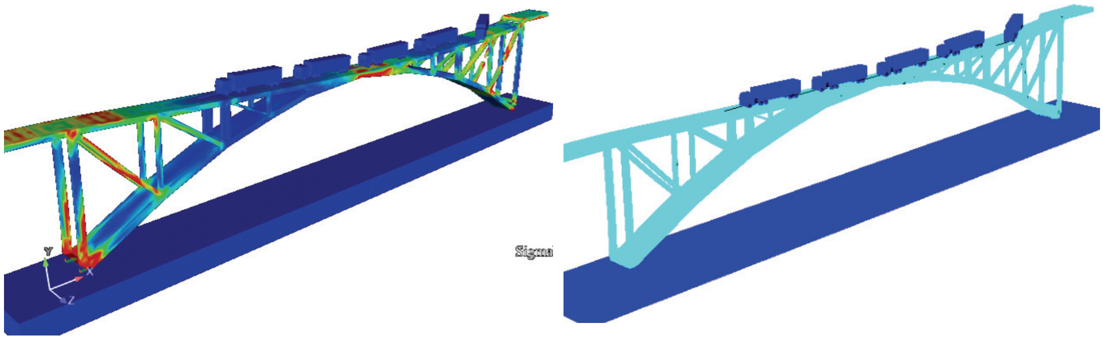

Fig. 6: The dynamic simulation in Marc and the scene simulation in OSG (7.8s)

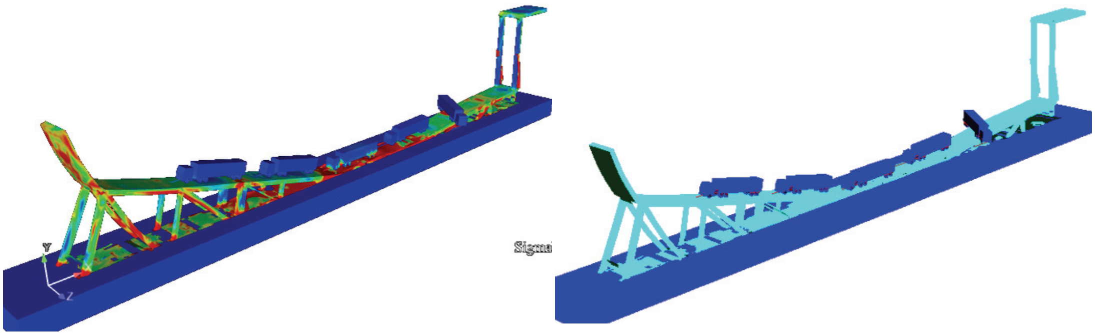

Fig. 7: The dynamic simulation in Marc and the scene simulation in OSG (9.4s)

By figure 5 to figure 7, we can find the scene simulation in OSG is consistent with the dynamic simulation in Marc and the scene simulation of bridge collapse is scientific and accurate by the method presented in this paper. However, the scene simulation above lacks realistic images, because textures, special effects and some VR technology are not applied in this simulation yet. For realistic scene simulation, the simple textures and primary scene are added into scene in OSG. Besides, a simple walkthrough system is developed for the bridge scene. The primary effects of the scene simulation of bridge collapse are showed in figure 8. From figure 8, we can find the collapsed bridge can be observed in any angle and position in OSG scene and the scene simulation of bridge collapse is realistic, but the realistic effects still need to be improved.

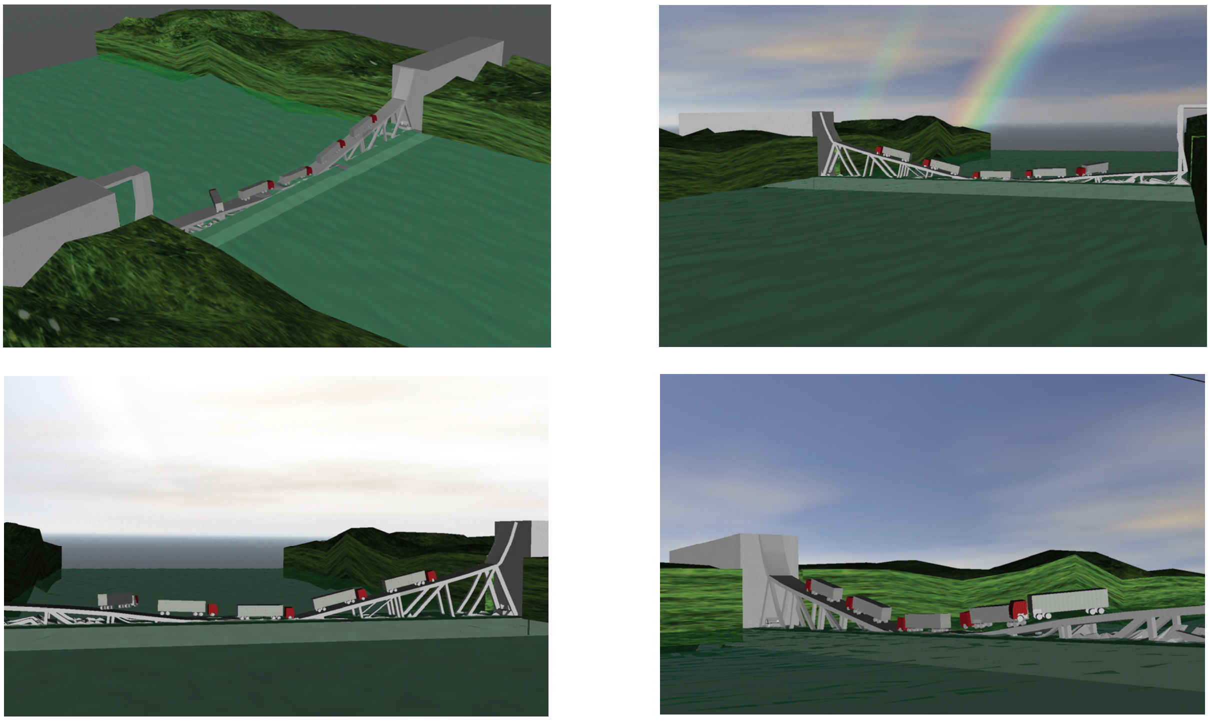

Fig. 8: Primary effects of the scene simulation of bridge collapse

6. CONCLUSIONS

By comparing the scene simulation of bridge collapse in OSG with the simulation of bridge collapse in Marc, the methods about the bridge scene modeling and the animation control based on OSG and Marc prove to be operative. The methods in this paper can be applied in the technical appraisals for bridge collapse accidents to replay the scientific and realistic accident scene of bridge collapse based on scene simulation and FEM. The special effect and the interactive functions of bridge collapse require further studies.

7. ACKNOWLEDGEMENTS

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III. AUGMENTED REALITY IN AEC

APPLICATION OF AUGMENTED REALITY TECHNOLOGY IN IMPROVING ASSEMBLY TASK PROFICIENCY

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ABSTRACT: *When referring to an activity of collecting parts/components and bringing them together through assembly operations, there is an interesting phenomenon that even though the novice assemblers have sufficient knowledge, the task performances are sometimes still poor. This could be possibly explained as the difference of assembly task proficiency between novice group and expert group. The task proficiency differentiation does not only depend on the expertise or knowledge, but on the capacity of working memory (WM) as well. The capacity of WM might help an expert assembler mentally construct the contents in assembly guidance without actually spending too much time on retrieving from it. This paper first introduces a promising alternative of enhancing the task proficiency by applying Augmented Reality (AR) technology, with which a technician can manipulate the virtual components directly inside the real environment. Then, this paper expounds the relation between spatial cognition and WM borrowing Logie's tripartite WM model (1995), and argues how the spatially augmented guidance facilitates the short-term memory of ongoing task. Last but not least, this paper introduces a developed AR animation prototype and elaborates the setup of it.*

KEYWORDS*: assembly task proficiency, working memory, Augmented Reality*

1. A REVIEW OF AUGMENTED REALITY IN ASSEMBLY

Augmented Reality (AR) is a more expansive form of Virtual Reality (VR) technology, it integrates images of virtual objects into a real world. By inserting the virtually simulated prototypes into the real environment and creating an augmented scene, AR technology could satisfy the goal of enhancing a person's perception of a virtual prototyping with real entities. This gives a virtual world a better connection to the real world, while maintaining the flexibility of the virtual world.

Through AR, an assembler can directly manipulate the virtual components while identify the potential interferences between the to-be-assembled objects and existing objects inside the real environment. Furthermore, for the purpose of better supporting the feedback of augmentation, the additional "non-situated" augmenting elements could be also added into the assembly process like recorded voice, animation, replayed video, short tips and arrows. This way, the reality being perceived is further augmented. AR is envisaged to provide great potentials in product assembly task. Some critical examples are introduced as follows: Liverani (2004) combined binary assembly tree (BAT) algorithm with the personal active assistant system (PAA) and succeeded in optimizing the product assembly sequence. Salonen et al. (2007) used AR technology in the area of industrial product assembly and developed a multi-modality system based on the commonly used AR facility, a head-mounted display (HMD), a marker-based software toolkit (ARToolKit), image tracking cameras, web cameras and a microphone. Xu and others (2008) implemented their research to realize a markerless-based registration technology, for the purpose of overcoming the inconveniences of applying markers as the carrier in assembly design process. Although a markerless-based AR system named real-time 6DOF camera pose tracking system was developed, it still could not overcome the relative technical limitations such as the radial camera distortions, perspective projection and so on. The utilization of AR technology has extended to the assembly guidance of a wide range of products, e.g., furniture assembly design (Zauner et al., 2003), toy assembly design (Tang et al., 2003), and so on (Yamada & Takata, 2007).

Notwithstanding, these research works have achieved fruitful results, there are still some issues far from being well solved in the assembly area. For instance, previous works have not completely eliminated the assemblers' cognitive workload when using AR as alternative guiding means of manuals. To most past applications, the virtual images of to-be-assembled objects are typically registered for merely reflecting the bilateral or multilateral position relations of to-be-assembled objects, but the assembly process is a dynamic process that should include the dynamic context like displacement path, spatial interference and so on. Accordingly, to acquire the sequent information context such as assembly path and fixation forms of part/component, the assemblers still need a positive cognitive retrieval after reorganizing these static augmented clews in mind.

2. USING AR ANIMATION AS A MEDIA FOR PROFICIENCY ENHANCEMENT

2.1 The prototype of Augmented Reality animation system

The general thinking is that: integrate the dynamic animation with the existing AR facility, and make them as a dynamic augmented agent to guide the assembly task. In practice, an average assembler based on manual assembly should conduct at least three-times attentional transfer within each step of the assembly operation, say among manuals (retrieving information and interpreting), workpiece stocking area (picking to-be-assembled components) and assembling area (assembling). However, the information retrieval process in AR can be integrated with assembly operation itself by reconstructing the dynamic animation as guidance in working area where an assembler' sight would mainly stay. The to-be-assembled components could be conveniently placed at the destinations in working area by following the virtual frameworks and the animated paths shown from HMD. Moreover, since the information context regarding numerous assembly steps is obliged to scatter in consecutive pages (paper carrier) due to the limited size of pages (paper-based manuals), the difficulty for information orientation is getting bigger and the continual visual transfer is needed. For example, aside from movements like picking, comparing, grasping, rotating, connecting and fixing the to-be-assembled components in workpiece stocking area (or in assembling area), assemblers cannot spare to conduct several non-assembly-related kinetic operations to cater for the guidance comprehension such as paging up or paging down, head swiveling, mouse stretching, rotating, etc. (Fig. 1). Through AR animation agent, if necessary, some certain cost-saving and non-interfered assembly paths will be preliminarily defined so that an assembler could securely follow. Here, it is hypothesized that such an idea not only works for cognitive facilitation, but also contributes to human memorial mechanism, especially the short-term memory.

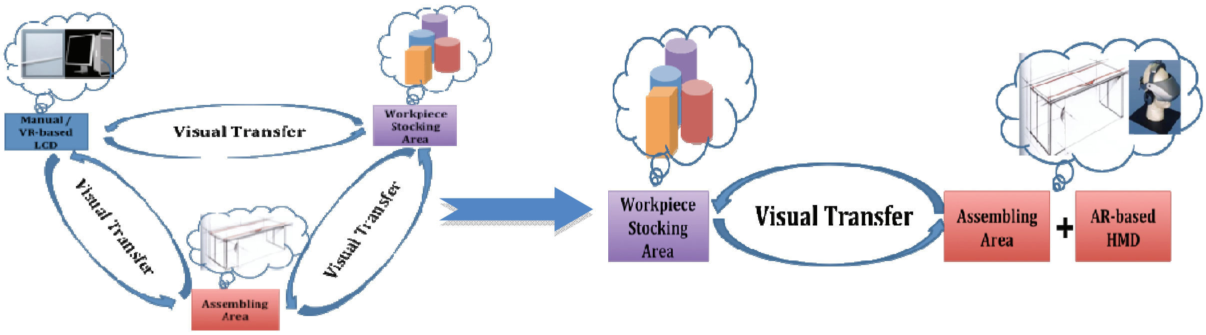

Fig. 1. A comparison of visual transfer among three means

2.2 Task Proficiency and short-term memory in assembly

Proficiency differentiation does not only depend on the expertise or knowledge, but on the capacity of short-term memory as well. A paper review has disclosed an expert assembler typically shows a good ability of information recall and reorganization from related short-term memorial sections while a novice assembler typically performs a poor capacity of that (Phillip, 2007). Such capacity might help an expert assembler mentally construct the contents in assembly guidance without actually spending too much time on retrieving from it. By comparison, an information novice typically demonstrates a high extent of dependency on it. Because of the differences in strategy of handling memorial pieces or capacity of short-term memorial store, the memory that stores previous transient physical information could be differentially retrieved in a specific time or in a specific step to the assemblers.

2.3 Short-term memory and spatial cognition

Working memory (WM) was proved to be a form of "short-term memory" or "short-term store", and reflected the capacity of maintenance and recall of short-term memorial segments in human memory. Perhaps to date, it is the limit of individual capacity of cognition and strategy difference in short-term memory storage and retrieval that embody the different level of WM. A consensus has been reached that WM has both storage and processing functions, and it enables both the temporary maintenance of active representations in memory and manipulation of these representations in the service of current processing demands. A review of bypass WM models is helpful to facilitate this research by understanding the mechanism of how WM functions in information store and retrieval.

2.3.1 WORKING MEMORY MODELS

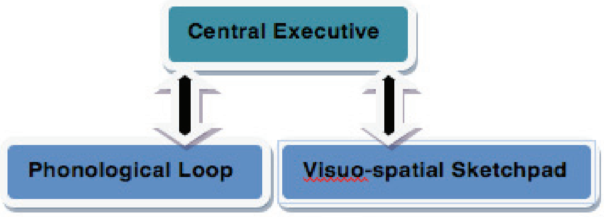

Fig. 2: A tripartite WM model by Baddeley and Hitch (1975)

The Baddeley and Hitch model (1975) as shown in figure 2 is a multi-component WM model comprised by two subsystems, phonological loop and visuo-spatial sketchpad, and a supervisory system, central executive. The phonological loop stores short-term phonological information (maintains speech-based information) and prevents decay by articulatory rehearsal while the visuo-spatial sketchpad stores brief visual and spatial information and prevents decay by visual-spatial rehearsal process. Functioning as an attention controller, central executive is responsible for directing attention to relevant information, suppressing irrelevant information and inappropriate actions, and for coordinating cognitive processes when more than one task must be done at the same time. The visual-spatial sketchpad can be further divided into visual and spatial components that respectively handle shape, color, texture and loci information. One of the deficiencies of their model was it could not explicitly reflect the relations between WM and long-term memory. The concept of episodic memory was put forward in Baddeley's learning theory (2000) to explain the principle of memory recall. That is, if one is to retrieve a specific episode, then he/she must have a means of specifying that episode, and the most likely mechanism would seem to be via the use of context. This learning mechanism is able to explain why AR animation prototype could contribute to novice training. Via providing the consecutive assembly information context (stimuli) in AR animation prototype, e.g. recorded voice, animation, replayed video, short tips and arrows, links between different contexts and stimuli seem to allow one memorial section to evoke others with more ease, and hence form a most active and successful areas of recent memory recall span. Should the assembly expertise be engraved and recalled to use by the novice assemblers once and again, they would be closer to the expert assemblers. Here, an improved WM model was carried out below.

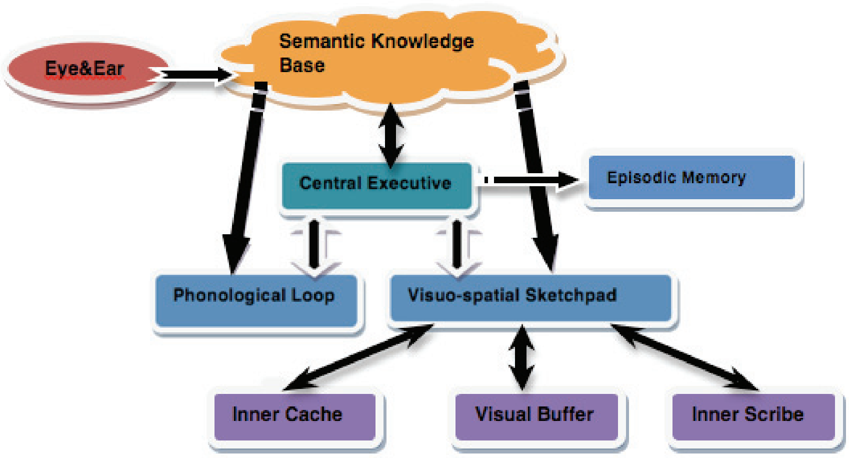

Fig. 3: An improved tripartite WM model by Logie (1995)

In this improved version as shown in figure 3, phonological loop is in charge of sub-vocal rehearsal and prevents memory decay by continuously articulating contents. This process is capable of maintaining the material in the phonological store by a recycling process, and in addition, is able to feed information into the store by a process of sub-vocalization. Similarly, visuo-spatial sketchpad is to construct and manipulate mental map via the providence of memorial agents such as shape, color, texture and location. Such a mechanism is also precisely consistent with the thread of AR animation prototype mentioned above. That is, vocal tips are effective to stimulate the assemblers' memorial system, enable a potential sub-vocalization to the assemblers and strengthen their memory of assembly expertise gained in assembly task. Also, shape, color, texture and loci information of real and virtual components can be as the visuo-spatial stimuli from real and virtual environment, which could be easier to be refreshed, responsible for involving a brief memorial store and be capable of evoking memorial links through the augmented feature in AR animation interface. Once the images are imported into assembler's visual buffer, they will start to decay rapidly. However, a necessary adoption of rehearsal mechanism could regenerate the images continually and preserve them from decay in buffer. The providence of three extra sub-components of visuo-spatial sketchpad can conveniently explain the application of spatial images and maintenance of visual representations. For example, visual buffer utilized as visual information entrance is supported by the visual cache and inner scribe, which respectively act as a temporary back-up store and functionality for encoding of spatial loci (Andrade et al., 1997).

2.3.2 Retrieval mechanism and WM

In assembly task, different guidance enables assembly information context to input the WM buffer in forms of different stream and shape diverse memory representations. Generally, when specific memory buffer is strengthened and reinforced by constant spatial information input, this buffer could be refreshed and become available in a temporary manipulation during cognitive task. When resuming the information retrieval process, the more activated memorial section will be easier to be first retrieved in phonological loop or visuo-spatial sketchpad, and be linked together later to output all the items with the right sequence (Brown, 1997). Another scrutinized evidence has proved that visuo-spatial processing occurs more easily than phonological processing after stimuli (Comoldi & Vecchi, 2003). These reviewed evidences seem to provide a good speculation that using AR animation as assembly guidance through real-scaled visuo-spatial animation input might make the memory representations in mind easier to be retrieved as reflected in retrieval integrality and sequence correctness of retrieved items than others.

Resource and speed-limited theory

Rosen and Engle (1994) further disclosed a close phenomenon that the attention-demanding task could hurt the performance of information maintenance in their experiments. According to an observation to people's performance of remembering words of different span, Turner and Engle (1989) detected the differences among people's performance were due to a difference of cognitive resource, as high-span people would be able to use their greater resource to overcome the effect of such a load. Besides, an analogous experiment conducted later by Rosen and Engle (1994) also discovered that people defined as high or low in WM did not differ greatly in terms of automatic strategy of memorization but differed greatly in terms of amount of controlled or intentional resource. These fruitful research outcomes brought up the predecessor of resource-limited theory, which first appeared as the "inhibition resource theory" (Rosen & Engle, 1994). Via investigating the cognition changes of people of different ages, Salthouse (1991) found that one of the most influential interpretations of age effects on WM was the difference in rehearsal speed of memorial representations (speed-limited theory). This theory is explained as that cognition change in ages is best conceptualized in terms of decreases in the general speed of information rehearsal, and there has an upper level for rehearsal speed to the specific age group.

In order to explain the human WM with the help of AR animation, I intentionally formulate the resource and speed-limited theory on the basis of the combination of resource-limited and speed-limited theories. This derived theory is envisaged to provide the theoretical support for the plausibility of using AR animation as an agent for WM improvement by interpreting the rehearsal mechanism (refresh mechanism). It is not difficult to learn through AR animation means, more usable cognitive resource could be set aside and utilized in WM model via largely lowering the cognitive workload. People with more cognitive resource would be better able to memorize the relevant information via restraining the irrelevant one at intervals. This guarantees the assemblers sufficient refreshment intervals when they are concurrently retrieving visuo-spatial context (cognitive processing) and assembling components (motor processing) based on what they have retrieved. Therefore, they could remember previously retrieved context more easily and recognize the particular clue as one that had been previously exhibited in a specific time and place.

Retrieval competition theory

The formulation of retrieval competition theory originates from Hasher and Zacks (1988), who confirmed that human performance would be good if the retrieved representations were closely tied to the goals of ongoing task. This explanation refers to an inhibitory mechanism of irrelevant retrieval of memorial representations (a competition between irrelevant and relevant material at the time of encoding). In the sense that if the inhibitory mechanism is poor, the ultimate consequence of information retrieval would be an increase in irrelevant or marginally relevant ideas in WM, thus dividing attention and producing interference. This mechanism serves to restrict the contents of WM to information that is relevant to the task being carried out at the time (Hasher & Zacks, 1988). They also argued that because WM was limited in terms of the amount of information that can be held, there was less task-relevant information available when the competition between relevant and irrelevant retrieval was more intensive. Besides, competition could also slow down the immediate retrieval during the memorial searching. A typical case of this is giving speech, during which a presentor should try to maintain the content coherence by suppressing the improvisational retrieval of non-speech relative materials (a process of interference inhibition). This was regarded as the predecessor of retrieval competition theory.

The retrieval of a specific plot of information context may be blocked by the randomly increased activation of other different plots. Based on the retrieval competition theory, the key to successful processing is to suppress the irrelevant information from WM, which is actually allowing the relevant information to enter WM. The best bet is considered to be the introduction of augmented step-by-step assembly guidance, which can be technically realized by AR animation. Here, a concept called "connectionism" (a mechanism of forming association) is aided to explain this (Brown, 1997). The amount of short-term memorial communication among a serial of representations depends on the "strength" of the connection, and the level of activation of one representation is determined by all the activations that it receives from other representations. This memorial impact that one representation has on another depends on both the extent of its own activation level and the strength of the connection between the two representations. As a result of this simple mechanism, specific activation over a serial of memorial representations can give rise to a pattern of activation of another memorial representation. If each of these patterns of activation can be regarded as representing one representation, then the provision of this representation can lead to the retrieval of another. In AR animation, when each augmented step of assembly becomes represented on the next one, memorial activation will spread through the connectionism until the whole memorial chain is established. To some extent, this alleviates the competition effect and increases performance of short-term recall.

2.3.3 Spatial cognition and WM

The definition of spatial cognition could be typically associated with comprehending geometric properties such as distance and size, as well as physical properties such as color, texture, mass, etc. AR creates a framework of associations that aids recall and learning, called the spatially augmented stimuli (e.g., an array of callouts and attached parameters in a workpiece scene). Each association of a virtual object with a workpiece feature is a basis for linking memorial pieces in human memory. When starting recall process, the subject "mentally walks" onto the links. As he or she encounters the artificial hints or landmarks, the item associated with the landmark also appears, and is therefore available to WM. Using an augmentation interface to do assembly guidance in AR condition, the real and virtual components can be "held in hand", while the assembly paths, sequences and fitting relations can also be "shown in hand". In the real assembly task, these elements can be triggered as by-products of the enhanced workpiece scenes and are more subject to the visuo-spatial sketchpad. According to Logie's theory (1995), a system that incorporates an "inner eye" and "inner scribe", which have direct links with the processes that underlie visual perception and enable visual materials to be maintained by a form of visual rehearsal respectively, possibly supports visual WM. In AR animation prototype, visual spatial perception can be embodied by the visual virtual images of the to-be-assembled objects while the visual rehearsal is processed by the step-by-step assembly operations of real components. Therefore, visuo-spatial assembly representations are relative to their materialized real components. When engaged in this relevance, users' short-term memory could be strengthened through the visuo-spatial cognition mechanism.

3. SYSTEM SETUP

Our prototype is based on marker registration technology and uses animation as its agent. The AR animation interface for assembly application provides the relevant information about the next components to be mounted. It outputs the current assembling step so that the assembler is aware of his/her progress, i.e., what was and needs to be mounted. The position of the next components allows the movement from the current location to the target location without bumping into the already assembled components. Technologically, the traditional marker-based method is not discarded. Firstly, the prototype involves the effective setup and implementation of AR facility, including a computer monitor, pre-defined paper-based markers, an interactive computer graphics modeling, animation and rendering software (3ds-max), ARToolKit and attached OpenGL. Next, the virtual counterparts of real entities are acquired from 3ds-max and then plugged into ARTookKit via a developed interface by Ozzy in 2010. Following, the locomotion along virtual assembly path of each virtual component and the methodological hints for assembling are registered into the real components by using the ARToolKit and paper-based markers. Last but not least, the significant parameters of the to-be-assembled and assembled objects are graphically synchronized shown as the forms of hint and notation, e.g., part/component texture, weight, color, specification and so on.

3.1 Hardware setup

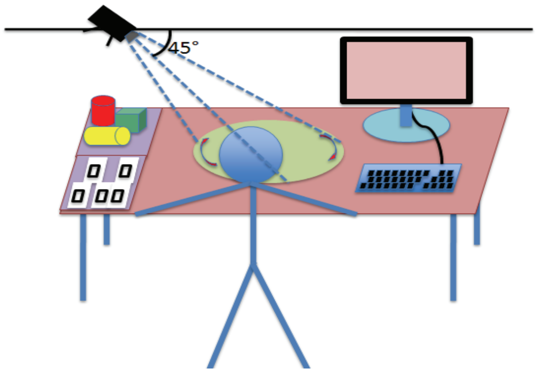

Fig. 4: Hardware setup and system layout design

Rotatable workbench (assembling area)

This is where the assembly process is executed and the markers are positioned. The size of the workbench is big enough to sustain the product components and the markers as well. When starting assembly, assemblers lay the markers on the surface of the workbench, so the animation could be shown on the monitor. Since defined as real-scaled, the images of virtual components are able to spatially coincide with the real components of ongoing task. Besides, the rotatable workbench eases assemblers' observation from different angles and facilitates their operations from most convenient direction.

Monitor

It is placed in the top right corner of the workbench, showing the guidance of AR animation. When running the system, the assemblers are able to execute the assembly process while have a quick view of the screen synchronously.

Tracking camera

It is located in the upper-left corner of 45 degrees, projecting to the rotatable workbench. By tracking the pre-defined markers, the customized animated guidance could be displayed on monitor. Generally, the images captured from the set of 45 degrees tracking camera are possibly to arise the spatial perception as human eyes see an ordinary object in 3D space.

Keyboard

Keyboard is to provide the assemblers with function keys to control the animation play, pause and the replay of key frames.

Paper-based markers

Markers are all trained under ARToolKit. One marker is used to animate the process throughout the entire product assembly, while other markers are designed for the specific steps. Considering the entire information flow is too crowded to see in one marker, some aided markers will be necessarily applied.

Assembly task

The dumper of LEGO TECHNIC tilting car (Model No.8263) is selected as experimental prototype (Fig. 5). This part consists of 65 spatially functioning pieces and some of them have specific shapes and colors (Fig. 6). These components are detached in advance and kept in a specific region, which I define as "workpiece stocking area" in the top left corner of the workbench. The complexity of assembly task is controlled at the point that without any means of guidance, an average person is hard to complete in a certain period of time. Also, since some components are similar in shape but of tiny dimensional discrepancies, assemblers need to compare under the guidance before they can select correctly. Therefore, blind attempts under no guidance could not possibly lead to a final product.

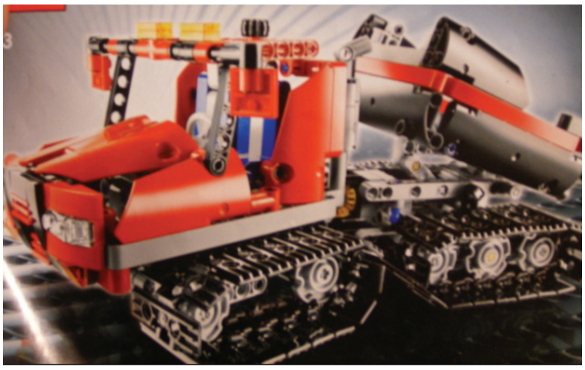

Fig. 5. A snapshot of LEGO TECHNIC tilting car (Model No.8263)

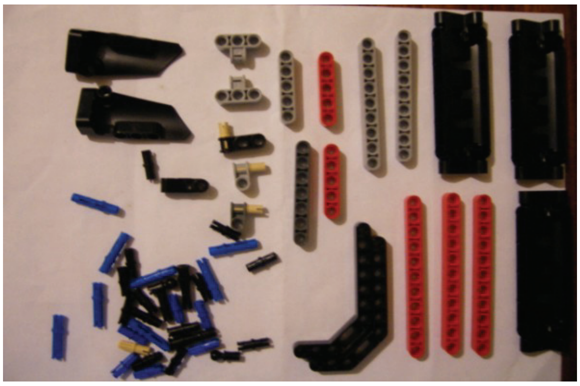

Fig. 6. Components of dumper of LEGO TECHNIC tilting car (Model No.8263)

3.2 Software setup

AR animation interface development

The AR animation interface is built on the ARToolkit framework and OpenGL, and it provides functions that could load files with a *.3ds extension. It realizes the interface between ARToolKit and any drafting software that could export *.3ds file, and the user is facilitated by directly generating animation via 3ds-max or Maya. By saving files as *.3ds format via the self-attached exporter, the animation could be imported to AR system and recognized by the pre-defined markers without applying the specialized exporter like OSGExp. Originally, this interface only supported the loading of single marker, the recognizing of one animation and the controlling of frame of one animation. With the aim of recognizing multi-markers, we dynamic add scripting based on C++ code and apply the marker training method provided by traditional ARToolKit, where the context of multi markers is stored in a structure and is resumed by new calling functions later. For the purpose of registering animations in multi markers, different classes are defined, with each of them in charge of a separate marker registration. This way, adding or deleting any one of the markers is merely through adding or invalidating the specific class. Last but not least, according to the control of a public variable "Frame", animation on each marker can be easily handled via keyboard.

Virtual images and animation development

The virtual components of LEGO TECHNIC tilting car (Model No.8263) and the animation of assembly process are created via 3ds-max. A marker (pattern "Hiro") presents 65 virtual versions of physical functioning pieces that are used for dump assembly (Fig. 7). Another marker (pattern "人") animates the entire assembly process, where the proper assembly method and sequence are defined to make sure the assembly paths of to-be-assembled components have no interference (Fig. 8). Special hints are used in specific steps, e.g., red arrow.

Fig. 7. 65 virtual components on paper-based marker

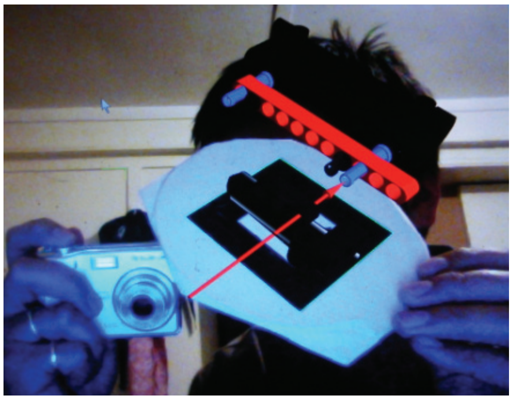

Fig. 8. (a)

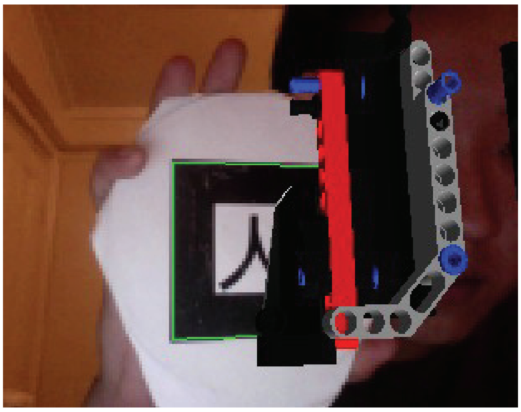

Fig. 8. (b)

Fig. 8. (c)

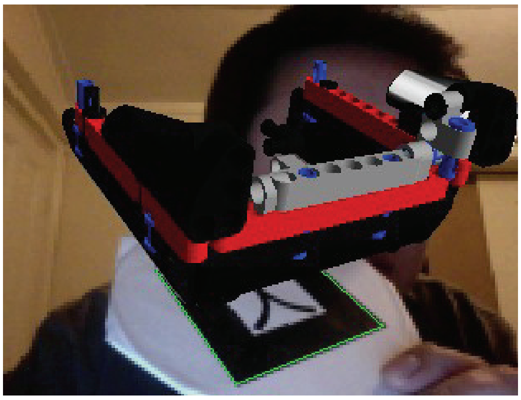

Fig. 8. (d)

(a) Red arrow as path hint in pin-hold assembly step

(b) Completion of right part of dump assembly

(c) Completion of left, right and front parts of dump assembly

(d) Completion of entire dump assembly

4. EXPERIMENT DESIGN

The target of experiment is to investigate if task proficiency is increased from AR animation to real work task. According to the theory that working memory is involved in decision-making (Richardson et al., 1996), the capacity of working memory may reflect the time taken for the properties of the stimulus to be gleaned and for that interpreted information to become available and be processed. Also, such a decision-making could reflect the motor performance such as error rate for components option and incorrect trials. Therefore, the experimentation is designed like that: we intentionally hide some specific guiding steps in manuals and in AR, and to the assemblers they should decide what should be installed in those steps and how to install according their subjective recalling for information context from previous assembly. During this, camera is used to record their performance.

5. CONCLUDING REMARKS

The next step we are going to carry out is the experimentation, from which we expect to attain a conclusion that AR animation assembly guidance is of an average effect of lowering cognitive workload than manuals and people who are trained under AR animation (compared with manuals) are capable of gaining more usable cognitive resource and are of more and longer mental resource rehearsal, which might further facilitate human WM memory.

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Functional Requirement of an AR System for Supervision, Commenting, and Strategizing in Construction

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ABSTRACT: *The main purpose of this study has been to comprehensively establish the detailed functional requirement of an AR system called the ARPad for supervision, commenting and strategizing, which are some of the AR application areas in construction identified in a previous study by one of the authors. The previous study suggested the two AR system concepts (AR design renderer and AR coordinator). The three works tasks (supervision, commenting and strategizing) which this study focuses on were found to be appropriate with the system concept of AR design renderer in the previous study. Even though the general functional requirements for AR design renderer are identified in the previous study, they are not specific enough for the realization of the ARPad tailored for the three work tasks. In order to develop the ARPad from the system concept of AR design renderer, the functional requirements of the three work tasks must be more detailed. In this study, the detailed functional requirements of three work tasks are investigated through the interviews with experts in construction. Based on the detailed functional requirements, the ARPad system will be created in the CoSIL (Construction System Innovation Lab) at INHA University. The ARPad will reduce the interference on site, the inefficient use of time and construction cost.*

KEYWORDS*: Augmented reality, Functional requirement, Supervision, Commenting, Strategizing, Construction*

1. INTRODUCTION

Augmented Reality (AR) is an advanced computer-based visualization technology that has the potential to provide a significant advantage in the Architecture, Engineering and Construction (AEC) industry. Most of the studies on AR in the AEC industry have suggested feasibility of AR technologies based on a limited investigation of individual AEC tasks. However, realization of the use of this technology requires not only demonstration of feasibility but also validation of its suitability. This requirement indicates the necessity of the comprehensive identification of AR application areas in AEC based on the suitability of AR technologies. From this requirement, in a previous study by one of the authors (Shin and Dunston 2008), the AR application areas were identified in the construction phase based on the suitability of AR technologies. The previous study revealed that eight work tasks (layout, excavation, positioning, inspection, coordination, supervision, commenting, and strategizing) out of 17 classified work tasks may potentially benefit from AR support. On the other hand, the other work tasks (penetrating, conveying, cutting, placing, connecting, spreading, finishing, spraying and covering) had no advantages with AR technology. The previous study also suggested the two primary AR system concepts, the *AR design renderer* and *AR coordinator*, to support the eight work tasks.

Based on the *AR design renderer* concept, an AR system called the ARPad for supervision, commenting, and strategizing is under development in the CoSIL (Construction System Innovation Lab) at Inha University. These three work tasks have been focused on in the development of the ARPad because they allow relatively large tolerances in the accuracy of the image registration. Due to the large tolerances, it is relatively easy to practically realize an AR system for the three work tasks, out of consideration for the current limitations of AR technologies such as tracking and calibration.

The ARPad will enable the three work tasks to be conducted more efficiently by providing visual information required for them in more effective formats. As a result, the development of ARPad will reduce the interference on site, the inefficient use of time and construction cost.

The main purpose of this study is to investigate the detailed functions required in the ARPad for supervision, commenting, and strategizing. This investigation is the first step of the development of the ARPad. The detailed functions are identified through the interviews with construction managers, supervisors, and foremen on the processes and human factor issues of the three work tasks and the expected usability of the ARPad. The interviewees have experience of plant construction. The findings of the study are fundamental to success in developing the ARPad. Based on the detailed functions identified in this study, the ARPad system will be created in the CoSIL. The benefits of the ARPad will be also experimentally evaluated. The adoption of AR in AEC will be facilitated by quantifiably demonstrating the benefits of AR in tasks with AR systems such as the ARPad.

2. SUPERVISION, COMMENTING AND STRATEGIZING

As mentioned in the introduction, the previous study by one of the authors (Shin and Dunston 2008) identified the AR application areas in the construction phase based on the task-technology fit (Goodhue and Thomson 1995). AR application areas have potential benefit that is revealed in eight work tasks out of 17 classified work tasks. Among these eight work tasks, the authors decided on three work tasks (supervision, commenting and strategizing) for the development subject of ARPad due to the technical limitation as mentioned above. The processes and AR-based solutions of the three work tasks found in the previous study (Shin and Dunston 2008) are summarized in Table 1.

Table 1: Process and AR-based solution of supervision, commenting and strategizing (Shin and Dunston 2008)

Supervision (Definition: Seeing if works is performed as planned)	
Process	Supervisors scrutinize whether work is processed as planned by referring to design drawings and specifications. This process typically involves converting 2D drawings and specification requirements to a 3D mental image of the work process in terms of necessary tasks and resources. The mental image is situated by reference to location cues in the real work site.
Solution	The 3D design of a desired area, which is rendered spatially onto a site in actual scale, location and orientation, with virtual contextual data of specification requirements rendered in correct location may reduce the work load for supervision significantly because it allows the supervisors to see the solid 3D drawing and contextual data from the specification requirements in a real 3D space without inferring or searching them from the 2D drawings and specifications.
Commenting (Definition: Conveying supplementary information regarding a task)	
Process	Inspectors or field personnel convey some comments about a task to field personnel or foremen through a face-to-face communication to ensure the comments are understood. The communication is typically accompanied by supporting gestures (i.e. pointing), observing work areas and sharing relevant drawings and specification requirements. For sharing design drawings and specification requirements, inspectors, field personnel and foremen typically need to mentally convert 2D drawings and specification requirements to 3D image in a real 3D space. This is discussed in the supervision section.
Solution	The 3D design of a desired area, which is rendered spatially onto a site, with virtual contextual data from specification requirements rendered in correct location may significantly reduce work load for commenting and prevent misunderstanding of others' comments. Inspectors, field personnel, and foremen can see the solid 3D drawing and contextual data of specification requirements in a real 3D space without inferring or seeking them from the 2D drawings and specifications.
Strategizing (Definition: Figuring out the detailed procedures for specific tasks)	
Process	While coordination is to discuss and determine upcoming work flows or resource allocation among activities, strategizing is to figure out detailed procedures for a specific construction activity. For strategizing, foremen infer a 3D mental image of the process of a desired work in terms of necessary tasks and resources, typically based on 2D design drawings and specification requirements, as mentioned in the supervision section. The mental image is situated by reference to location cues in the real work site.
Solution	A 3D design of a desired work, which is rendered onto the work site in actual scale, orientation and location, with virtual contextual data from specification requirements in correct location may free workers from inferring the 3D image of the work process in a real 3D space from the 2D drawings and specifications, thus significantly reducing the work load for strategizing.

The previous study (Shin and Dunston 2008) suggested the two AR system concepts (*AR design renderer* and *AR coordinator*) for the eight work tasks which were found to have potentially benefits from AR. The three works tasks (supervision, commenting and strategizing) which this study focuses on were also found to be appropriate with the system concept of *AR design renderer* in the previous study. Shin and Dunston (2008) also derived the general functional requirements of *AR design renderer* (as summarized in Table 2) from the AR-based solutions of work tasks such as solutions in Table 1. However, the realization of the ARPad tailored for the three work tasks from the concept of *AR design renderer* requires more details on the functional requirements for the work tasks beyond the general requirements of *AR design renderer*.

Table 2: General functional requirements of *AR design renderer* (from Shin and Dunston 2008)

AR system concept	General functional requirements
AR design renderer	・Following the user's viewpoint by means of a tracing system ・Superimposing virtual objects onto user's view of a real world scene ・Rendering combined images of virtual objects and a real world in real time ・Locating virtual objects in a real world scene in correct scale, location and orientation

3. INVESTIGATION ON FUNCTIONAL REQUIREMENTS

In order to develop the ARPad from the system concept of *AR design renderer*, the functional requirements of the three work tasks must be more detailed.

3.1 Investigation methodology

In this study, the detailed functional requirements of three tasks were investigated through interviews with experts in the field. The experts involved in the interview consisted of 4 construction engineers from construction firms in South Korea; one with over 25 years experience in plant construction works, one with over 10 years experience, one with over five years experience and one with one year experience. The interview process was conducted via face-to-face talk or e-mail based on the three-step questions as shown Fig. 1. The questions were designed to make the interviewees to deeply think of an opportunity of a new technology, AR in the practice and suggest valuable ideas for functional requirements of the work tasks on an AR system, instead of just adversely avoiding or resisting to the idea of the adoption of AR in construction.

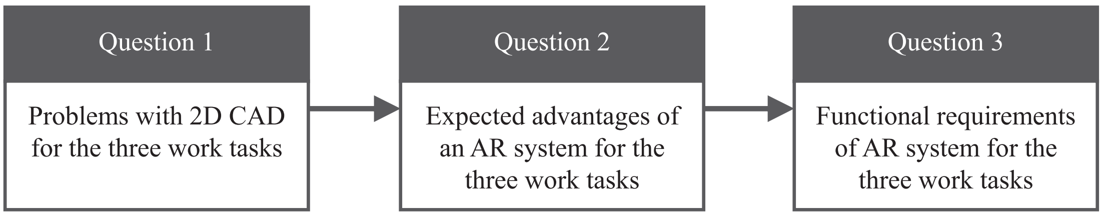

Fig. 1: Three-step questions in the interviews

3.2 Investigation results

Table 3 shows the detailed functional requirement of the AR system for the three work tasks found from the interviews.

Table 3: Detailed functional requirement of AR system for three work tasks

Supervision	
Functional requirement	・Visualizing as the unique color on each trade (civil, mechanic, electronic, and etc.) to the 3D model ・Visualizing only the 3D model of one's trade ・Visualizing drawings of all of trades to the 3D model in order to preview an interference ・Alerting to the 3D model when presented a different work result in comparison with drawings ・Visualizing specifications of the requisite work trade to the 3D model ・Visualizing the schedule information for each work activity to the 3D model ・Visualizing drawings of performed works during requisite period to the 3D model ・Visualizing the sequence of work task in order to comprehend the overall progress of project ・Specifying on the drawing the problems found to be caused by difficulties in interference or construction, and visualizing the situation in a manner that enables every project manager to check
Commenting	
Functional requirement	・Visualizing as the unique color on each trade (civil, mechanic, electronic, and etc.) to the 3D model ・Visualizing only the 3D model of one's trade ・Alerting to the 3D model when presented a different work result in comparison with drawings ・Visualizing the schedule information for each work activity to the 3D model ・Grasping working progress situation of close activities, and the relevant antecedent and consequent activities ・Visualizing drawings of performed works during requisite period to the 3D model ・Scrolling and pointing using touch technology ・Specifying on the drawing the problems found to be caused by difficulties in interference or

	construction, and visualizing the situation in a manner that enables every project manager to check
Strategizing	
Functional requirement	・Visualizing as the unique color on each trade (civil, mechanic, electronic, and etc.) to the 3D model ・Visualizing only the 3D model of one's trade ・Visualizing the schedule information for each work activity to the 3D model ・Grasping working progress situation of close activities, and the relevant antecedent and consequent activities ・Visualizing the activity to be constructed in real-time 3D drawing

Especially, from Table 3, it has been found that preventing interference among each trade is a main requirement which is commonly applied in the three work tasks. From reviewing comments of the interviewees, the rework caused by interference is revealed to be the most significant problem in construction practice. Because supervisors and foremen carried their own heavy 2D drawings, they do not know about the changes caused by other trades, thus not recognizing interferences. Therefore, an AR system for supervision, commenting, and strategizing should be developed focusing on a detailed function to prevent interference. In addition to this function for interferences, the detailed functions found in Table 3 also should be reflected in the development of an AR system for the three work tasks.

4. THE SCHEME AND CONFIGURATION OF ARPad

The ARPad will be developed in the four steps as illustrated in Fig. 2. As the first step for the development of the ARPad, the detailed functions that the three work tasks (supervision, commenting and strategizing) require in the system are understood in this study. .

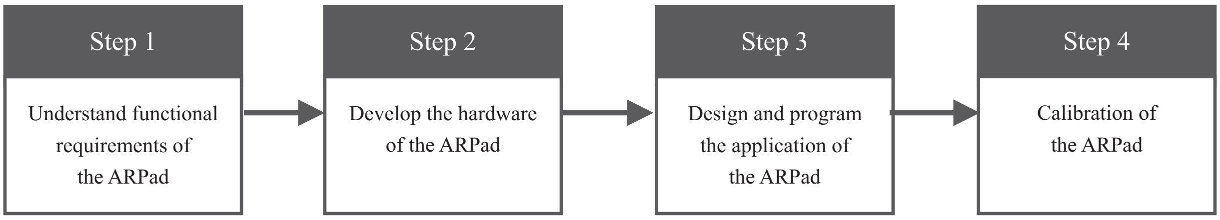

Fig. 2: Four steps of the development of the ARPad

The second step in the development of the ARPad is to construct the system hardware by reflecting the functional requirements found in the study. While this will be understood in more detail in the advanced analysis, the conditions of the construction site should be well reflected in both the engineering and the making of the system. The hardware of the ARPad will be composed of a tracker, video camera and mobile computer. The tracker is to track the viewpoint of the video camera in real time, and the video camera is to capture real images. The mobile computer runs the application which produces the AR scene based on the viewpoint of the video camera from the tracker and the real world scene from the video camera. Fig. 3 conceptually shows the system components of the ARPad.

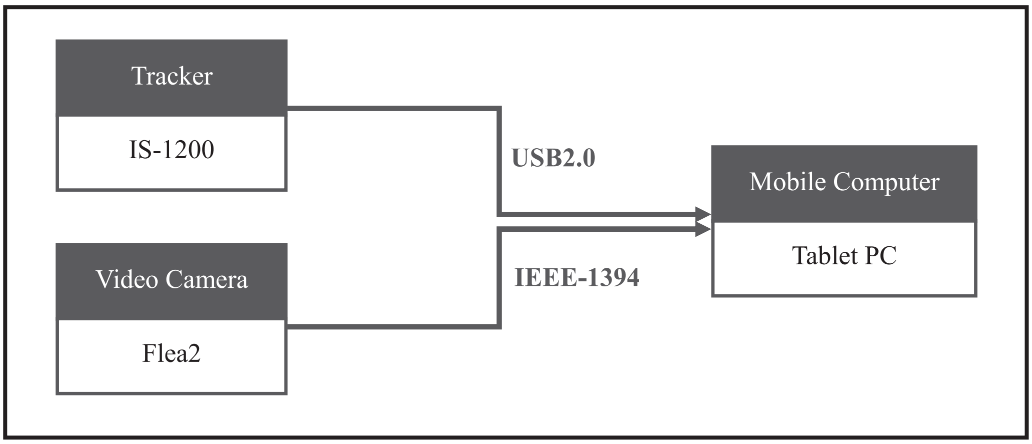

Fig. 3: System components of the ARPad

For the tracker, the IS-1200 from InterSense will be employed due to its mobility and accuracy. The IS-1200 is expected to be suitable to the construction site, because it provides a high accuracy in tracking the position (2-5 mm RMS) and orientation (0.1° RMS) of a sensor with a computer vision based on fiducial markers while continuously tracking with an inertia mechanism even if it meets obstacles between a sensor and markers. The IS-1200 is connected to the mobile computer through the USB 2.0 connection. For the video camera, the Flea2 from Point Grey Research will be used because it is small and light-weighted, and supports a good resolution of 1288 x 964 and 30 FPS. Using the Flea2, the real world scene is captured and transmitted to the mobile computer through the IEEE-1394 connection. The mobile computer has to operate the tracker and the video camera while running the application in real time. Therefore, the mobile computer requires a high mobility and computing performance. A laptop provides a limited usability in a mobile environment, while a small computing device such as a PDA provides a low computing performance. Thus, the researchers decided to use a tablet PC, which provides a high mobility and a moderate computing performance, for the ARPad.

The third step in the development of the ARPad is to create the application which runs in the mobile computer. The application will modify the 3D CAD drawing in real time according to the changing viewpoint based on the tracking measurements obtained via the IS-1200 tracker. This feature works as though a live scene of a virtual 3D object in a virtual space is taken with a virtual camera that moves following the viewpoint of the real video camera. The application will combine the modified 3D CAD drawing with a live video stream of a real world scene from the video camera so as to produce the AR images of a 3D CAD drawing superimposed in real time onto the real world scene. The AR images will be displayed on the screen of the mobile computer.

The fourth step in the development of the ARPad is to calibrate the system. For compelling AR images, the viewpoints and the view volumes of the video camera and the virtual camera have to be identical, respectively. For this requirement, the intrinsic and extrinsic parameters of the virtual camera which are the same with those of the video camera will be found through the calibration. Calibration processes for the AR environment are generally tedious and laborious. To reduce time and labor for the calibration, the authors plan to adopt a semi-automatic approach in the calibration process for the ARPad. The semi-automatic approach will automatically capture the pixel points of the reference points from video images for the calibration, which would require significant time and labor if conducted manually.

5. CONCLUSION AND FUTURE WORK

This study investigated the detailed functional requirements of an AR system for supervision, commenting and strategizing in the AR application areas in construction. These three work tasks have been focused on in the development of an AR system called the ARPad because they allow relatively large tolerances in the accuracy of the image registration. As the first step of the development of the ARPad, several functional requirements for the three work tasks were found in the study through the interviews with experts in construction. Especially, from reviewing comments of the interviewees, the rework caused by interference is revealed to be the most significant problem in construction practice. Therefore, the function to prevent interferences is fundamental to the success of developing the ARPad. The other detailed functions found from the interviews also should be reflected in the development of the ARPad.

In a future study, the researchers will develop a system prototype of the ARPad for three work tasks based on the detailed functional requirements revealed in the study. The ARPad will reduce interference on site and the inefficient use of time and construction cost, by providing visual information required for the tasks in more effective formats.

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Bored Pile Construction Visualization by Enhanced Production-Line Chart and Augmented-Reality Photos

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ABSTRACT: Applications of visualization techniques in bored pile construction are often associated with high cost while delivering limited benefits to construction engineering. In this paper, two cost-effective and easy-to-apply visualization techniques, namely, enhanced production-line chart and augmented-reality (AR) photos are applied to visualize bore pile construction with practical case studies. The enhanced production-line chart consolidates productivity data, including geological compositions, construction methods, and time records, to facilitate planning and control for constructing an individual pile in a straightforward fashion. And AR photos analytically merge the still images of both the real world and the virtual world in three dimensions into one seamlessly integrated view, which is valuable to improving communication and decision making in construction operations management. The resulting AR photos are not only intended for progress visualization and presentation, but serve as a precise tool for dynamic site construction planning. Practical case studies are given to demonstrate the applications of the visualization techniques in the construction field.

***KEYWORDS**: Augmented-reality, Site photo, Visualization, Productivity, Cost-effective.*

1. INTRODUCTION

Interacting with and making sense of huge amounts of relevant project data would be tedious and overwhelming, if not impossible. This has presented a distinct challenge for engineers and managers to attain cost efficiency in executing large-scale, complex construction projects. By making better use of human spatial memory, visualization in three dimensional (3D) computer models brings the full power of human's visual system to bear on processing information in tackling highly convoluted problems (Sheridan 2008). Especially, underground infrastructure construction features high uncertainty due to invisibility and variations in geological compositions. A large volume of productivity and geology data are recorded with significant efforts, while only being utilized to a limited extent in practice. Timely review and frequent evaluation of project productivity enabled by cost-effective visualization means are desired by site engineers and managers, but remain difficult to realize on site. In order to tackle this visualization challenge as identified in a straightforward manner, two methodologies, namely, enhanced production-line chart and augmented-reality (AR) photos, are introduced in this paper.

The enhanced production-line chart combines site geological data and method productivity data to visualize the progresses of major piling activities with regard to time and depth dimensions. The resulting visual aid is beneficial to predict the total duration as needed for constructing individual piles; and to facilitate communications on intertwined site information in terms of methods, productivity, engineering geology, and quality control. The AR photos visualization technique is based on an analytical method for integrating 3D models of building products (as designed vs. as built) with site photos, so as to lend decision support to site management and construstability analysis. By conducting case studies on real sites, the two techniques are applied in the context of bored pile construction and found to be cost-effective.

Previous research efforts in productivity study resorted to numerical estimations by using regression, artificial neural networks or self organizing maps. Zayed and Halpin (2005) used regression and artificial neural networks to assess piling process productivity; Adel and Zayed (2009) conducted productivity analysis of horizontal directional drilling by integrating neural networks and fuzzy logic; while Oral and Oral (2010) proved the feasibility of implementing self organizing maps for crew productivity prediction. However, as Russell et al.

(2009) pointed out, there is very little literature addressing construction data visualization. Gong and Caldas (2010) applied videotaping to extract productivity information by automatic object recognition in a concrete column pour application. Yet, visualizing related productivity information for invisible building elements, such as underground bored piles, is more difficult and has been less attempted.

In terms of reality visualization technology, 3D modeling of site elements including building products, equipment, and temporary facilities was proved feasible for visualizing construction processes. Researchers employed four-dimensional computer aided design (4D-CAD) to visualize project progress and examine construction constructability. However, 4D simulations consume a substantial amount of development time and effort, which may not be justified with commensurate gains (Mahalingam 2010). The augmented-reality (AR) technology has evolved in recent years aimed at enhancing modeling realism while reducing modeling effort. Comprehensive AR applications in construction were evaluated by Shin and Dunston (2008). Several experiments were carried out for illustrating the feasibility (Behzadan and Kamat 2007, Shin and Dunston 2009). The AR system relied on expensive tracking devices such as GPS, three-degree-of-freedom orientation tracker or head mounted display to determine the position and orientation of a camera (Kensek et al. 2000, Wang and Dunston 2006). The limitations of AR applications lie in poor precision in image superposition and slow response in image registration. Kim and Kano (2008) conducted an experiment to identify the differences between the as-built products and as-designed drawings by applying image-superimposing techniques. In addition, a photogrammetry-based augmented-reality (Photo-AR) technology is also capable of creating coordinate-referenced, augmented-reality photo analytically (Siu and Lu 2009).

This paper demonstrates the applications of two visualization techniques proposed for bored pile construction. The enhanced production-line chart holds potential for forecasting activity or project duration on each single pile while augmented-reality photos visualization integrates site photos with 3D models of invisible piles and geological composition profiles, providing a precise visual aid for dynamic site construction planning in constructing a system of piles over a congested site layout plan. In the following sections, the bored pile construction sequence is first illustrated, followed by applications of the enhanced production-line chart and AR photos.

2. BORED PILE CONSTRUCTION SEQUENCE

Dry method, casing method and slurry method are commonly practiced bored pile construction methods. The method selection depends on the actual ground condition. The casing method represents the mainstream practice. Temporary casing is used to prevent excessive lateral deformation towards the shaft cavity, and to prevent the collapse of subsoil during excavation and cause minimal settlement disturbances in the adjacent areas. Thus, this research narrows down its scope to investigate the bored pile construction by casing method.

Before bored pile excavation commences, a pre-drilled hole is dug at each tentative bored pile location in order to verify the rock head level and identify any existing underground obstructions. The case driving process is then triggered by sinking temporary steel casing segments underground by the use of an oscillator or vibrator. The casing segments are conjoined by either bolt or weld connections. As excavation proceeds, the excavated soil is removed by chisel and grab. The process terminates at the rockhead level. A reverse circulation drill (RCD) replaces the oscillator for further rock excavation with the casing firmly standing at the rockhead level. Finally, if necessary, the bored pile base enlargement is formed by applying the RCD bellout drill bit according to the design.

Airlifting the pile shaft and installing the steel cage follow. Airlifting is to clean the pile shaft and ensure concreting quality. The ultrasonic test (also referred to as Koden test on site) is then employed to check the borehole's base dimensions and shaft verticality. After checking and verification, reinforcement steel cages are inserted and installed by lapping (U-bolts connections). Concurrently, mild steel interfacing coring pipes are welded onto the steel cage in preparation for later concrete and rock interface testing.

Placing concrete by tremie pipe is the final step prior to the steel casing extraction. Progressive extraction of steel casing is carefully monitored as the concrete level continuously rises and eventually reaches the designed cut-off level. After the concrete hardens and gains adequate strength, the interface coring test is conducted to check the final pile and rock joint at the pile base. The core hole is then backfilled with cement grout.

Site photos during construction were taken to capture the complete construction sequence, as shown in Figure 1. The remaining sections present the applications of the enhanced production-line chart and AR site photos visualization techniques in bored pile construction.

Grabbing | Case Jointing | RCD Drilling

Air Lifting | Steel Cage Extension | Concreting

Fig. 1: Bored pile construction sequence

3. ENHANCED PRODUCTION-LINE CHART

Engineering geology is a key factor affecting the bored piling construction productivity. N-value is used to denote the soil stiffness: the higher the N-value, the stiffer the soil. In short, a higher N-value implies more efforts are needed to drive the casing segments underground and excavate the soil, thus increasing the construction progress time. The enhanced production-line chart entails recording productivity data such time and depth for key construction stages, which include driving casing, excavation, bellout, air-lifting and steel cage installation, concreting and casing removal. Production rates for different stages are evaluated. The resulting visual aid consolidates all the productivity-related data retrieved from site, facilitating the assessment of the total duration required to construct an individual pile.

The underground foundation system of a building in Wai Chai, Hong Kong consisted of ten bored piles. There were eight bored piles of 3m shaft diameter with 4.5m bellout, and the remaining two had 2.5m shaft diameters without bellout. The bored piles with bellout were chosen for conducting the case study.

The geology information was obtained from pre-drill records. Soil layers were classified into fill (FILL), marine deposit (MD), alluvium (ALL), completely decomposed granite (CDG), moderately decomposed granite (MDG) and slightly decomposed granite (SDG). For simplicity, FILL, MD and ALL (with N-value less than 60) were grouped into the combined soil layer, as these layers made no marked difference in productivity during temporary casing driving and soil excavation; CDG (N-value between 54 and 200) was the second layer, and soil with N-value greater than 200 such as MDG and SDG were grouped to the last soil layer.

Time and depth data for main excavation and concreting stages were collected from site records. Table 1 shows the raw data recorded on site. Results are processed as shown from Table 2 to Table 5. Note the time and depth were averaged and the corresponding production rates were evaluated.

Table 1: Data Collection for Enhanced Production-line Chart

Excavation Stage	Concreting Stage
Depth of casing (D_C)	Depth of concreting level (D_L)
Depth of excavation (D_E)	Depth of casing (D_C)
Time of casing diving per hour (T_C)	Time of concreting per hour (T_L)
Time of excavation per hour (T_E)	Time of casing removal per hour (T_C)
Time for casing joint connection	Time for removing case joint
Time for installing reverse circulation drill	
Time for bellout, airlifting and steel cage installation	

Table 2: Excavation Stage - Casing Level (D_C and T_C) - By Oscillator

Geology	D_C (m)	T_C (hr)	Rate (m/hr)
Fill, MD, Alluvium	21.6	2:40:00	8.10
	Joint 1	0:51:15	-
	Joint 2	0:50:37	-
CDG	37.0	9:56:52	1.55
	Joint 3	0:50:37	-
	Joint 4	0:49:23	-

Note the joint represents the bolt connection for two case segments.

Table 3: Excavation Stage - Excavation Level (D_E and T_E) - By Grabbing and RCD

Geology	D_E (m)	T_E (hr)	Rate (m/hr)
Fill, MD, Alluvium	21.61	11:30:37	1.88
CDG	37.01	15:23:45	1.00
RCD Installation	37.01	3:38:45	-
MDG, SDG	40.66	7:18:45	0.50

Table 4: Time for Bell Out, Air Lifting, Steel Cage Installation

	Time (hr)
Bell Out	12:36:53
Air Lifting	8:16:15
Steel Cage Installation	6:01:15

Table 5: Concreting Stage (D_L and T_L)

	Time (hr)	Rate (m/hr)	Depth (m)	Volume (m^3)
Place Concrete	7:03:08	5.40	-	294.25
Remove Joint 2	1:33:08	-	-	
Stop Concreting	-	-	2.85	

The standard temporary casing segment was employed, each being 8m in length. Totally, five segments connected with four bolted joints were sunk to build the pile. The excavation start time was two hours after the case driving start time. The temporary casing removal start time was 3 hours after the start time of placing concrete. The casing removal rate was determined as 7.5m/hr.

By using Table 1 to 5, the cumulative average time and average depth for bored pile construction were calculated as shown in Table 6. Figure 2 shows the resulting enhanced production-line chart. The visual aid presents each key construction process with regard to time, depth and soil geology compositions. In Figure 2, the blue line indicates the temporary casing depth while the red one represents the excavation depth before bell-out, air lifting and steel cage installation. Note the red line continues to represent the concrete level depth once the airlifting is carried out and concreting starts. The methodology is proved to be easy-to-apply and straightforward to comprehend.

Table 6: Cumulative time and depth for the constructing phrases

	Time (hour)	Depth (m)
	0	0
	0.988	8
	1.842	8
	2.829	16
	3.673	16
Case Driving	4.366	21.6125
	5.015	24
	5.859	24
	11.020	32
	11.843	32
	15.077	37.0125
	69.771	37.0125
Case Removal	71.893	21.0125
	73.443	21.0125
	76.230	0
	2	0
Excavation	13.510	21.6125
	28.906	37.0125
RCD Installation	32.552	37.0125
Excavation	39.864	40.6625
Bell Out	52.479	40.6625
Air Lifting	60.750	40.6625
Steel Cage Installation	66.771	40.6625
	71.891	13.0125
Concreting	73.443	13.0125
	75.325	2.85

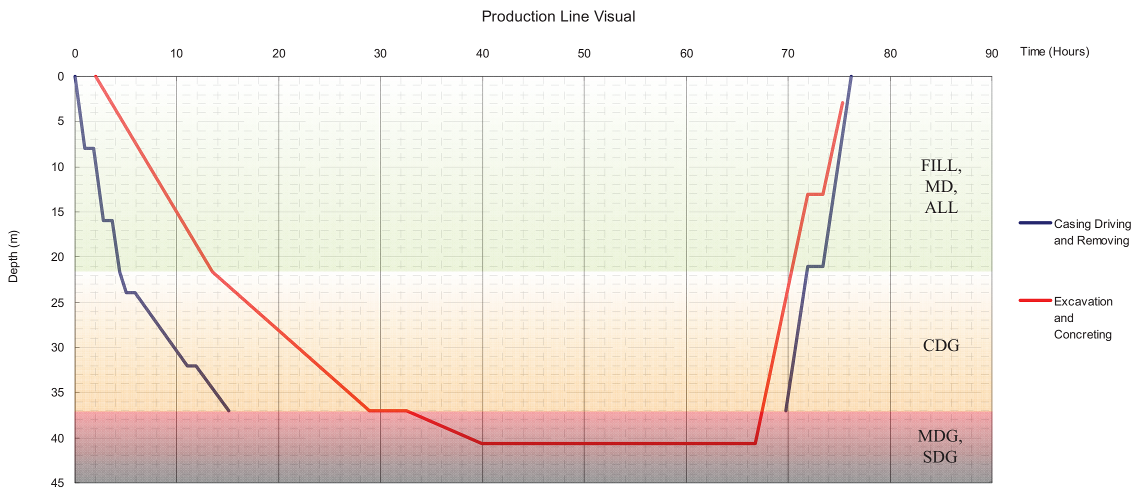

Fig. 2: Enhanced Production-line Chart in Bored Pile Construction

Planners can predict the individual bored pile construction duration with the aid of Figure 3. The blue line represents the temporary casing depth as described. J_1 to J_4 represent the bolted joints for the casing connection. The temporary casing advances from the layer composed of FILL, MD and ALL to stiffer layer CDG, with the casing driving rate decreasing from 8.1m/hr to 1.6m/hr. The casing settles on the rockhead level without any further advancement. Three hours after starting to place concrete, the steel casing was removed with a rate of 7.5m/hr. Noted that the casing removal rate depends on the rate of placing concrete, regardless of the geology

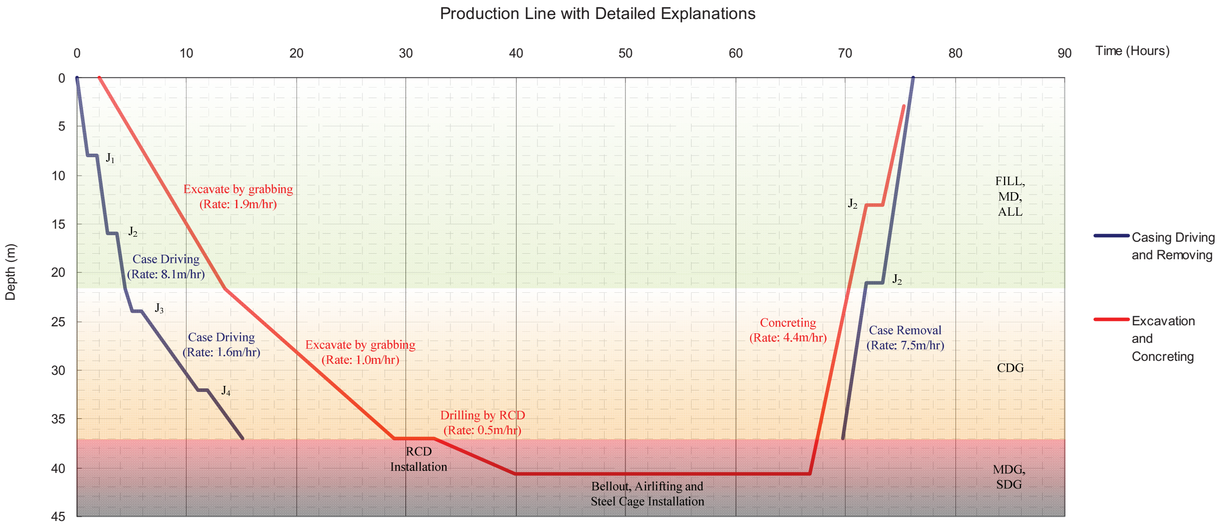

Fig. 3: Enhanced Production-line Chart with Detailed Explanations

profile.

By examining the red line the excavation start time was found out to be 2 hours later than the casing driving start time. The underlying engineering consideration is to ensure no over-excavation would occur without lateral load support. The excavation rate by grabbing decreases from 1.9m/hr to 1.0m/hr when drilling from the first soil layer to the second layer. Then, it takes approximately 3 hours to replace the grab with the RCD. The RCD drilling rate is 0.5m/hr. The line becomes flat with the depth reaching the maximum as no further excavation is carried out. The bellout drilling by RCD, airlifting and steel cage installation processes follow. Further the red line extends to represent the concreting level. During the 4.4m/hr concrete pouring process, only Joint 2 on the casing is required to be disconnected in order to retrieve and remove the casing. The concreting process terminates when the concrete level reaches 2.85m higher than the cut-off level. In this case study, the averaged total duration of individual pile construction is 76 hours.

The proposed enhanced production-line chart synthesizes various sources of site data collected for different management purposes, lending effective support to planners in predicting or estimating the individual bored pile duration and communicating construction progress between different project stakeholders. The underlying data can be readily updated and the enhanced production-line chart is reusable given similar methods and underground conditions.

4. AR PHOTO VISUALIZATION METHODOLOGY

In the current practice, two-dimensional computer aided design (2D CAD) visualizations are employed for detailed designing and planning. The drawings are used to convey the geometry and positioning of the planned building elements (such as bored piles). In contrast, the photogrammetry-based augmented-reality (Photo-AR) application has been developed to analytically superimpose 3D graphics of site element models over real world photos. The analytical formulas underlying photogrammetry (the collinearity equations) are shown in Equation (1) and (2). Dai and Lu (2009) simplified photogrammetry for construction visualization applications, which uses the tilt-swing-azimuth system and only two points to define camera's perspective angular orientations. The photo-AR technology was further implemented to visualize microtunneling project progress (Siu and Lu 2009).

$$x_n = x_o - c\frac{m_{11}(X_n - X_o) + m_{12}(Y_n - Y_o) + m_{13}(Z_n - Z_o)}{m_{31}(X_n - X_o) + m_{32}(Y_n - Y_o) + m_{33}(Z_n - Z_o)} \tag{1}$$

$$y_n = y_o - c\frac{m_{21}(X_n - X_o) + m_{22}(Y_n - Y_o) + m_{23}(Z_n - Z_o)}{m_{31}(X_n - X_o) + m_{32}(Y_n - Y_o) + m_{33}(Z_n - Z_o)} \tag{2}$$

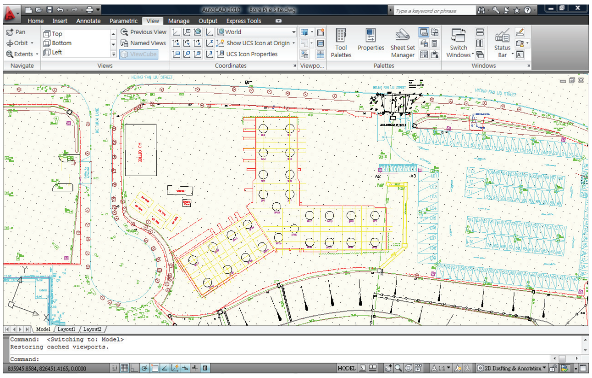

Fig. 4: 2D CAD Drawing

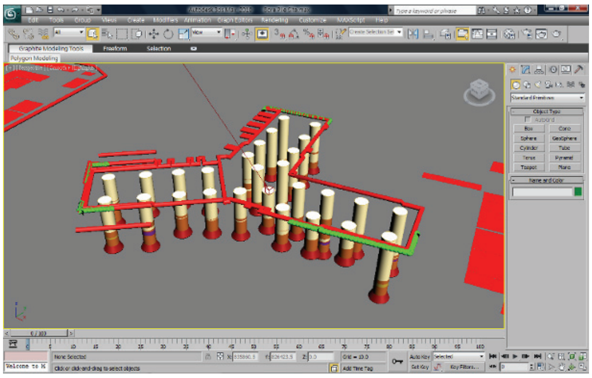

Fig. 5: 3D Planned Bored Pile Model

The collinearity equations geometrically relate the image space coordinates (x_n, y_n, c) to the object space coordinates (X_n, Y_n, Z_n). Parameters are explained as followed: c is the camera's focal length; Those m elements make up the rotational matrix which defines the angular orientations; While X_o, Y_o, Z_o correspond to the camera's position with respect to the object coordinate system and x_o, y_o denote the camera's principle point with respect to the image plane. In short, collinearity equations transform the object space coordinates to image space coordinates to achieve analytical Photo-AR superimposition. The Photo-AR technology is used to integrate the site photos and invisible building products and geological composition profiles, resulting in AR photos to support decision making.

A case study was conducted on the construction site located at Sha Tin, Hong Kong to illustrate the Photo-AR application. The 2D CAD drawings of a bored pile are shown in Figure 4. The 3D bored pile models were built based on 2D CAD drawing as shown in Figure 5. Figure 5 gives the final bored-pile models with accurate as-designed pile positions and dimensions. Soil layers are key factors to be considered in productivity analysis as described in the enhanced production-line chart section. In this study Photo-AR applications aim at integrating the visible situational information contained in site photos with information of the invisible soil layer and building elements. The current practice requires a planner to scrutinize the soil layers and analyze different soil layer thicknesses based on pre-drilling records. It is mentally demanding and error prone for the human planner to connect site construction methods, piling positions and geological profiles. Any mistakes can cause delays and any remedial and preventive measures can be costly.

To visualize the soil layers together with the bored piles, colored schemes are proposed to apply to 3D bored pile models, given in Table 7. With the 2D CAD drawing and pre-drill records, bored pile models are built as shown in Figures 5, 6 and 7, depicting each pile's dimensions, soil layers and the site layout with accuracy.

Table 7: Soil Layer Color Classification

Layer	Color
Soil	White
Grade 3/4 or Worse Rock	Yellow
Grade 3 or Better Rock	Brown
Quartz	Purple

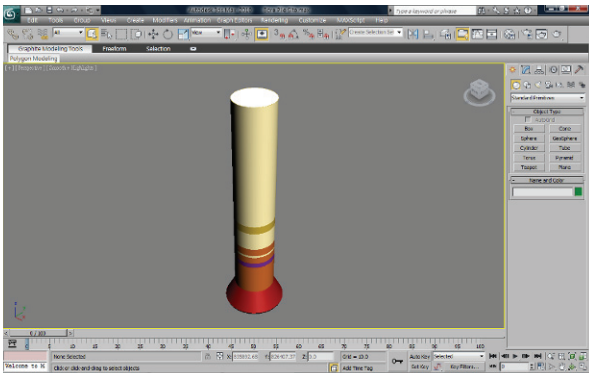

Fig. 6: Bored Pile Model with Soil Visualization

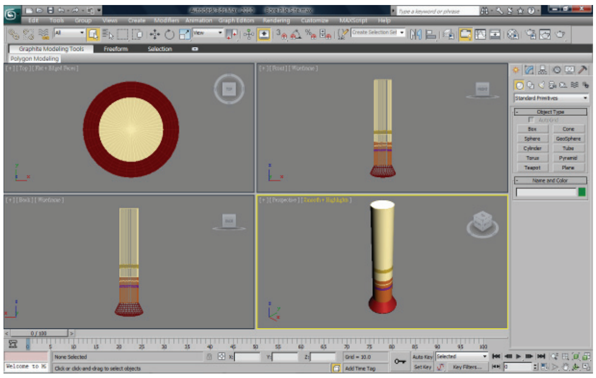

Fig. 7: Different perspective views encountered


Fig. 8: As-Designed Bored Pile Model


Fig. 9: As-Built Bored Pile Model

AR photos are generated by superimposing real photos with virtual model graphics. A real photo records the view from a particular camera's perspective captured in the real world. A virtual photo is viewed from the identical perspective by a virtual camera, generating a computer graphic of the 3D virtual environment. Note that the real and virtual cameras coincide in both position and angular orientations.

The object coordinates in Equation (1) and (2) can directly apply the World Geodetic System coordinates (E_n, N_n, Z_n). The control point (E_n, N_n, Z_n) and the camera position (X_o, Y_o, Z_o) are taken on site. In contrast with manually superimposing photos, the real photo and virtual photo can be superimposed by using Equations (1) and (2) (Siu and Lu 2009).

Figures 8 and 9 show the AR photos that depict the as-designed and as-built bored pile models respectively. Those non-started bored piles are transparent and the completed bored piles are rendered in solid grey. For those piles which are under construction, the colors are consistent with Figure 6. The AR photos integrate the building elements, site conditions and soil profiles for visualization. Figure 10 shows the zoom-in view of Figure 8. They help planners to visualize the current site situation including the congested layout, equipment locations and soil profiles. With this effective means, communication and decision making in construction management can be enhanced as follows.

AR site photos reflect site situations and are valuable to estimating productivity and allocating key construction equipment. The planners can effectively decide the bored pile construction sequence with such a visual aid. As shown in Figure 11, at a particular instant, six sets of construction equipment were available and thus six sets of arrows were marked. The arrows represent the pile construction sequence, which is depicted on the AR photos. Construction planners and managers can thus remove vagueness and ambiguity to quickly identify potential risks


Fig. 10: Zoom-in view of AR Photo

in executing the bored pile construction project.

With the precise coordinate information, planners can also conduct real-time precise measurements in the AR photo. For instance, according to safety regulations on site, no excavation is allowed within a distance of five times the diameter of the current pile being processed. At a certain stage, two bored piles were scheduled for construction in parallel (with red and green circle), as visualized in Figure 12. The planners intended to check the affected area in real-time. With the measurement capability of the AR photo model, the circle automatically displays and indicates the influential area for a pile construction. As a result, the pile with red circle was forced to halt construction until the concreting process of the green one was completed. During the halt, the idling equipment could be allocated to advance the construction on other processing piles.

The real-time analysis facilitated by Photo-AR was used to examine pile construction constructability. Note that the 2D CAD drawing also can be employed standalone to achieve this propose. However, 2D CAD drawing cannot reflect and capture the rich features of the actual site situation to enable reviewing constructability, e.g. the real-time equipment status and location, soil layer information and existing building elements.

5. CONCLUSION

Visualization is the effective means in processing complicated data for construction progress and constructability evaluation. In this research, the enhanced production-line chart and augmented-reality photo visualization methodologies are proposed and applied on practical bored pile construction sites.

The enhanced production-line chart illustrates the key method productivity information, consolidating productivity data, including geological compositions, construction methods, and time records, to facilitate the prediction and estimation of duration for key steps in individual bored pile construction.

The photogrammetry-based augmented-reality technology gives rise to augmented-reality photos. The resulting augmented-reality photos analytically capture the perspective view of actual site situation, invisible building elements and soil profiles. Case studies were conducted to demonstrate the potential benefits of applying Photo-AR as real-time visual aids in support of decision making in construction, such as construction sequencing, major equipment allocation and accessing project construability.

The visual aids of the enhanced production-line chart and augmented-reality photos assist practitioners in planning and executing bored pile construction projects. Integrating subsurface infrastructure engineering and cost-effective visualization technologies potentially advance current practices for construction engineering and management.

Fig. 11: Construction sequence determination

Fig. 12: Constructability testing

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Photogrammetry Assisted Rapid Measurement of Earthquake-Induced Building Damage

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ABSTRACT: *The presented research investigates the application of close-range photogrammetry surveying techniques and Augmented Reality (AR) visualization to design a semi-automated method for rapidly measuring structural damage induced in tall buildings by seismic events such as earthquakes or explosions. Close-range photogrammetry algorithms were designed to extract spatial information from photographic image data, and geometrically measure the horizontal drift (also called Inter-Storey Drift) sustained at key floors along the edge of a damaged building. The measured drift can then be used to compute damage indices that correlate the drift to the building's structural integrity and safety. In this research, the measurement accuracy of the calculated drift using photogrammetry is particularly studied. The experimental results revealed an accuracy level of 5 mm, demonstrating the potential of photogrammetry assisted rapid measurement of earthquake-induced building damage.*

KEYWORDS*: Buildings, Damage, Earthquakes, Reconnaissance, Computer applications, Photogrammetry*

1. INTRODUCTION

Timely and accurate evaluation of damage sustained by buildings after seismic events such as earthquakes or explosions is critical to determining the building's safety and suitability for their future occupancy. Time used in conducting the evaluations substantially affects the duration for which the potentially damaged buildings remain unusable. The elapsed time may lead to direct economic losses to both public societies and private owners. Current practice of evaluating the damage to buildings mainly resorts to licensed inspectors manually inspecting the building's integrity and habitability based on their personal experience and knowledge. Though inspection guidelines exist (for example, contained in the ATC-20 1989 and ATC-20-2 1995), the work of manual inspection remains labor-intensive and time-consuming, and the results are subjective and can often be error-prone (Kamat and El-Tawil 2007).

The presented research makes an attempt to alleviate this situation. By investigating the application of close-range photogrammetry surveying techniques and Augmented Reality (AR) visualization, a semi-automated method is designed to rapidly measure the structural damage induced in tall buildings by seismic events such as earthquakes or explosions. Close-range photogrammetry algorithms are designed to extract spatial information from photographic image data, and geometrically measure the horizontal drift (also called Inter-Storey Drift) sustained at key floors along the edge of a damaged building. The measured drift can then be used to compute damage indices that correlate the drift to the building's structural integrity and safety.

In this research, vision-based AR techniques identify the pixel positions of key points along a building's edge in photographs, and close-range photogrammetry computes the 3D coordinates of those points into the global object space, considering only the drift component that is perpendicular to the direction of the camera's line of sight. The inter-storey drift can be subsequently derived by comparing the shifted position of each floor against the pre-disaster outer geometry of the inspected building that is obtained or available a-priori from building owner or government databases. The Global Positioning System (GPS) and 3D electronic compasses are used to track the position and orientation of the camera's perspective.

Studying the measurement accuracy of the calculated drift using photogrammetry has been a primary focus of this research. Theoretically, components that account for measurement error mainly comprise the internal errors induced by the camera lens distortion, calculated approximation of the principal distance, the combination of the camera resolution, shooting distance and the focal length, and the external errors transferred from the tracking systems utilized to obtain the camera position and angular orientation. This research models the internal errors as mathematical formulations and correspondingly proposes solutions to minimize those errors. In order to quantitatively assess the level of accuracy, three groups of laboratory experiments were conducted to simulate a building damaged in an earthquake. A two-storey reconfigurable steel frame was designed to resemble a building structure. The frame was calibrated with known displacement values at the second floor, and images were taken with a Canon EOS Rebel T1i digital camera. The images were post-processed to yield the spatial coordinates of two bolted connections on each of the frame's two floors. By subtracting horizontal axis components of the two connections, the inter-storey drift was computed. The experimental results revealed an accuracy level of 5 mm, demonstrating the potential of photogrammetry assisted rapid measurement of earthquake-induced building damage.

The remainder of this paper elaborates on the photogrammetry assisted methodology in detail, followed by the analytical study of the internal components of cameras that induce the measurement errors, based on which the solution to minimize those errors is proposed. Finally, the laboratory experiments conducted to validate the level of measurement accuracy by photogrammetry are described, followed by a description of ongoing work toward full automation of the proposed method.

2. METHODOLOGY FOR RAPIDLY MEASURING BUILDING DAMAGE INDUCED BY EARTHQUAKE

2.1 Previous work

This study builds on prior research conducted at the University of Michigan. Previous research (Kamat and El-Tawil 2007) established a schematic overview of a rapid, augmented reality based, post-earthquake building damage reconnaissance method. As shown in Fig. 1, the previously established reconnaissance methodology utilized the augmented reality visualization techniques to superimpose the building's pre-earthquake geometric outer lines onto the view of the actual structure captured in real time through a video camera in an AR setting. The methodology proposed that equipped with a GPS receiver and 3D electronic compasses to track the position and orientation of the observer's perspective, the in-situ reconnaissance inspectors see through a head-mounted display to qualitatively evaluate the damage by comparing two views of the structure in a real time.

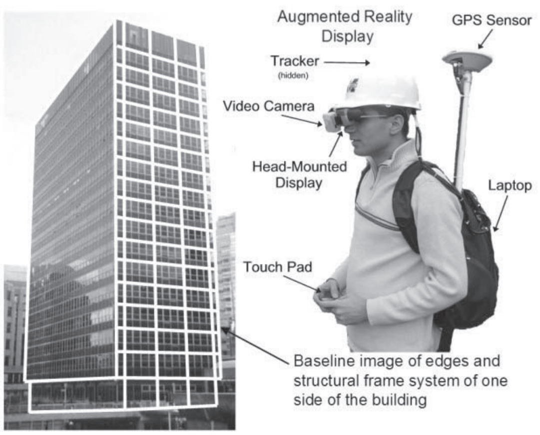

Fig. 1: Overview of previously established reconnaissance methodology (Kamat and El-Tawil 2007)

Some proof-of-concept experiments were conducted to achieve a quantitative result in the previous research. In the UM Structural Engineering Laboratory, the large-scale cyclic shear walls were selected as the test-bed and the CAD images of the walls were overlaid onto the actual wall specimens. As loading was applied on the wall specimens, the displaced horizontal drifts were measured by placing the baselines of the CAD images in the augmented space and comparing the baselines with the edges of the actual wall specimens. The experimentally measured drifts were compared with the actual wall drifts quantified in a predetermined displacement regime. The results indicated a promising potential of applying AR for rapid building damage detection (Kamat and El-Tawil 2007).

Though AR visualization techniques work well in laboratory environments, some hurdles must be addressed before AR can be implemented in a field-deployable system, one of which is that the line of sight of the inspector (video camera) must be exactly orthogonal to the floors of the inspected building such that the trigonometry calculation can be applied to infer the deformed drifts (Fig. 2a). Any oblique, even slightly, line of sight to the floors of the inspected structure will lead to non-linear, biased drifts that fail to represent the actual drift measurements (Fig. 2b). Successfully applying AR techniques to measure the building damage largely depends on the standing point and viewing perspective where the inspector observes the structure. However, in potentially chaotic disaster scenarios, the inspectors who wear the reconnaissance systems can, at best, find it challenging to intuitively fine-tune their perspective to achieve the desired perpendicularity, thereby limiting the widespread use of AR visualization technology for post-earthquake reconnaissance in reality.

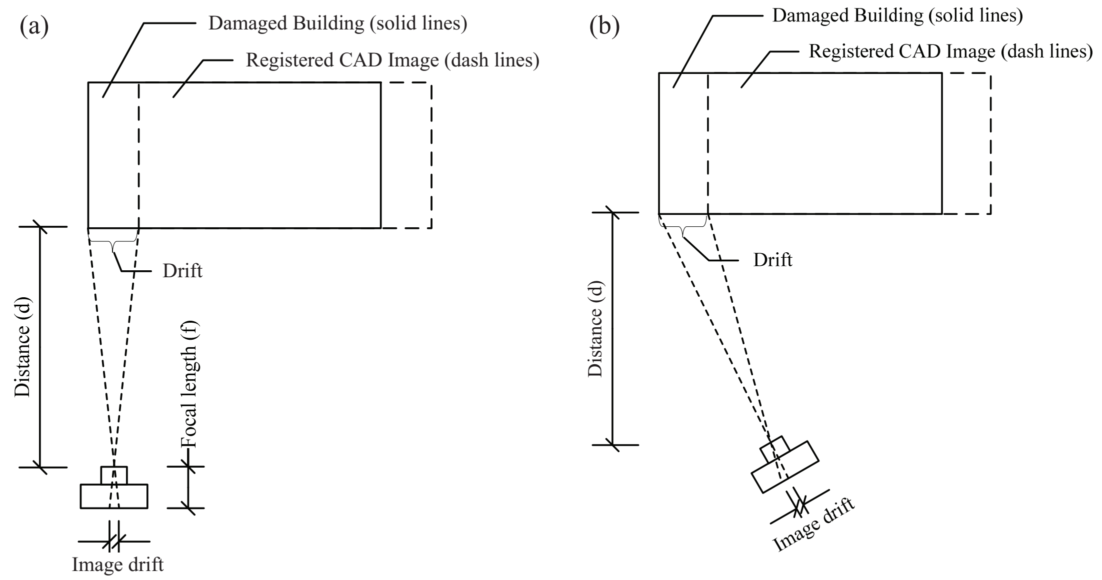

Fig. 2: Camera line of sight (a) orthogonal to building wall to derive the damage drift, but (b) oblique resulting in a non-linear, biased drift

The surveying technique of close-range photogrammetry is powered with capacity of spatialized computation and is capable of establishing a relationship between two-dimensional (2D) photo images and the three-dimensional (3D) object space (Blachut and Burkhardt 1989). Using photogrammetry allows for the inspectors to observe the structure at a standing point and viewing perspective that does not impose orthogonality, thereby complementing AR well in manipulating image data into 3D coordinates and extrapolating the inter-storey drifts. In the next section, the close-range photogrammetry technique is meticulously investigated in order to design a practical and universal AR-based method for rapid post-earthquake building damage reconnaissance.

2.2 Photogrammetry assisted damage measurement

Photogrammetry is employed mainly to quantify the spatial coordinates of each floor of the damaged building. The vision-based AR technology is used to identify and extract x, y positions of building floors on the captured images. Then the x, y position data is used as the input for post processing of the photogrammetry to derive the corresponding spatial coordinates X, Y, and Z readily for the computation of the *Inter-Storey Drift* sustained at key floors along the edge of a damaged building.

In the earthquake engineering community, based on the performance-based seismic design specifications such as FEMA (2000), the *Inter-Storey Drift* (*ISD*) is used to compute indices that are unanimously suggested as a reasonable measure to reflect the extent of a building damage induced by earthquake. The *Inter-Storey Drift* can be interpreted as the horizontal displacement of each building floor that is permanently moved relative to the one beneath in regard to the damaged building. Fig. 3 illustrates the inter-storey drifts using a simplified two-storey building frame. In Fig. 3, the building frame drawn by solid lines denotes the geometric building profile pre earthquake and the one drawn by dash curves represents the building's inclined outer walls post earthquake. From Fig. 3, the inter-storey drift of the first storey is the horizontal movement of the second floor (L_2) relative to the ground floor (L_1) which is denoted by Drift_1 (Fig. 3), and the inter-storey drift of the second storey (Drift_2 in Fig. 3) is that of the third floor (L_3) relative to the second floor (L_2) instead of the ground floor.

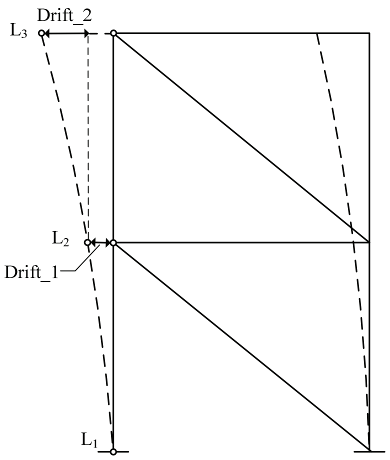

Fig. 3: A simple two-storey building frame illustrating inter-storey drifts

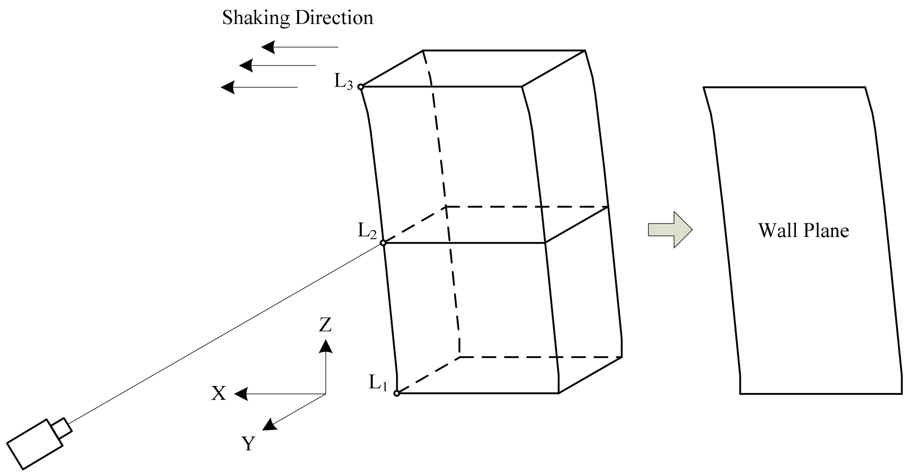

Fig. 4: An inspector inspecting the damaged building, focusing on one of the key floors at certain moment (e.g., the second floor)

The two-storey reconfigurable building frame constructed by the authors, and described earlier, will be used to demonstrate the computing algorithm for the inter-storey drift for each of the building floors, in which the 3D coordinates of the inspected floors of the damaged building should be derived first. Fig. 4 models an inspector inspecting the damaged building, focusing on one of the key floors at a certain moment (e.g., the second floor). The inspector is simply modeled by a video camera that is mounted on the inspector's helmet to capture the images of the structural damage sustained by the building. The video camera and the inspector have the same position and orientation when the building is viewed. A line of sight of the video camera is formed to link the point of the floor intersecting the building edge (e.g., L_2) in the global space with its corresponding projection on the captured image inside the camera. We denote the floor along the building edge (e.g., L_2) as its 3D coordinates in the object coordinate system of the global space (X_n, Y_n, Z_n) and its 2D coordinates on the image plane inside the camera (x_n, y_n). Thus, the line of sight can be modeled by the well-known photogrammetric *collinearity equations* (Wong 1980; Wolf 1983; McGlone 1989), as in Eq. (1):

$$
\begin{aligned}
x_n - x_p &= -c\frac{m_{11}(X_n - X_c) + m_{12}(Y_n - Y_c) + m_{13}(Z_n - Z_c)}{m_{31}(X_n - X_c) + m_{32}(Y_n - Y_c) + m_{33}(Z_n - Z_c)} \\
y_n - y_p &= -c\frac{m_{21}(X_n - X_c) + m_{22}(Y_n - Y_c) + m_{23}(Z_n - Z_c)}{m_{31}(X_n - X_c) + m_{32}(Y_n - Y_c) + m_{33}(Z_n - Z_c)}
\end{aligned} \tag{1}
$$

In Eq. (1), (x_p, y_p) is the *principal point* on the image plane and c is the *principal distance*. They describe the internal orientation of the camera station, which can be referred to as the projected position of the light ray on the image plane through center of the lens opening of the camera (perspective center) from infinity (*principal point*), and the perpendicular distance between the perspective center and the image plane (*principal distance*). The camera internal components can be determined by performing the camera calibration, which will be described in the ensuing section entitled "Camera Calibration". Eq. (1) also has (X_c, Y_c, Z_c) and m_{ij} (i, j = 1, 2, 3) to define the exterior orientation of the camera station. (X_c, Y_c, Z_c) refer to the position of the perspective center and m_{ij} are the elements of an rotation matrix M, which are expressed as functions of the Euler orientation angles - azimuth (α), tilt (t), and swing (s) (Wolf 1983), as elaborated in Eq. (2):

$$
\begin{aligned}
m_{11} &= -\cos\alpha\cos s - \sin\alpha\cos t\sin s \\
m_{12} &= \sin\alpha\cos s - \cos\alpha\cos t\sin s \\
m_{13} &= -\sin t\sin s \\
m_{21} &= \cos\alpha\sin s - \sin\alpha\cos t\cos s \\
m_{22} &= -\sin\alpha\sin s - \cos\alpha\cos t\cos s \\
m_{23} &= -\sin t\cos s \\
m_{31} &= -\sin\alpha\sin t \\
m_{32} &= -\cos\alpha\sin t \\
m_{33} &= \cos t
\end{aligned} \tag{2}
$$

However, only one line of sight (Eq. 1) is not sufficient to determine the position of the inspected floor where it intersects the vertical edge of the building wall (i.e. two equations fail to solve for three unknowns.) One more extra component as a constraint is required in order to define a third equation.

In seismic engineering, it is mainly the destructive forces of an earthquake coming along the horizontal direction that induce structural damage in buildings. To simplify the problem in this research, the inspected floors' deformation is assumed to take place only on the walls whose axes are parallel or close to the shaking direction of the seismic forces (Fig. 4), leading to which the deformed floors remain in a plane that is unchanged pre and post earthquake as shown in Fig. 4. The wall plane thus can serve as the extra component constraint for the line of sight, as modeled in Eq. (3):

$$AX_n + BY_n + C = 0 \tag{3}$$

Note that the wall plane is vertical to the ground such that the variable Z_n along Z-axis is not necessary for Eq. (3). The A, B, and C are the coefficients of the equation denoting the wall plane, which can be referred to from the pre-disaster outer geometry of the inspected building that is obtained or available a-priori from the building owner or government databases.

Using the line of sight formula Eq. (1) and the plane equation Eq. (3) where the wall deforms along the shaking direction, the coordinates (X_n, Y_n, Z_n) of the inspected floor along the building edge can be finally computed. Simply denoting (X_u, Y_u, Z_u) as the edge position of the inspected floor and (X_l, Y_l, Z_l) as that of the floor beneath, the inter-storey drift (*ISD*) of the inspected floor can be subsequently computed by Eq. (4), as per:

$$ISD = (X_u - X_l)/|X_u - X_l|\sqrt{(X_u - X_l)^2 + (Y_u - Y_l)^2} \tag{4}$$

where $(X_u - X_l)/|X_u - X_l|$ indicates direction of the inspected floor's movement, i.e. plus (+): along the X-axis, minus (-): against the X-axis, and $\sqrt{(X_u - X_l)^2 + (Y_u - Y_l)^2}$ calculates the absolute value of the movement.

Applying the photogrammetry assisted computing equations also needs the camera station' external components (X_c, Y_c, Z_c, α, t, s) and internal components (x_n, y_n, c) to be determined in advance so as to fit the parameters of the *collinearity equations* (Eq. 1), which will be discussed in the following sections.

3. MEASURING CAMERA POSITION AND ORIENTATION

The camera station's spatial coordinates (X_c, Y_c, Z_c) and orientation angles (α, t, s) are traditionally determined by means of identifying corresponding points on multiple images taken from different perspectives and fixing absolute position of camera by use of known reference points, giving rise to a lack of the ease of operation and applicability. In this research, we employ the Real Time Kinematics Global Positioning System (RTK-GPS) and a 3D electronic compass to measure the (X_c, Y_c, Z_c) and (α, t, s) of the camera's perspective respectively, which enables a maximal degree of freedom for the proposed method applied in the outdoor environment. The RTK-GPS applied is the Trimble Ag GPS Base Station 900 with a horizontal accuracy of 1-2 ppm (parts-per-million) and vertical accuracy of 2-3 ppm (parts-per-million), namely, if the distance (baseline length) between the base station and the rover receiver is 10 km, the horizontal error of the RTK-GPS is 10 - 20 mm and its vertical error is 20 - 30 mm. The 3D electronic compass is the PNI TCM 5 which uses the rotation definition of flight dynamics as per: -90º ~ 90º in pitch, -180º ~ 180º in roll, and -180º ~ 180º in heading (yaw), and has a level of rotation accuracy of 0.3°. The mapping between the flight dynamics rotation angles and the photogrammetry tilted rotation angles for Earth Axes is as: azimuth (α) = heading, tilt (t) = 90º + pitch, and swing (s) = 180º - roll, if pitch ≤ 0º; and azimuth (α) = 180º + heading, tilt (t) = 90º + pitch, and swing (s) = 180º - roll, if pitch > 0º.

4. EVALUATING CAMERA'S SYSTEMATICAL ERROR

Camera systematical error refers to the measurement error on the image plane induced by the imperfection of the camera lens and its internal mechanics with a consistent effect that cannot be statistically eliminated (Viswanathan 2005). In this section, we discuss two major aspects that induce the camera's systematical error, namely – the lens distortion and the approximation of the principal distance.

4.1 Lens Distortion

In an ideal situation, a spatial point P is projected through a camera lens opening (O) on the image plane to have an image point p, and the three points P, O, and p lie along a straight line (Fig. 5). But in reality owing to the lens distortion of the camera, the projected image point is shifted from its true p (x_n, y_n) to a disturbed position p' (x_n', y_n') as illustrated in Fig. 5, resulting in an offset between the two positions. Denoting the offset by dx and dy, thus the true coordinates of any image point can be compensated by Eq. (5):

$$\begin{aligned} x_n &= x_n^{'} + dx \\ y_n &= y_n^{'} + dy \end{aligned} \tag{5}$$

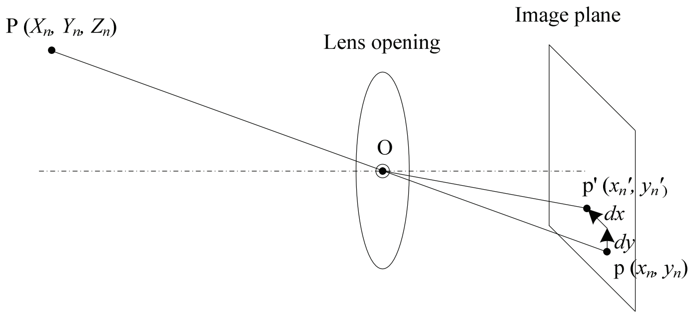

Fig. 5: Camera lens distortion inducing an offset between true and disturbed positions of a point on the image plane

For modern digital cameras, the camera lens distortion (i.e. dx and dy) can be taken as the aggregate of the radial distortion and the decentering distortion (Beyer et al. 1995; Fraser 1996). As the lens of a camera is actually composed of a combination of lenses, the centers of those lens elements are not strictly collinear, giving rise to the decentering distortion. In contrast, the radial distortion occurs in each single optical lens and the distortion effect is magnified along the radial direction of the lens: the further a point is away from the center of the lens, the larger error is produced for its projected image point. Therefore, *dx*, *dy* can be decomposed by Eq. (6):

$$\begin{aligned} dx &= dx_r + dx_d \\ dy &= dy_r + dy_d \end{aligned} \tag{6}$$

in which dx_r , dy_r is the radial distortion along x-axis, and y-axis; and dx_d , dy_d is the decentering distortion along x-axis, and y-axis. Assuming the optical axis of the lens is perpendicular to the image plane, Brown (1966) developed the mathematical model for correcting the lens distortion by Eq. (7):

$$\begin{aligned} dx_r &= K_1(x_n^{'} - x_p)r^2 + K_2(x_n^{'} - x_p)r^4 + K_3(x_n^{'} - x_p)r^6 \\ dy_r &= K_1(y_n^{'} - y_p)r^2 + K_2(y_n^{'} - y_p)r^4 + K_3(y_n^{'} - y_p)r^6 \\ dx_d &= P_1[r^2 + 2(x_n^{'} - x_p)^2] + 2P_2(x_n^{'} - x_p)(y_n^{'} - y_p) \\ dy_d &= P_2[r^2 + 2(y_n^{'} - y_p)^2] + 2P_1(x_n^{'} - x_p)(y_n^{'} - y_p) \\ r^2 &= (x_n^{'} - x_p)^2 + (y_n^{'} - y_p)^2 \end{aligned} \tag{7}$$

Here x_p and y_p are the coordinates of the principal point, K_1, K_2 and K_3 are the radial distortion parameters, and P_1 and P_2 are the decentering distortion parameters. A camera calibration can be used to determine the lens distortion parameters.

4.2 Approximated principal distance

The *principal distance* (c) of a camera in photogrammetry is defined as the distance of the perpendicular line from the *perspective center* (center of lens opening) to the image plane of the camera, which is approximated as the *focal length* (f) of the camera in the *collinearity equations* of Eq. (1). In this research, we seek the actual principal distance instead of the approximated camera focal length as the reconnaissance project requires the achievable level of measurement accuracy to be as high as possible.

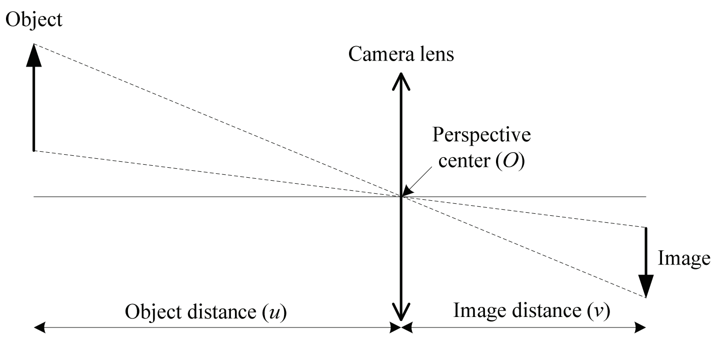

Fig. 6: Illustrated object distance and image distance when a camera is photographing an object

Fig. 6 shows a camera photographing an object where the photographic object distance and the image distance are illustrated. The principal distance c equals the image distance v when the image plane is at the exact position along the optical axis that an object is clearly focused. Meanwhile, the distance between the object and the camera lens is defined as object distance u. The conjugated distances u, v and the focal length f are related by the *lens conjugate equation* (Ray 1984) as: $1/u + 1/v = 1/f$, by which the image distance can be derived by Eq. (8):

$$v = \frac{uf}{u - f} \tag{8}$$

Eq. (8) computes the actual length of the principal distance. Also, as an object is actually shot, the object distance u usually is much farther than the image distance v. As such, the denominator (u - f) can be approximated as u, which yields: $v \approx f$. This proves the assertion that the *principal distance* (c) can be practically approximated to the focal length of the camera lens when focused at infinity, namely, $c \approx f$.

5. CAMERA CALIBRATION

5.1 Description of calibration

The calibration procedure is important for the successful implementation of this earthquake reconnaissance project, and its goal is to determine the camera's lens distortion parameters and interior parameters in terms of the fine-tuned focal length and the displacement of the principal point in a single run. The camera calibration usually involves two steps: (1) taking the calibration photos, and (2) deriving the camera parameters with those photos. Take an example of a calibrator in the well-established commercial software system – PhotoModeler® (Eos Systems Inc. 2009), which prevails both in the industrial market and in the research field. Twelve photos of a calibration grid are recommended to be taken from four edges of the grid with a combination of a portrait orientation and two landscape orientations (left and right) (PhotoModeler User's Manual 2004). The camera's focal length needs to be kept constant during the entire course of photo taking. In order to ensure that the entire lens is calibrated, the photo frames should cover as much as possible the grid dots when taking photos, and each four photos should have the grid dots align along the left, right, and top and bottom edge of the photo respectively (as illustrated in Fig. 7a). The calibration grid is a pattern of dots designed specifically for the Camera Calibrator in PhotoModeler®, and the Camera Calibrator is a computer program running on the algorithm to automate the derivation of camera parameters. Fig. 7b shows the cameras' positions and orientations when twelve photographs were exposed in PhotoModeler® as part of the camera calibration result.

(a) (b)

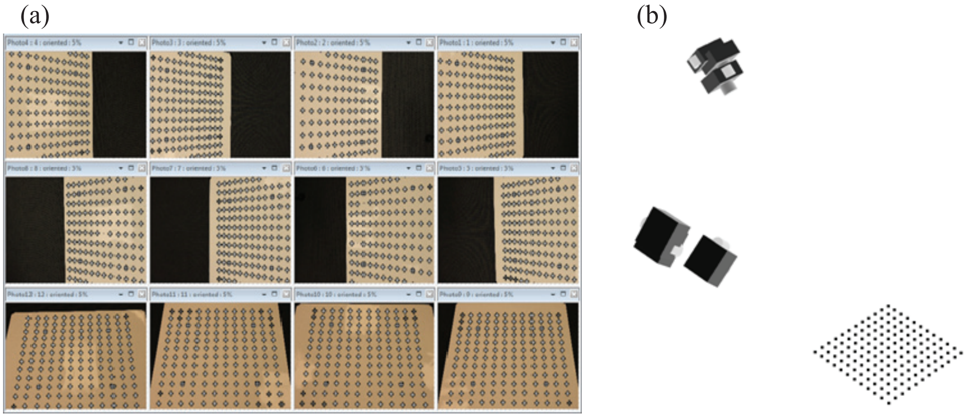

Fig. 7: Illustrated (a) calibration grid dots covered in twelve photos, and (b) twelve camera positions evaluated in PhotoModeler® as part of camera calibration result

5.2 Calibration results

The camera used to imitate the inspector's camera in this research was an off-the-shelf digital single lens reflection (DSLR) camera – Canon EOS REBEL T1i with its focal length set at 55 mm to obtain the longest shooting range of the camera. By following the calibration procedure described above, we have the calibration results for the designated camera as: the radial lens distortion parameters ($K1$ = -2.203e-005, $K2$ = -1.267e-008, $K3$ = 0), decentering lens distortion parameters ($P1$ = -1.179e-004, $P2$ = 0), the image coordinates (x_p, y_p) of the principal point (12.1573 mm, 7.7877 mm), and the adjusted focal length (f = 55.4121 mm). The threshold for evaluating the quality of calibration is that the maximum residuals are less than one pixel (PhotoModeler User's Manual 2004). In this research, this calibration yielded the maximum residuals value as 0.9191, reflecting a good calibration of the camera parameters. A residual here means the discrepancy of the distance between the calibrated each grid dot and its most likely value that is statistically calculated.

It is noteworthy that the calibration work is only needed during the first time of using the camera to take source photos. As long as the focal length doesn't change, successive modeling work can use the same calibration results to determine the internal camera parameters. The obtained camera interior parameters and lens distortion parameters will be used to calculate the undistorted coordinates of the projected image points in the experiments in order to test the validity of the proposed method, which is discussed in the next section.

6. LABORATORY EXPERIMENTS AND RESULTS

The indoor experiments were conducted in the UM Construction Laboratory to validate the feasibility of the proposed earthquake reconnaissance method. In the first phase, we primarily focused on the internal components of a digital camera that account for the measurement error. Thus, we used a tape rather than the RTK-GPS to manually measure the 3D coordinates of the camera position. Fig. 8a gives an overview of the setup for the experiment environment, in which a two storey reconfigurable steel frame was installed to mimic a building structure. The frame was calibrated with known precise displacement values at the second floor. To measure the camera's rotation angles, a 3D electronic compass was customized with a flat plate attached on the camera's hot shoe, and the angle readings were transmitted real time to a connected laptop with a data wire (Fig. 8b). The inter-storey drift between the second and third floor of the frame was studied in this experiment, and the positions of the inspected floors were denoted by two bolted connections that lie along the left edge of the frame as illustrated in Fig. 8c. Subtracting the horizontal axis components of the two connections thus helped compute the desired inter-storey drift.

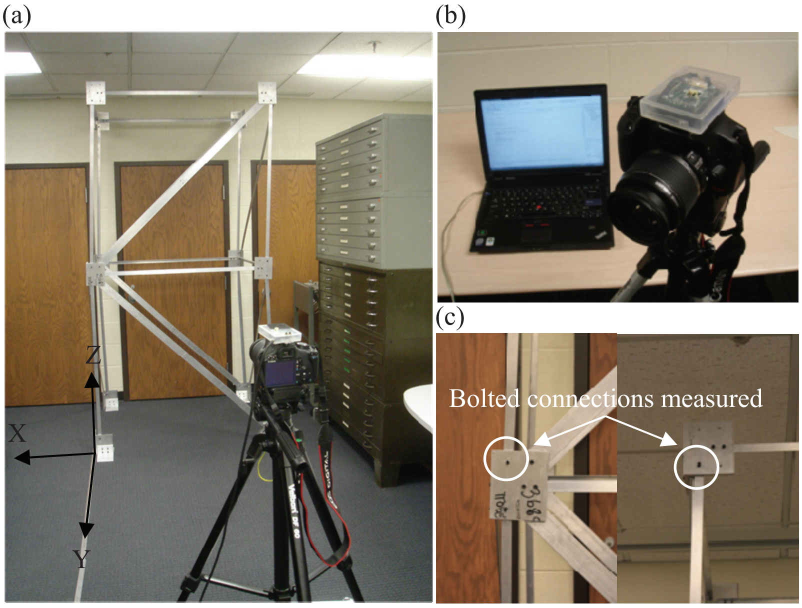

Fig. 8: (a) Experiment setup overview, (2) customized compass attached on the camera, and (3) bolted connections denoting positions of two inspected floors

The parameters for line of sight of the camera (*collinearity equations* Eq. 1) were fitted with the measured camera's coordinates and angles together with the adjusted camera focal length. For ease of computation, we simply assume that the X-axis of the global coordinate system is aligned with the horizontal movement of the inspected floors, the Z-axis is perpendicular to the ground that points upward, and the origin is at the left frontal corner of the frame (Fig. 8a). As such, the formula of plane to represent the inspected wall was obtained as Y = 0. Using the derived *collinearity equations* and the formula of plane, the spatial coordinates of horizontal axes for the bolted connections could be calculated from the captured images. Subsequently, the inter-storey drift could be determined.

The camera setup was as: the position coordinates (-0.489, 5.613, 1.34) m with the focal length set 55 mm. Three groups of experiments were conducted, of which each group had the camera's perspective rotated within a certain range to extensively verify the accuracy and consistency of measurements. The calibrated actual displacement was 45 mm to the left. The resulting measurements of the three experiments are presented in Table 1. The average errors for three groups of drift measurements are -5.87, -2.2, and -6.21 respectively with small standard deviations, all indicating a good level of accuracy in the proposed method.

The experimental results also reveal that the photos taken under the indoor laboratory condition (illuminated by fluorescent lamp) can have a satisfactory quality for applying photogrammetry. The camera used, which was the off-the-shelf Canon EOS REBEL T1i with the maximum resolution 15 mega pixels and autofocus functionality, is expected to take photos of even higher quality in an outdoor setting, where the reconnaissance system is genuinely utilized.

Table 1: Second-storey drifts measured using photogrammetry

	Group 1		Group 2		Group 3	
Frame No.	Drift (mm)	Error (mm)	Drift (mm)	Error (mm)	Drift (mm)	Error (mm)
1	-50.81	-5.81	-47.61	-2.61	-51.26	-6.26
2	-51.02	-6.02	-46.97	-1.97	-51.28	-6.28
3	-50.16	-5.16	-46.66	-1.66	-50.73	-5.73
4	-51.08	-6.08	-47.18	-2.18	-50.75	-5.75
5	-51.18	-6.18	-47.48	-2.48	-51.16	-6.16
6	-51.33	-6.33	-47.34	-2.34	-51.41	-6.41
7	-50.55	-5.55	-47.64	-2.64	-51.11	-6.11
8	-50.35	-5.35	-47.17	-2.17	-51.23	-6.23
9	-51.16	-6.16	-46.79	-1.79	-51.61	-6.61
10	-51.10	-6.10	-47.17	-2.17	-51.58	-6.58
Average Error (mm)		-5.87		-2.20		-6.21
Error Std Dev (mm)		0.39		0.33		0.30

7. CONCLUSIONS

This paper proposed a semi-automated method to rapidly measure structural damage induced in tall buildings by seismic events such as earthquakes or explosions by applying close-range photogrammetry surveying techniques and Augmented Reality (AR) visualization. Analytical measurement algorithms were devised, lens distortion and approximated calculation of camera focal length that account for camera systematical error were assessed, and laboratory experiments were conducted to validate measurement accuracy.

Future extension of the presented research is to implement the proposed reconnaissance system in non-laboratory outdoor conditions that real life seismic disasters reside in. External tracking Global Positioning Systems will be included to account for overall accuracy of this technique in extrapolating the inter-storey drifts. Recent advances in satellite transmission technology allow the dual-frequency GPS receivers to achieve a centimeter level of accuracy for RTK work without base station (Trimble® Vrs Now™ 2010), which promises to overcome the technical hurdle of tracking the inspector's (camera's) perspective for the proposed technique to be deployed in the field.

Another extension is an endeavor toward full automation of the reconnaissance method by looking into techniques in the research area of computer vision for direct detection of edges of key floors sustained in a damaged building on images. Preliminary study has found that the outline of a damaged building can be effectively extracted by the Active Contours technique (Caselles et al. 1997) embedded in Augmented Reality visualization. Nonetheless, the technique's validity and applicability should be further meticulously investigated.

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IV. GAME ENGINE AND EDUCATION

LEARNING AND TEACHING DOMESTIC CONSTRUCTION COMPETENCE USING SERIOUS VIDEO GAME TECHNOLOGY

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ABSTRACT: *For the accreditation of standards in all vocational higher education learning contexts, the question of how to develop and assess competence is central. There are certain situations where relevant skills can be assessed in the workplace, but for most the only viable option is to simulate a practice setting in something like a workshop/studio, by modelling or through role-play. The possibility of replicating a dynamic workplace situation and the competences that go with it in an immersive virtual reality offers perhaps the first practical opportunity for large student cohorts to practice and assess technical competence in a robust and secure setting. This paper outlines a pilot project currently under development that seeks to develop a serious video game built in CryENGINE2 to enable first-year construction management students to learn and demonstrate their technical competence in domestic construction. A theoretical framework for the design, development and evaluation of serious video game technology is detailed, based on the various work of de Freitas and of Luckin. The project development to this point is described and illustrated. Learners playing the game are required to source a variety of tools which they use to deconstruct (demolish) a selected building model. For example, at the simplest level, they might use tools such as a virtual crow-bar or an excavator to dismantle a domestic house model piece by piece. Alternatively, using a form of forensic analysis, the learner is required to determine how particular domestic house models (constructed with deliberate design faults) may or may not fail to satisfy statutory and other building regulations.*

KEYWORDS*: Competence, Serious Video Game, Domestic Construction, Production Framework.*

1. SOME BACKGROUND TO LEARNING AND TEACHING DOMESTIC CONSTRUCTION COMPETENCE

Construction technology is a significant, core component of all undergraduate built environment degrees. In Australia it constitutes more than 20% of the first year architecture degree (Ostwald and Williams, 2008:126) and 25% of the building degree curriculum content (Williams *et al*, 2009: 20). A significant component of this construction technology curriculum traditionally has been provided through site visits to building projects currently under construction, where students can observe the process and technology of construction work in action. However, as class sizes increase, occupational health and safety regulations are tightened, potential site locations become more distant and the temporal nature of construction means there is only ever a minimal window of opportunity to witness particular aspects of construction technology in action, it has become increasingly infeasible to provide direct student exposure to the broad practices of construction technology in a realistic setting (Mills *et al*, 2006). Equivalent difficulties face all vocational education programs where the practice situation involves dangerous and/or expensive process/technology contexts: invasive health procedures, high-technology manufacturing processes, special events and emergency response management, etc.

In such situations, the potential of replacing direct student exposure with a virtual simulation is apparent. In construction technology education, for instance, a number of previous initiatives have utilised a mix of Computer-Aided Design (CAD), QuickTime VR, video and multimedia as virtual substitutes for actual site visits (Horne and Thompson, 2008; Ellis *et al*, 2006). Such initiatives certainly provide useful illustrations of the technical understanding required of architects and builders, including (though generally indirectly) illustrations of relevant technical skills such as the scheduling of construction work tasks, project team management and the forensic analysis of construction defects.

Whereas knowledge-based learning can quite readily be demonstrated and assessed through written and oral tests, skill-based learning (competence) requires the student to practice and demonstrate actual activities. Competence is fundamentally about the assessment of an individual's capacity to perform certain professional tasks in given situations in a particular way (Cowan *et al*, 2007). Neither actual nor virtual site visits are, as and of themselves, sufficiently interactive for competence-based learning outcomes then to be demonstrated by the student or directly assessed by the teacher. The question of how students might practice and demonstrate competence in core discipline-specific skills (such as construction technology), particularly where such skills are best exercised in a difficult practice setting (such as a construction site), is yet to be resolved. The same question also still applies to those students who might study to become a doctor, engineer, surveyor, or for any number of professional practice outcomes.

The classic approach to competence assessment has involved simulated or quasi- professional practice settings. For example, in architecture it is the design studio and in medicine it is the clinical placement. In building and engineering construction technology, one equivalent approach has been a form of, so-called, 'constructionarium' (Ahearn *et al*, 2005). A constructionarium, in this sense, is any controlled site setting where students under supervision work in teams to produce a construction outcome that might range from building a discrete brick wall, to a short-span bridge and potentially a complete (simple) building. In a constructionarium-type situation, students are able to experience, practice and (most critically) demonstrate (ie. be assessed on) the technical, process and management aspects of particular construction activities. Unfortunately, whilst constructionarium-type exercises provide excellent learning experiences, the significant material and organisational costs associated with such projects renders them entirely impractical to apply across the curriculum and/or to large student cohorts.

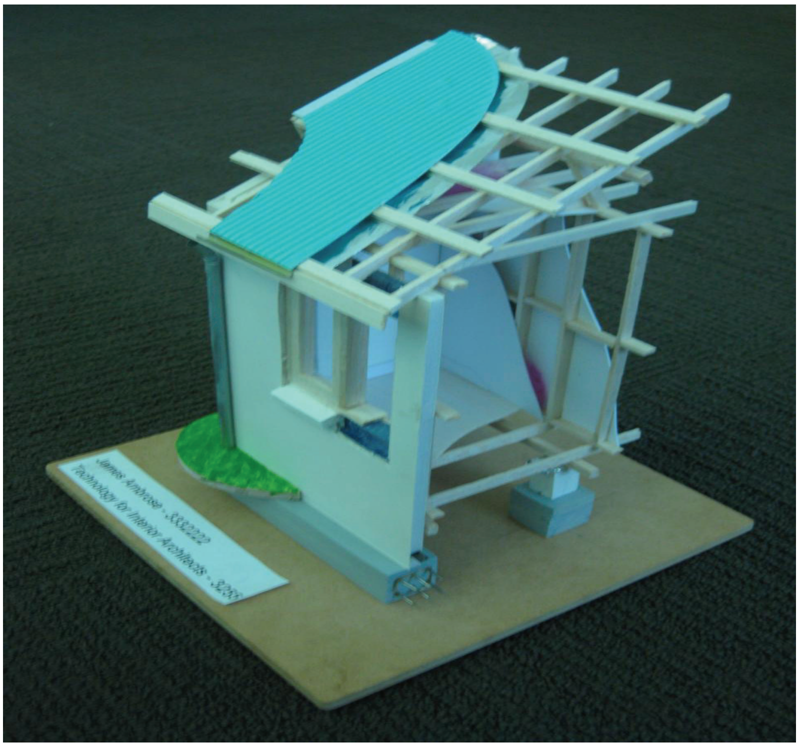

Figure 1: A student 1:10 scale model outcome for a typical domestic construction exercise.

One alternative to the full-scale constructionarium-type exercise is to operate on a smaller, more economic scale. For example, to have students construct, say, a 1:10 scale-model of some construction outcome or construction component in a workshop environment. Figure 1 illustrates the 1:10 scale model outcome for one student exercise which models a typical domestic construction in Australia. Such a modelling exercise is able to address both the process and the technical details of a simple domestic construction project (see, for example, Forsythe, 2009). The scale-modelling approach is certainly a more viable exercise than the constructionarium-type exercise in terms of the resources consumed/required, but its utility in learning and teaching terms often depends as much on the generic model-building skills of the student as it does on their technical competence in construction technology.

So, the basic question behind the pilot project described in this paper is the extent to which the controlled site-setting and full-scale nature of a constructionarium-type exercise might effectively be replicated using a virtual reality technology in order to assess technical competence in a way that is more scalable across the curriculum.

2. A BRIEF CONTEXT FOR THE CHOICE OF SERIOUS VIDEO GAME TECHNOLOGY

The most sophisticated interactive virtual reality simulation environments are to be found in video games. Video games use high performance graphics engines to render moving photo-realistic scenes in real-time and 3D along with the potential for associated surround-sound audio and tactile feedback to a user who controls the action with a variety of input devices. The 'action' is in fact variously controlled not only through input devices, but also by the particular rules and properties 'coded' into the video game by the developer. Rules and properties are not fixed, but are available to be modified by game designers using tools supplied by the developers (see below in Section 4 for further detail). Such coded rules and properties are now extremely sophisticated, and many incorporate models of real-world mechanical behaviours ('physics engines') that simulate physical properties such as mass, gravity, velocity, volume, etc. in equivalent detail. Objects in such games can variously be opened, pushed, bent, lifted, broken and/or be used to trigger a myriad of other actions. Artificial intelligence and social dynamics are also now being modelled and incorporated into video games to simulate agency and the group behaviour of different game 'actors'.

What is particularly timely about the potential development of video games for learning and teaching, is the recent initiative to make available the 'game engines' themselves (the kernel of coding used to drive a collection of actual game implementations) on a basis equivalent to open-source. Even the most powerful game engines are now relatively cheap to buy (or come free of charge), are intentionally configured to allow third party modifications to be created and embedded seamlessly into the game engine, and are increasingly supported online by a significant and committed community of users and developers. This all is important, because it lowers the potential barriers to the deployment and uptake of video game technology by and within the teaching and learning sector.

Several examples of 'serious video games' (a serious video game is one designed for a primary purpose other than pure entertainment) have now been developed as modifications to game engines across a range of game genres. For example, 'vehicle simulation engines' have long been used to train and test vehicle operators from fighter pilots to crane drivers (Rouvinen *et al*, 2005); 'strategy game engines' are variously used for teamwork and project management training; 'business simulation games' model economic and manufacturing environments. The project described in this paper will focus on a specific genre of video game known as a 'first-person shooter' (FPS) game. FPS games are characterised by the use of an avatar which presents the first-person perspective that enables the player to see and be seen as a person would conventionally occupy a space (ie. bound by and to one's own body). Other similar game genres adopt either a more abstract form of engagement (such as the third-person perspective characteristic of games like Sim City, and entirely command-driven game controls) or tend to focus more on the interaction and communication capabilities across a social network (as is the case in Second Life worlds, for example).

The important context particular to this paper, however, is how the design and development of any serious video game might be evaluated not just as a game, but as a learning technology – and not just as a stand-alone learning technology but as part of a constellation of teaching and learning resources. In this regard, the standard design and production process for video games has to be broadened in scope to include explicit consideration of the teaching and learning context and within what Luckin (2008:449) terms a "learner centric ecology of resources". New serious video game initiatives are beginning to fashion such an explicit and specific overarching design and evaluation framework specific to the teaching and learning sector (de Freitas and Jarvis, 2006). This paper further develops such a theoretical framework.

3. A THEORETICAL FRAMEWORK FOR THE DESIGN, DEVELOPMENT AND EVALUATION OF SERIOUS VIDEO GAME TECHNOLOGY

The video game industry itself is massive, with a recent Nielsen Games survey of U.S. consumers showing that expenditure on video games now represents 5% of total household spending on entertainment – more than for books, films or music (NielsenWire, 2010). Hardly surprising then, that the video game industry now has in place a robust general framework for the overall production process (ie. the design, development, deployment and evaluation of video games – see for example, Adams, 2010). The typical framework adopts an integrated production approach that seeks to promote the key user requirements as critical success factors throughout a traditional, strongly iterative, ‘analysis-synthesis-evaluation’ production process (Kirjavainen *et al*, 2007). That said, the learning and teaching context does introduce novel and additional factors into the production requirements of any technology application (Woods, 2004).

A structured approach to the production of a learning technology, it might be argued, is important so that lessons can be learned and applied going forward. However, few such frameworks with relevance to the more highly immersive video game technologies exist. Established, and more generic, learning technology production frameworks (such as TILT, CIAO! and Flashlight – see Oliver, 2000) tend to limit the scope of consideration to include just the educational outcomes that a learning technology is intended to address/promote (the pedagogical approach – pedagogy); the educational context within which it functions (how it is deployed – context); and how the technology functions *per se* (how the technology presents itself to a user – representation).

Recently, de Freitas and Oliver (2006) have extended the generic production frameworks for games-based design and production to a four-dimensional model. That evaluation framework is now also being used “… to support the development processes of training games applications to ensure that the game will have efficacy for targeted learner groups.” (de Freitas and Jarvis, 2006:3). Figure 2 presents the four-dimensional framework.

Four Dimensional Framework	
Learner Specifics Profile Role Competencies	**Pedagogy** Associative Cognitive Social/Situative
Representation Fidelity Interactivity Immersion	**Context** Environment Access to learning Supporting resources

Figure 2: A Four-Dimensional Framework for Game-Based Learning (de Freitas *et al*, 2010:72).

According to de Freitas *et al* (2010), these four dimensions are necessary to provide the full complement of considerations relevant to a teaching and learning application that builds on the immersive character of FPS (and similar) games. In a way that parallels previous frameworks, this model requires consideration of the pedagogy (the theory and practice models that frame the learning activities), context (including the resources available to deliver, access and support the game), and representation (the form or mode in which the content of the game is made manifest to the user – explicitly, implicitly, vicariously, etc.). However it also extends this consideration through a more explicit inclusion of learner specifics (including learner attributes and preferences).

The ‘fourth’ dimension in this case requires presumed and actual learner activities during the use of the learning technology to be profiled and analysed explicitly. Profiling the user directly is of particular significance in the design and evaluation of serious FPS games, because, in a sense, the interaction between the user and the game ‘is’ the learning experience. Matching the learning activities possible within any given serious FPS game with the required learning outcomes and then scaffolding the learning pathways is critical.

Whilst the de Freitas and Oliver (2006) four-dimensional framework for game-based learning already includes elements of pedagogy, context and learner specifics, those elements are included from a particular (and limited) point of view – the technical development of a particular serious game technology implementation. A broader theoretical framework is required to capture the range of educational technologies, implementation strategies, available learning resources, types of learners and timeframes. For a broader perspective setting this paper has adopted the concept of a learner-centric ecology of resources, as proposed by Luckin (2010). In this theory, the learner is placed at the centre of three dimensions: the skills and knowledge to be learned, the resources available to support learning, and the environment within which learning occurs (see Figure 3 for a representation of this model).

In broad terms, this framework includes the same general elements for consideration: pedagogy, context, representation and learner specifics. In this model however, the relationship of each dimension to the learner is processed/filtered through a particular delivery medium: knowledge (pedagogy) is filtered through the particular design of the curriculum; available resources (context) are filtered through the particular way those resources are administered and made available to the learner; and the environment is represented to the learner (representation) through the particular organisational/technological structure within which they learn. Luckin (2010) also articulates a further dimension for all considerations (represented in Figure 3 by the grey box surrounds to each element), that recognises each aspect emerges from and impacts upon the broader historical/cultural background against which they must be set. The significance of this historical shadow to each element (the history of experience that impacts upon how the various elements interact) is still to be demonstrated empirically, but certainly in principle the existence and the importance of this wider cultural perspective needs to be recognised if possible in the game production process.

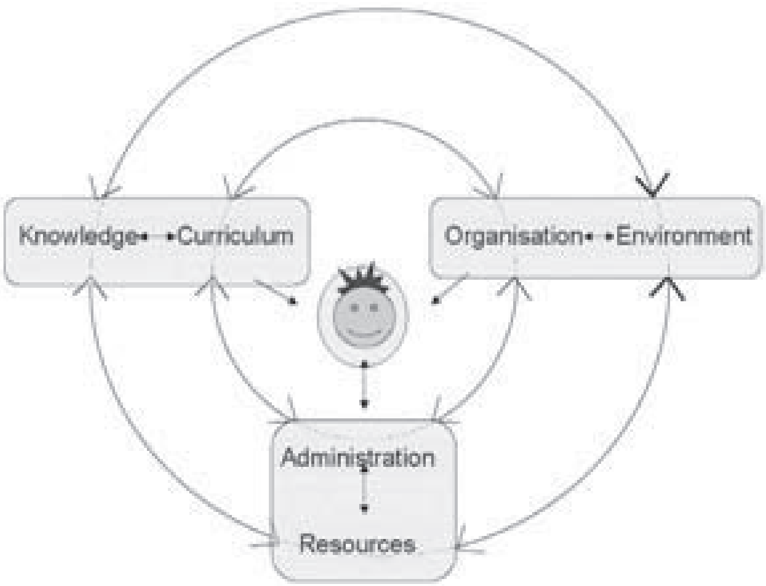

Figure 3: The Learner Centric Ecology of Resources (Luckin, 2008:453)

The current pilot project is following previous examples of how the notion of an ecology of resources, linked to the tools and techniques identified through the de Freitas and Oliver (2006) model, can be used as a design and evaluation framework for education technology (see, for example, Luckin, 2010). However, this particular pilot project will also relate very directly to the development of professional knowledge and competence – see for example Eraut (1994). Fortunately, the ecological framework seems entirely in keeping with most models of professional competence, and any framework that promotes and improves our understanding of the sociocultural context of and for professional practice will contribute to the broader consideration of learning as a situated activity (Wenger, 1998). In particular, it extends the research program proposed in Chaiklin and Lave (1996:30) to "focus on the content of and the ways people participate in changing social practices singled out for study because they appear to lie at the heart of the production and reproduction – the transformation and change – of the sociocultural order." In other words, the particular opportunity offered by serious video games to situate learning within an authentic professional context is critical.

Of course situated cognition is not without its critics (Vosniadou, 2007), and an approach that is exclusively sociocultural would undoubtedly ignore key cognitive aspects of learning and teaching. The focus of this project is on competence-based learning and assessment. It presumes that knowledge-based learning is a necessary precursor to skill-based learning. So, whilst we might never reach a definitive expression of competence in sociocultural terms alone, it seems equally inconceivable that competence is something that can ignore human dispositions and social constructs (Hager and Holland, 2006). The growing significance of competence in higher education requires that more urgent attention is given to how we might teach and assess skill-based learning in that sector.

Returning to the concluding statement of Section 1 above, the basic question driving this project is the extent to which a virtual reality technology enables specific technical competence to be assessed in a way that is scalable across the curriculum. In doing so, however, we must also guard against complacency in the face of seemingly ever increasing sophistication (and ‘reality’) in the simulation technologies available. Virtual reality technology is impressive, but it is patently not ‘reality’. The ‘experience’ of a construction site and the practice and demonstration of construction technology competences in a virtual environment does not equate in every respect to the same experiences and demonstrations on an actual construction site. The entailments of a virtual versus a real situation are both positive (the virtual situation can be controlled, is available, scalable, specific, etc.) and negative (the virtual situation lacks serendipity, is abstract, simplified, sanitised, etc.). It is important, therefore, to examine the strengths and weaknesses of serious video games as a replacement for actual construction project experience. Of course it need not be an either or replacement. A particular advantage of video gaming technology is the relative ease with which a game designer is able to adjust and balance these entailments to suit a particular context.

4. A DESCRIPTION OF THE PILOT PROJECT DEVELOPMENT TO THIS POINT

A pilot project is currently in development, adopting the hybrid development framework as outlined in the previous section. A full articulation of that framework and how it is being applied is beyond the scope of this paper, but a broad specification and description of the game prototype now follows.

The implementation has been developed as a ‘first person shooter’ (FPS) game based on the CryENGINE2 video game engine. The choice of an FPS genre is considered in Section 2 above. The choice of CryENGINE2 is a consequence of our having designed and implemented a number of teaching-based and research-based initiatives using this (or directly equivalent) platform(s) in the past. For example, Lowe (2008) details the use of a FPS application used in a first-year architecture studio on design development and representation, at the University of New South Wales. This studio has run over several years and successfully involved hundreds of students in the use and modification of a serious video game application. Lowe and Goodwin (2009) details one of various applications where a FPS game engine has been used by the authors in a research context.

CryENGINE2 is also appropriate to the current application because it features more advanced graphical, physical and animation technologies than many others. For example, Figure 4 demonstrates the quality of graphic representation possible using CryENGINE2, and the goal of the current project. Image A is taken directly from http://wonderlandblog.com/ and Image B from http://forum.i3d.net/. In this case the modelled buildings have been fabricated using corrugated sheeting for the roof, with timber structural elements and large sheet cladding, which would suit the intended narrative structure of the game very well (see below).

Figure 4: Two examples (**A** and **B**) of the graphic capabilities of CryENGINE2, specific to domestic construction.

The proposed FPS game will replicate the current physical scale modelling activities of first-year Construction Management students studying domestic construction technology (refer again to Figure 1). In the first instance, however, the interactive construction of models will not be possible and student interaction will be restricted to the demolition of existing models in the game. Thus, the broad game narrative has been developed around the use of various high-definition building information models imported into the CryENGINE2 environment. A range of domestic buildings that model a variety of foundation, floor, wall and roof construction options in detail will eventually be incorporated. Each imported model represents a different form of domestic construction, and is generally being replicated and placed across a range of site conditions within the gaming environment.

The construction options to be included contain a mix of correct and problematic technical solutions for each particular site context and construction combination. Learners playing the game are required to source a variety of tools which they use to deconstruct (demolish) a selected building model. For example, at the simplest level, they might use tools such as a virtual crow-bar or an excavator to dismantle a domestic house model piece by piece. The use of such tools in this way will enable students to practice and demonstrate their understanding of how different building examples are constructed, through the subsequent production of process maps and schedules of the work tasks specific to the building models they selectively deconstruct and subsequently reverse engineer. Students essentially demolish the buildings and then produce a report on the findings of their analysis.

Alternatively, using a form of forensic analysis, the user will be required to determine how particular house models (constructed with deliberate design faults) may or may not fail to satisfy statutory and other building regulations. The forensic approach will use a further range of specially designed virtual game tools to provide such things as x-ray views of wall constructions, sample testing of concrete finishes, etc. Using the information gleaned from such tools, students are required to diagnose and account for any failures/incorrect construction details/poor work practices expressed again in terms of the process maps and schedules that builders are expected to produce in practice. All of the virtual game tools are modifications to existing 'weapons' (such as swords modified to become crow-bars), 'vehicles' (such as trucks modified to become cranes), and 'material parameters' (such as adjusting opacity to simulate x-ray vision). The modification involves existing models of objects in a game (say, a sword or a truck) being visually modified to look like a crowbar or a crane and adjusting the relevant physical properties/behaviours of the objects (as registered in the game) accordingly.

For example, Figure 5 shows a screen-grab of one model already incorporated into the pilot game. This model was first created in as a conventional Building Information Model (BIM) using Sketch-up and ArchiCad. The BIM approach allows actual construction details and properties to be included, and for the final CAD model to represent individual building components in significant detail. The model is then imported into a prepared CryENGINE2 environment and multiple learners/users are then able to roam around the environment and examine each model (and other users) in real time. In this particular case, one user has employed a simplified cutting device to demolish and expose critical elements of the building, including details of the upper floor construction and window/wall joints. The result is equivalent to the modelling approach used with physical scale-models, as illustrated in Figure 1. In this case, however, the learner must select the cut-backs to reveal particular construction details in order to make a judgment on the choice of construction technology employed.

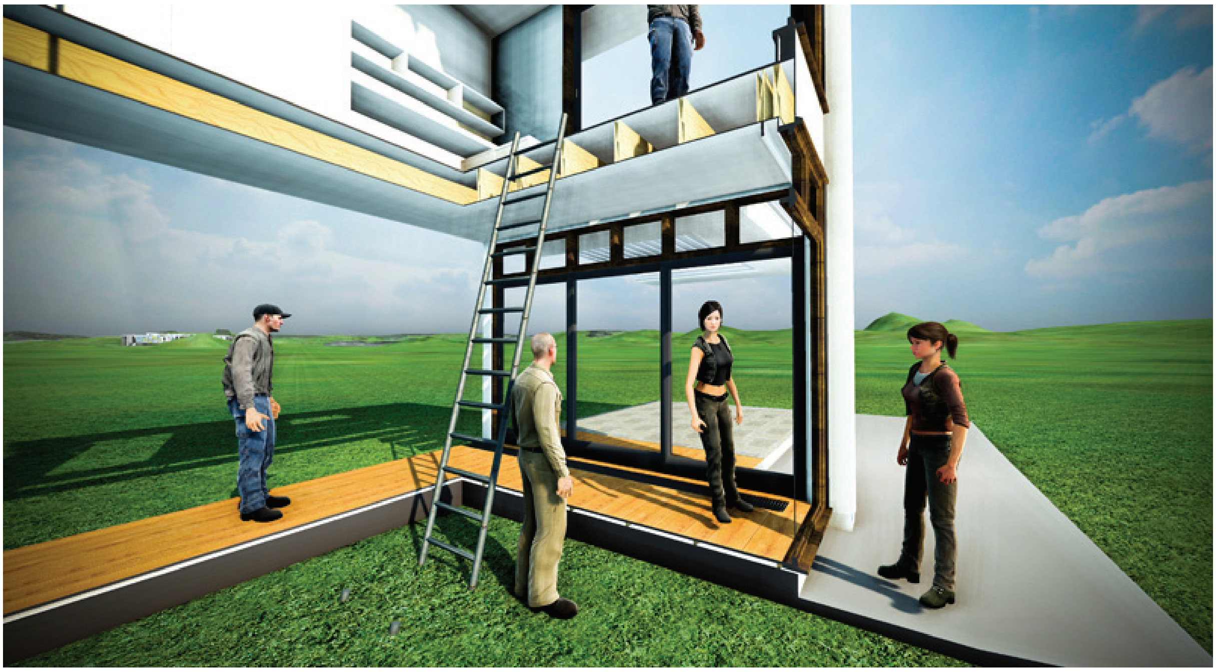

Figure 5: An example screen-grab from the pilot project, courtesy of Andrew Wallace (Lara Calder Architects).

Teacher and tutors will be able to deploy the developed system in a variety of ways. They may wish simply to make the system available to students to complement traditional teaching and learning material. Alternatively, they might teach the knowledge and skills required using conventional methods and employ the system specifically for the assessment of technical competence. The goal, however, is for the system to become a primary teaching and assessment tool within a broadly problem-based learning approach. In any event, extensive documentation, examples and case study material will be developed and made available to other institutions and analogous discipline groups along with support for the necessary academic development required to incorporate the approach into existing curriculum effectively. The more teachers/tutors who become active users of serious video game technology, the easier it will be for a community of practice to support various development activities. Online support, in the form of community discussion lists and open forums, is already an established practice for the gaming community.

5. OTHER ISSUES AND FUTURE DIRECTIONS

Any high-end computer application is going to raise a number of concerns and problems for potential adopters at the institutional, teacher/tutor and learner levels. At the learner level, there are always issues of equity raised when students are required to use a novel learning technology because not everyone relates to a particular technology intuitively. Care will be taken to provide the necessary exercises and tutorial material specific to the game implementation that many students need to scaffold their effective use of such technologies. There is already a substantial body of online tutorial material associated with the generic interface and use of CryENGINE2 available within the public domain. More specific tutorial support material for the domestic construction technology application will be developed as part of the second phase of system evaluation.

The main challenge for the dissemination of this technology is likely to be at the institutional level. Serious video game technology puts particular demands on computer capabilities, particularly in terms of the graphics and processing power. Particular attention will be given to the production of documentation aimed at the technical computer support required for the deployment and subsequent maintenance of relatively sophisticated video game engine applications across a range of different computer lab configurations. The project group are encouraged that they have been able to facilitate over 250 first year students to utilise a complete suite of the software required, using a significant range of personal laptop configurations, including Mac and several Windows operating systems. Effective download speeds and the amount of internet traffic generated by such high-end graphics do, however, remain an issue.

Ultimately, although the technical development of such a game is rather more ambitious, students will be provided with the opportunity to source a variety of building components (and materials) which they will then be required to assemble into viable domestic house constructions. In this way, students will be able to demonstrate the full range of technical competence expected of them (mapping the construction process, planning the sequence of tasks, selecting a viable configuration of materials and design options, ensuring compliance with relevant building codes and regulations, coordinating the construction activities, etc.). Buildings completed by the students in this way could then be included as part of the set of building information models placed in the game for analysis (and review) by their peers and teachers.

For the accreditation of standards in all vocational learning contexts, the question of how to develop and assess competence is central. There are certain situations where relevant skills can be assessed in the workplace, but for most the only viable option is to simulate a practice setting in something like a constructionarium/studio, by modelling or through role-play. This opportunity extends across all professional education disciplines: in the built environment it might relate to work practices on a construction site; in health, to triage work in an emergency situation such as an explosion on an underground train; in engineering, to work in remote or treacherous locations such as capping deep-sea oil wells; in science, to work in restricted areas such as a nuclear power-station; in defence, to work on expensive facilities such as a submarine; in business, to work in the service sector such as event management; in education, to work in classroom layout and design; and so on. The possibility of replicating a dynamic workplace situation and the competences that go with it in an immersive virtual reality offers perhaps the first practical opportunity for large student cohorts to practice and assess technical competence in a robust and secure setting.

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LEARNING FROM VIDEOGAMES LEVEL DESIGN: AN EDUCATIONAL POINT OF VIEW FOR ARCHITECTURE

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ABSTRACT: There are two fundamental aspects that characterize the profession of an architect: design and construction. Usually in schools of architecture, inside the design laboratories, students never participate in the construction phase. It would be very educational to follow a project from the initial concept to the final result, but this is often not possible due to lack of analysis, funding and equipment. In this paper we propose to look at level design for the creation of 3D worlds of videogames as a method of design education. This could be an interesting topic of study for a university course in a faculty of architecture through the development of a methodology and the complete process from a basic concept to a finished product, complete, playable, and usable. Level design is one of the topics closest to architecture, both in design methodology and arguments to be developed, like space and activities taking place inside it. We believe that making a level could represent an important technical and creative exercise for students because they can carry out and develop some themes more in depth and in a more innovative way than with traditional courses.

KEYWORDS: *Architectural Design, Level Design, Design Methods, Educational Methods, Game Engines*

1. INTRODUCTION

The term Architecture derives from the Latin *architectus* which means architect, although this word has Greek origins. *Architekton* is a word composed by the terms Arche and tekton and it could be translated as first craftsman, the head manufacturer. This definition reveals the basis of architecture. By playing the role of chief manufacturer, an architect should be able to design a building, starting from a context and a basic idea, and to control its construction. In fact, architecture, although it has different meanings in its traditional sense, is defined as the art and science of designing and constructing buildings. Hence the two fundamental issues that characterize the profession of an architect are included in its meaning: design and construction. This discipline hence belongs to two cultural spheres, the humanistic and the scientific.

We agree with Biondillo (2008) that architecture is the most beautiful academic discipline, the most exciting and the most varied. In fact an architect has to know many subjects like history of art, construction techniques, aesthetics, urban planning, restoration and composition, just to name a few. This means that architecture is "the last discipline which is still quintessentially Renaissance, where everything leads to everything." (Biondillo, 2008) A knowledge so wide that you need to interface with all other players in the building process, because the architect is a coordinator of complex processes, and for this reason can also be compared to a movie director. He/she does not know every single subject in details, but is able to coordinate the work of other professionals and talk with everyone. The variety, complexity and vastness of these topics and the relationships between them can be problematic for young students of Architecture, who are faced with a discipline that does not show precise boundaries.

In fact, the aim and the main challenge for a young student of architecture is to learn how to develop and manage the different phases of a project, often passing from the details to the general and vice versa, up to the final result. An architectural project is a complex of interdependent activities that, starting from an initial idea, through several steps, will enable you to obtain the documents essential for the construction of a building. It would be very educational to develop and follow all the stages of a project, starting from the initial idea up to the implementation phase itself, using all the tools you need. Unfortunately, very often, because of various difficulties, this is not possible. The analysis, time, resources and equipment to carry out, for example, even of a small prototype for a garden, are not always available to everyone. The universities courses such as Architectural Design, Architectural Technology and Design of Construction Systems which are undoubtedly very useful, but most often, at the end of the said courses, they leave the student with a number of pending questions.

In this paper we will analyze the various stages of a methodological design course by comparing the methodology of a traditional course with that used in creating virtual environments for videogames, a technique called 'level design'. Our goal is to demonstrate how level design can be useful to students, and how this interesting subject can be added in a course of architecture, It would allow to address some design issues in greater depth and in an innovative way, helping to enrich and augment the student's knowledge.

2. REFLECTIONS ON THE DESIGN PROCESS IN A TRADITIONAL COURSE

The main aspect of training a student of architecture is represented by learning a design methodology. In the various Italian schools of architecture, the design disciplines can be divided into two categories: compositional and technological. The various steps of the design process are very similar for both, but the subjects belonging to the technology area stand generally for a more analytical approach. In addition, a course of traditional architectural design, usually, without neglecting other features, is more oriented to the study of the aesthetic qualities and composition of the project. In a course such as Architectural Technology or Design of Construction Systems the student should develop, in addition to the aesthetic and compositional characteristics, the technological and constructive features essential to facilitate the construction of the building. The aim is to produce a project that is technically feasible. In this way we try to bring the student through a design experimentation, from which they discover the key aspects of the professional practice of an architect, as already mentioned in the introduction: design and construction.

2.1.1 THE METHODOLOGY OF A TRADITIONAL COURSE

The following scheme is a summary of the steps and instruments adopted during a typical exercise concerning a Design Course in Construction Systems (Prof. Sonsini). The methodological process can be divided into three basic steps:

Preliminary step:

- In this introductory phase we define: the subject of the design practice and objectives of the project also in relation to the specific needs;

First Step: Analysis

- The first phase is characterized by a series of analysis on site, on the activities and spaces. Once listed the user's main activities, differentiating categories, we take into consideration the relations between the spaces checking through the graphical matrix, any incompatibility and levels of communication. The last step is to develop two ideograms, one without real dimensions, and the other dimensioned, the latter starting from the identification and dimensioning of equipments and space needed for the use the of the client/user. In the ideograms the flows of movement and levels of communication are also shown (Fig.2);

Second Step: Design Process

- The design process begins with the translation of the dimensioned ideogram in a project idea, a shape, in other words, it represents a personal architectural vision. Through a series of drawings composed of layouts, sections and renderings, we analyze the following models: functional organization (spaces organized in a hierarchical way, the flow paths, etc..) Spatial (introduction of the levels of use and their related roles), structural (spatial structure of the model according to a geometric grid derived from the choice adopted by a static-type structure). When the project reaches an advanced stage we begin to study the significant details for assembling components and materials.

2.1.2 Considerations on the teaching method

From the educational results, we can say that the methodology described above (Fig. 1) is very effective in pursuing the objectives that the course intents to achieve. However this subject, despite being among those more oriented to define a buildable project, stops itself to the definition of construction details. It would be very educational to go beyond the project, continuing with the construction phase, but as we already mentioned in the introduction, this is not always possible for several reasons. In the schools of architecture there are also design courses that in some cases allow us to follow the complete process from the concept to the construction. However these are still objects, while a central role in architecture is covered by spaces and actions that take place both inside and outside. Therefore, is there a field alongside the traditional design and technology courses, which can be useful for the education of a future architect?

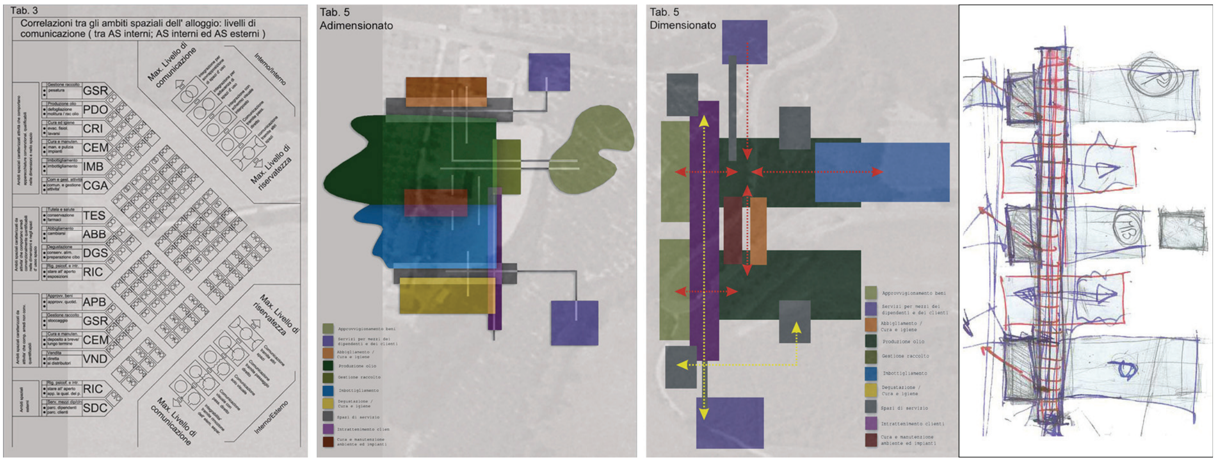

Fig. 1: Images from the methodology of a traditional course. From left to right: the graphical matrix to analyse the levels of communication, the ideogram without real dimension, the dimensioned ideogram and a sketch of study to translate the ideogram in a first architectural plan.

3. LEVEL DESIGN

3.1.1 A GENERAL OVERVIEW

Reflections and personal experiences permit to identify a discipline, relatively recent, which shows a design methodology similar to the one used in a design course or within an architectural firm. We are talking about level design for videogames.

The term 'level design' refers to the design of individual sections of a computer game. The idea of these levels comes from the first shoot'em-up games and platform games, where the game was divided by sections, each of which had increasing difficulties (Thompson, J. et al. 2007). In fact, it often referred to the next section as to the next level. In many games the term level is synonymous of map, mission or step. The first videogames were only in 2D, the screen was fixed and the players' movements and activities were limited to two dimensions.

Over the years, and with the advent of more sophisticated hardware and software, we reached video games where the action takes place in three-dimensional worlds. The two main types of 3D games are divided according to the player's point of view. A first-person viewpoint simulates the world as seen from the player's eyes, while a third-person viewpoint sets the camera at some distance behind the shoulders of the main character of the game. The choice of one of the two perspectives influences the player's experience (Fig. 2). Although the methodology to create a level for both types of games is almost identical, we prefer to concentrate on the games in first person, because they allow us to move and observe a space in real time, providing an experience and a freedom of movement much closer to reality.

Fig. 2: From left to right: An example of a game with a third-person view (Prince of Persia), and a game with a first person view (Unreal Tournament 2004. The map is a personal work of the author, Vertical Factory 2).

The level design is concerned with the creation of worlds and 3D architecture of video games, but the task of level designers, doesn't stop only to the design and creation of graphic and architectural features that make credible the various environments. The level designers are in fact also called to define the gameplay elements such as positioning in the map of the bonuses and other objects that the players can collect or with which they can interact (elevators, buttons, boxes, furniture, etc.) or paths supervised by enemies. The term "designer" also puts them in the same category of the 'game designer', but unlike those who are interested in a particular way of understanding the general idea that lies behind a game, level designers are also committed to the realization phase, to translate concepts into playable and interesting environments and experiences, adapted to video games. A level designer has to possess both artistic and technical skills and has to be able to control and bring together within a level aspects linked to gameplay, architecture, audio, programming, and cinematography.

3.1.2 THE DESIGN PROCESS OF A LEVEL

The following methodological process, describes the basic steps and tools used during the creation of some personal works, in particular deathmatch maps for some of the video game Unreal Tournament series.

Preliminary Step:

- We define the principal objectives, ie you decide the game mode you want to create the map, in this case, deathmatch, and the type of gameplay. At this stage you choose a theme that will determine the definition of space and architecture. It is useful to write down a brief description of the place and its history, to enrich the theme details.

First Step: Analysis

- Also the first phase of a design level provides analysis. You create several sketches and diagrams to study aspects of gameplay, the links between different areas of the map and the dimensions of space. From a first conceptual diagram, after one or more steps, we have reached a diagram that looks very much like a floor plan, with more defined areas and routes. During this phase we begin to study also the first visual characteristics of the places, such as height, architecture and decorations. To analyze these issues it is not necessary to use a software, but since this is still an early stage, it is sufficient to do some hand sketches in plan, elevation and section. All the information elaborated at this stage will be collected in a handwritten form in a level design document.

Second Step: Design and creation Process

- The second phase differs from that of a methodological traditional course because apart from being a design phase it is also a construction phase. We start by drawing in a 3D modeling package, or directly with the editor of the game chosen, the map layout, mainly composed of simple geometric figures. With this model, we can test the gameplay and the positioning of the basic objects. Once a functional layout, is defined, which determines how we see the game-flow, we move to the creation of the architecture and its details. Once the geometry is completed we proceed to the following step: the texturing, lighting and audio. All the decisions made must be coherent and must express the chosen theme and atmosphere to their best.

4. THE UTILITY OF LEVEL DESIGN FOR STUDENTS OF ARCHITECTURE

From this schematic comparison it is clear how the two methods present many points in common. In support of our consideration we can mention some architects with a passion for video games who have abandoned the traditional career to move into this new area, covering exactly the role of level designer. In their new work they have noticed that there are many similarities in the design process of both disciplines, a particularity that enabled to apply without many changes and difficulties the design methodology learned while studying for a degree in architecture in their new profession (Licht, MS, 2003). But, the task of the architect / level designer doesn’t stop at the design of levels: it also includes the explanation of certain architectural theories to the development team to communicate the basics of spatial composition. The production of architecture in many practices and offices is often linked to other disciplines such as marketing and communications. The role of the contemporary architect should therefore go beyond the boundaries of physical development (Azémar 2007).

But what might be the usefulness and effectiveness of teaching level design in a university course? Learning some concepts related to architecture in a different way (that we will discuss further), involving and giving more enjoyment to the students, may be more effective. Video games may in fact be applied in alternative ways to achieve different educational objectives (Hirumi, Stapleton, 2008). However we must not forget that the potential of videogames lies precisely in being enjoyable; therefore these tools should be used not as mere competitive activities and exercises (Botturi, Sebastian Loh, 2008). Also the Key Conclusions published in the Report on Educational Games, state "That there are many features of digital games, including game design approaches and digital game technologies, which can be applied to address the increasing demand for high quality education" (Federation of American Scientists, 2006).

But what specific skills might be gained by a student of architecture from an experience / exercise of this kind? What more can level design offer with respect to a traditional course?

4.1.1 FROM THE DESIGN TO REALIZATION: THE ADDED VALUE OF LEVEL DESIGN

We have previously underlined several times that the architect's work foresees both the design and the construction phase. In almost all university courses in the schools of architecture you can never proceed beyond the design phase. The student has often doubts and is forced to imagine, of course with quite a few difficulties, the following steps. We have already mentioned that there are some courses of industrial design or technology to track a project from concept phase to the final stage (like a piece of furniture), but although very useful these are far from the basic elements with which an architect must continually confront, space and activities taking place inside.

Marcus Vitruvius Pollio, the famous Roman architect and writer, in his celebrated treatise dedicated to the Emperor Augustus, *De Architectura* (*On Architecture*), states that all buildings must meet requirements of firmness, commodity and delight. The same characterization, with minor adjustments, can be made for a level of a videogame. Indeed, while the latter two conditions are practically the same meaning in both fields, the firmness, which refers to the static and constructive characteristics, in the case of a three dimensional environment is associated with the proper technical functionality of the map and thus its proper implementation. Again it is clear how the two definitions are not so far apart. We believe that to reflect and work on these themes, then also on the correctness technical / functional of the final product can be educational for students.

Innovation and added value of a course on level design, focusing in particular on video games in first person, within a course in architecture is that the creation of a level allows us to develop a methodology and a full process from concept to final realization. A final project of a design course may also have some errors with regards to some wrong choices for instance related to space, materials or construction solutions, which may compromise the correct operation of all or some parts of it, if the object would have been constructed. Even in the professional practice you often have problems to solve during the project execution phase, caused by errors in design or unforeseen situations. In creating a level you can also make several errors, but you would immediately notice because serious errors would compromise both the correct loading of the map and its gameplay. In fact it is possible to test the in work at any time during the design phase and check, for example, if the size of the spaces is adequate to perform several game actions such as climbing stairs, jumping or moving sideways. If certain movements are difficult or impossible to accomplish, you have instant feedback that helps us better recognizing and evaluating their errors (Gee, 2008). As in a real architecture the final result must be correct both in terms of functionality and construction techniques.

Another important feature is that once a map is completed, you can play it and release it publicly and receive from other people comments on several issues, first of all the gameplay, which is its main function. We are then talking about what in architecture is commonly defined by reference to a building, the "phase of use". There are also courses, but especially research projects, that, in addition to providing design and construction, also track a prototype for several weeks or months, during its use phase, to collect data and verify its proper operation. But this solution, as well as being an exception, is economically very expensive for most of the institutions. Also, the timing for obtaining reliable information is always very long. Checking the answers from the players/users to a level is a fast process, which carries no additional cost and is especially useful in terms of training. Its utility is to explain directly to the student/designer that the environment and the architecture that has been created must meet specific requirements to satisfy as many users as possible, and therefore is not creating something for him/herself, as unfortunately often happens, but for customers who use, evaluate and criticize their job. The response of the project is therefore not only assessed by the professor: in this case it is not a subjective assessment made on an hypothetical project, but is something formulated on the basis of its actual operation and its correct implementation. This will certainly be more objective compared to the results of a traditional course.

4.1.2 Other attributes of the design task which influence design education

We have seen as the main added value of integrating a course in level design in a school of architecture lies in the opportunity to study and develop a project idea on a path that goes up to a final product, complete, playable, then usable. Now we will analyze in more detail some features that may prove very useful in design education and that, in our opinion, are the interesting topics to be developed within a course of level design~~,~~ for architectural students.

The first step to make a new level is to define the history of the place, which hosted the events, the style and architectural references, time of day when the player's action takes place. Determining these issues requires choosing a project theme, a study of architectural references, from real or imaginary architectures, to define a style appropriate to the history of the place, and to define a suitable lighting for the gameplay. This contributes to the creation of atmosphere, essential to increase the involvement of the player and the credibility of the environment.

Establishing the history of the place also means making clear spatial and formal choices. Deciding to set your map inside a factory or an ancient palace or on the streets of a small city district, directly affects the size and shape of space. The choices must, obviously, respond to a type of gameplay. Working on shape and scale is an important exercise to understand the hierarchy of spaces and to learn to dimension as needed. These other aspects as mentioned above can be analyzed and verified during the entire process of level creation.

Once you choose the setting, the research phase for the architectural references begins, in order to create the style better suited to our level. It is a step in many aspects~~,~~ very similar to finding references for a project of architecture both professional and academic. So in this case what could be the added value? While in most cases the references to a real project or a didactic exercise come from modern and contemporary architecture, for a videogame~~,~~ we can range throughout the history of architecture (Fig. 3), similarly to the design of movie sets, mostly belonging to the genre of fantasy and science fiction, but with the important difference that these are spaces where we can move and that we can explore with complete freedom. Creating a map set in a fantasy world, and taking such inspiration from Italian Renaissance architecture, the Duomo of Florence or Florentine palaces, would put the theoretical knowledge acquired during a course of architectural history into practice, to better understand the value of space, form, construction and symbolism of past monuments. Instead of limiting ourselves to study and analyze an architectural work only through two-dimensional drawings and three-dimensional models, we can perceive space, shape, size and significance of some buildings in a virtual environment, certainly, but very similarly to reality. No movie is able to communicate the same feeling that a videogame is capable of transmitting. When, for example, we walk through the streets of a medieval city to reach the tower, which appears in the background, which rises above the roofs of buildings, we can turn the eyes to see the buildings that line the street and in the distance see domes, bell towers and landmark buildings, all bathed in the morning light.

Fig. 3: The references for a videogame comes from the world history of architecture. From left to right: Islamic architecture in Prince of Persia, and Japanese architecture in Unreal Tournament 3.

An important role in an environment where you have to perform any activity is carried out by lighting. In a traditional course hardly come to define the points at which position the light sources within a project or how to position windows and other openings to allow natural light to spread within a room. We could perform simulations with the advanced rendering programs, but as we have previously pointed out, we stopped at a display design, with no opportunity to verify directly, in fact, if our choices are effective to perform a specific activities or not. We believe that, for a student, adequate lighting so as to host the game action, is useful to enhance the awareness of the importance of this topic. Also in videogames, lighting helps to create a particular atmosphere and helps to emphasize particular spatial characteristics of the environment. The light has always played an essential role in both contemporary architectures such as Jean Nouvel and Tadao Ando, and masterpieces of the past such as the Pantheon and the gothic cathedrals (Fig. 4).

Fig. 4: Relationship between light and architecture. From left to right: the Pantheon (Rome, Italy), the St. Vitus Cathedral (Prague, Czech Republic) and the Museum Reina Sofia (Madrid, Spain) (pictures by the author).

5. TOOLS AND A REFERENCE EXAMPLE

In this section we will describe, the main tools of a level designer and a personal work of the author as a reference example to briefly illustrate some important steps in the process of setting levels. Both works are custom deathmatch maps, for two editions of the game Unreal Tournament, 2003 and 2004, and can be played either online in multiplayer mode with other players or offline, single player characters run against AI (Artificial Intelligence), called bots (short for Robot). The modality of deathmatch gameplay is very simple. Players will compete inside the levels that are conceptually like arenas. The goal is to achieve a certain score, eliminating the highest number of times the opponents. In some ways it recalls the fights of the gladiators of ancient Rome.

Using as an example deathmatch maps is interesting for several reasons: they don't have environments that grow linearly as in singleplayer games that follow a storyline; the few rules underlying the gameplay do not require creating a complex plot or dialogue, but allow focusing towards the creation of the environment and its architecture. For the reasons set out above, it could be ideal to develop levels for example in a semester course. Furthermore, these environments, even if they are focused on the gameplay may have a history, essential to ensure immersion and atmosphere. The two case studies also want~~s~~ to demonstrate how a game mode, so simple as deathmatch, may in fact be interpreted in various ways and create environments, architecture and atmosphere totally different. This may help students to communicate an important concept related to the design of a building or a space. In fact the architect should design buildings and places of quality, to transfer meanings and emotions to the users, not simply to create the anonymous functional containers, which unfortunately happens very often, especially in large urban peripheries.

5.1.1 LEVEL EDITOR

To create video game levels, a special software called the level editor is used. These tools allows you to achieve the three-dimensional environments (Managing 3d models, textures and lights) and inserting all the elements that make a playable map, the objects, the starting position of the players, the paths of the characters managed by the AI. One of the first editor for first person game play was the DEU (Doom Editing Utilities), released in 1994 for DOOM, the famous game from id Software that launched the type of games FPS (First Person Shooter). Today, after the success of the phenomenon of mod (user-modifications), most of the first person game on the market today~~,~~ is sold with its proper level editor, so it is a cost-free development tools, including versions of Unreal Tournament that we have used, which include the UnrealEd.

The level editors are not programs to replace a CAAD, a BIM, or 3d modeling packages because they have other purposes, but they are not totally different. Editors can be considered as a combination of CAAD and VR software. The level editing environment of UnrealED presents very similar characteristics to those of three-dimensional modelers as 3ds Max, Maya, XSI, Modo or Lightwave: the 4 viewports, Top, Front, Right / Left, Perspective and a system of movement and work in three dimensions, the main geometric selections (Object, Poly, Edge and Vertex). Therefore students do not need to learn a program from scratch: some basic concepts are already part of their cultural background. The commands to know are numerically reduced and it is not necessary to study a whole new program but only the main functionalities useful for the project. Thanks to an increasingly user-friendly level editor, the learning curve does not present great difficulties. We also believe that for an architecture student it is more useful to know this type of software than to learn dozens of mathematical formulas that will hardly have practical applications in the daily work of an architect. Maps can be created in two ways: using the libraries of objects already contained in the program or creating from scratch the contents of the map using for example any three-dimensional modeling package as 3ds Max, and importing the objects in the level editor . The use of the first method will allow the level design to students that do not have a good knowledge of three-dimensional modeling software. It is important to underline that our goal is to design a playable virtual environment and not simply to create 3D objects.

The following reference example is a work of the author, finalist at the International Competition Make Something Unreal Contest, and summarizes the key aspects of a design level. Very similarly to the design of a real building, the choices are all related to each other. Once the overall objective is defined you can start choosing the "theme" of the map or writing a brief "story of the place". The two aspects are of course related. To construct, as in our case, a factory, means having space, decorations, lights and materials of some kind. All decisions must be fitting with the chosen theme. Design choices must also be feasible. It is necessary to gather information so as to understand how to create a door or a lift by a means of a mover (in other words a special object that can be animated), or a glass skylight that lets you see the sky. The entire design process, interactive, will greatly help the student to improve his way of reflecting on the relationship between design and implementation, thanks to the possibility to immediately see if the choices are correct or not.

5.1.2 Example Reference: Vertical Factory 2

• General objective: to create a deathmatch map for a number of players between 4 and 10;

• Theme: Industrial;

• Story: A Space Corporation has purchased a factory in a strange location. The building has a central space on three floors, from this characteristic it derives its name vertical factory.

• Layout and Gameplay: The map layout was designed to promote a type of game with lots of vertical actions (z-fight). The level is symmetrical and has an organization of space, inspired by the cell spatial organization of buildings of the Italian Baroque architect Guarino Guarini (1624-1683). For this reason there is a lack of room-corridor-room, but the spaces are generally very large. The verticality of the central area, which houses a system of ramps to climb to the top floor, is inspired by the "Carceri d'Invenzione" by Giovan Battista Piranesi (1720-1778). (Fig. 5)

Fig. 5: Images from Vertical Factory2. From left to right: the central area with the system of ramps, the verticality inspired by the "Carceri d'Invenzione" and the atmosphere enriched by the steam that goes out from the ventilation system .

• Architecture, Geometry, Textures: The architecture incorporates typical elements of industrial buildings, such as beams, concrete blocks, grates, pipes, ventilation systems and wooden cases. Many 3D objects were designed and textured in a 3d modeling package and imported into dell'UnrealED. The theme has been interpreted as not realistic, but imaginative. New textures have been created to represent the main materials of the map: wood, brick, concrete and steel.

• Lighting and Special FX: The light contributes to create the industrial look of the map and the atmosphere of a building located in an unknown location. The map in fact takes place at night and you can see the sky only through a large central skylight and a few windows at a certain height from which you can't look out to see around. To increase the involvement of the environment, some emitters have been used to simulate the steam that goes out from the ventilation system.

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

The new opportunities offered by video games in educational field are generating increasing interest in the field of research. In 2008 NASA (BBC News, 2008) had claimed to believe in the possibility of finding the next generation of scientists and engineers thanks to a game that simulates the real space missions. Earlier this month (July 2010) NASA has released on Steam (an online game platform) for free, a video game called Moonbase Alpha, which uses the Unreal Engine 3, where the player must play as an astronaut committed in research on the lunar surface.

Our proposal is just part of this new line of research. We have shown how Level Design, especially for three-dimensional video games in first person, may be regarded as an innovative approach and constitute an interesting field of study within a faculty of architecture. The introduction of this new discipline would allow students to improve their skills by studying and analyzing things that normally wouldn't be possible in the traditional design course. It is useful to underline how important it is to observe and learn also from the possibilities offered today by one of the cultural forms of expression most interesting and complex of our time, video games, and not just remaining with concepts anchored to the past, but integrating the old with the new intelligently. An exercise of level design contains all the elements for good learning experiences, which can be summarized in goals, practices, explanations, debriefing and feedback (Gee, 2008). We agree with Gee's statement that "game design is applied learning theory and good game designers have discovered important principles of learning without needing to be or become academic learning theorists".

The principal value of the new type of educational approach is to look into the possibility of developing a project from the initial concept to the final realization, developing and testing all the various stages of the process, with the teacher, with other students and interactively with the computer. The methodological similarities between the realization of a level and a design studio exercise, together with the objectives behind the two disciplines, ie, designing forms and spaces that must hold the activities, confirm that both are mutually very close. Level design is certainly one of the subjects closest to architecture, and consequently the level designer is the professional figure closer to a traditional architect.

But subjects relevant to a student do not stop here. The creation of a level allows us to think about several other aspects such as: space, forms, architectural styles, and also on how to create an architecture coherent with the theme chosen, properly illuminated and functional for a certain type of game. All of these elements must eventually merge thanks to the work of the level designer within the same map by creating a single product in a manner conceptually similar to the way that an architect must manage and bring together aspects of the same project which can be functional, spatial, constructive, plant installation etc. The process we propose can be placed in the category of "Experiential Learning" because it is possible to learn directly through reflection on doing. The student is directly involved in the experience and we believe that interactivity and immediate feedback of methods and tools of the level design can be of great help.

The original analogy we found between architectural design and level design is not only supported by several references, but arises mainly from direct personal experiences in the field of architecture, education, level design and videogames. The reflections presented in this paper provide an initial basis for further studies. Having shown the utility of level design for architecture education, the next step would be to prepare a specific program for a semester course. The course could be divided into a first brief and theoretical part which describes and analyzes some outstanding examples of level design, in terms of architecture and gameplay, and a second practical part, in which students implement a simple level for a videogame. The teacher should be a hybrid figure, an architect with an extensive knowledge of video games, both from the point of view of the player and the level designer. Therefore, it is necessary for the instructor to have direct experience in the creation of levels for video games, and only a theoretical or superficial preparation is not adequate. And we should not underestimate either the experience as a player. In the past, for example, for the construction of fourteen levels of the ONI game, professionals architects were hired who probably were not even experienced players. The results of these levels were much criticized because of the space which was aesthetically sterile, too large, empty, uninteresting to play and explore (ONI).

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AN INNOVATIVE APPROACH TO INTEGRATE H&S ISSUES IN THE CONSTRUCTION PROJECT PLANNING USING SERIOUS GAME ENGINE TECHNOLOGIES

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ABSTRACT

Efficient health and safety (H&S) planning is crucial if projects are to be delivered on time, on budget, and without experiencing accidents or injuries on construction sites. The H&S legislation has been introduced to eliminate hazards and co-ordinate H&S issues throughout the each stage of the construction projects. However, many employers face difficulty in converting the regulation directive into actions and practical implementation. The aim of this ongoing research paper is to illustrate key literatures in the area of H&S planning and advanced visualisation techniques in construction projects and identifies important research elements to demonstrate conceptual research framework. This will contribute towards successful development of an interactive decision support system that integrates H&S issues into 5D planning enabling safer, efficient and more productive construction sites.

The system prototype will focus on assessing the risks on construction sites occurs due to workspace conflicts and support infrastructures in order to avoid H&S issues in the construction projects. The system prototype will improve safety awareness on the construction sites and assist planner to review construction plan to be consistent with H&S. The research methodology of this research paper involves extensive literature review and to develop a knowledgebase module for H&S and workspace issues which will integrate into construction planning processes. Literature review revealed the requirement of an integrated interactive tool that can bridge the gap between H&S issues and advance visualisation techniques by exploiting Serious Game engine Technologies. There is a need for advanced visualisation IT tools which can be used to comprehend the construction operations and processes in order to avoid accidents/injuries before actual construction commences.

This research presents the research matrix (includes key research in H&S planning and advance visualisation techniques) and demonstrates research framework for the presented hypothesis. It defines the system process and functionalities. The system prototype will allow H&S to be managed as a part of the construction project planning and can improve H&S performance which is a key element for every construction project.

KEYWORDS

Integrated Health and Safety planning, serious game engine, advanced visualisation planning

1. INTRODUCTION

The Health and Safety (H&S) cost failures in the UK industry are estimated up to £6.5 billion per annum (HSE, 2009). The HSE statistics demonstrates that construction industry ranked second dangerous industry. Every year over 200 people died in accidents and over two million suffer illnesses caused by, or made worse by, their work. Embedded different H&S regulation into the construction planning is crucial if the projects are to be delivered on time and budget without experiencing any accidents or injuries. The key objectives of the construction projects are to provide an effective schedule, minimise cost, and comply with H&S regulations. These objectives are becoming difficult to achieve since the construction sites are very dynamic includes space requirements, H&S issues.

In this regard, the aim of the research paper is to investigate how H&S rules and regulations can be embedded into 5D modelling to enable safer, efficient and more productive constriction sites. In order to deliver the aim, the number of objectives has been set:

- Investigate the research gaps, current theories and "State-of-the-art" techniques used in construction H&S planning and advanced visualisation of construction processes.
- Identify the important research components in order to develop a conceptual framework and prepared a knowledgebase database including Workspace, H&S risk assessment information.
- Implementation of an interactive decision support nD prototype to enable rehearsal of site construction processes, which uses several construction dimensions including safety, space, time and cost by exploiting Serious Game engine Technologies.
- Implementation of intelligent algorithm in order to identify the schedule, workspace and H&S conflicts in the construction sites based on empirical knowledge database to plan and control the construction processes.
- Run a case study to validate the model prototype through industrial experts.

The system prototype will identify conflicts in schedule, workspace and safety on the construction projects. This will assist planner/safety manager to review H&S issues in planning and provide an opportunity to amend it before the actual construction starts. The next section presents an extensive literature reviews related to H&S planning and advanced visualisation technologies in construction projects. It will be reviewed and classified in brief.

2. LITERATURE REVIEW

The number of literatures have been investigated related to H&S planning and advance visualisation technologies. This section mainly divided into two parts I) H&S planning and II) Advance visualisation technologies.

2.1 H&S planning

A number of research projects have been review related to H&S planning. It has been widely acknowledged that construction industry is the most dangerous industry among all. Chong Pui Ho et. al. (2000) discussed safety plan should work on important aspects such as hazard and risk. Therefore, it is always important to investigate possible H&S issues before commencing the work on sites. Approximate 5% of budget spends on H&S plan and procedures. However, many contractors argued that is it worth spending such amounts on safety plans? The proposed research identified that it is significant to assess hazards and risks on the site to be able to more productive and prevent accidents/injuries. The safety plan should review different constraint that includes the site factors, key constraints and effective plan. Rowlinson and Hadikusumo (2000) proposed IT tool as VR methodology Design-For-Safety-Process (DFSP) to simulate the safety hazards which inherited by construction objects and operations. It was an instruction based online guideline that accumulates the information from the research theories and H&S regulations. It has a mechanism for hazard identification, object picking, collision detection and possible hazard information from the accumulated knowledge. Carter and Smith (2001) strongly recommended that identify the hazards on the construction sites are the fundamental principal for any construction projects. Therefore, author argued that the projects have always a constraint related to time, cost and resource so operations need to be prioritising on the bases of risk assessment. Authors extended an approach to have a better understanding of safety hazards and risk measures associated with site operations by integrating the risk assessment into the research methodology. Three tier applications, Dynamic Data Driven (DDD) web prototype has developed to enter an accident report to the central database. It was helped to populate the possible accidents related operations and priorities task execution during construction phase. The prototype calculates the probability of hazard based on input historical data. It enables to achieve transparency for project planner and supervisor to identify possible H & S issues on sites. However, it can cause a problem because of poor data collection so it primarily depends on data collection.

Soltani and Fernando (2004) suggested that one way to make this industry a better working place is to implement effective H&S regulations during the planning of a construction project. The failure in planning appropriate support infrastructure affects safety, quality, and productivity adversely. To incorporate H&S into the construction project, several legislations have been introduced including CDM (Construction Design and management) 2007 to eliminate the hazards as the project progress. The primary goal of such legislations is to integrate H&S regulations to co-ordinates the H&S issues with the construction projects throughout the each stage of the construction process. Other literature indicated that the implementation of H&S regulation within the organisation will improve the project performance (Ciribini and Galimberti, 2005; Cameron and Hare, 2008). However, many employers found difficulty in converting the regulation directive into actions and practical implementation. Hare and Cameron (2008) discussed about implementing the regulations in the construction industries. The literature research supports that implementing such standards required a huge amount of documentation to satisfy H&S regulations. It results into very tedious process. Author has discussed about current practices related to the H&S management systems during the planning stage to communicate H&S information with different stakeholders including client, designer, planner, H&S coordinator and sub-contractors. These tools will extract H&S information from paper documents; dig up H&S file data and present it into the effective way so the user can take the more precise detailed decisions on H&S matters. Author has classified some tools such as Responsibility chart and Risk register were identifying management of risk including H&S risks. Operation evaluation chart was developed to make design decisions. The Hazard ID tool was used for collaborative planning where different stakeholder can discuss how to identify and solve H&S problems. H&S milestones can plan the strategic level alignment into the programs. RAG (Red, amber and green) were prepared a checklist to sort the possible options of H&S risk. Kazi et. al. (2006) proposed a scenario based SIMCOM+ tool to investigate safety on the construction sites. It analyzed the structure information including temporary facilities, equipment, workers and materials in order to detect the collision among different entities on the construction sites.

Dolores et al. (2009) used questionnaire methodology to analyses the H&S regulation and requirements in construction industry and obtained the statistics. The authors determined that there are 10% lower accident rate in general after the H&S policies came into force. Hu et al. (2008) reviewed time-dependent structure theories during building construction. The authors argued that safety and structures analysis is not only dependent on static structures but also depend on other factors such as material behaviour and loading conditions, which kept change during building construction process. The authors have proposed an advanced digital framework of Building Information model (BIM) and 4D technology integrated with safety analysis method. This research provides an integrated solution of architectural design, structural calculation and construction management. It will help to achieve accuracy and efficiency of a complicated architectural design.

Kuan-Chen and Shih-Chung (2009) conferred that the construction processes are getting more complicated due to the large number of objects including structural elements and equipments in Virtual Construction. The authors proposed algorithm VC-COLLIDE identified conflicts on static or dynamic construction sites and determined distance between large dynamic 3D objects in virtual construction sites by different scenarios. The Open Dynamic engine (ODE) was used to rehearse the operations sequence efficiently and detect the collision status in the real-time virtual construction processes. Sacks et. al. (2009) proposed algorithm based methodology CHASTE (Construction Hazard Assessment with Spatial and Temporal Exposure) that calculates the probability of a potential victim during loss-of-control events.

In conclusion, failure of H&S planning affects the construction project economically as well as productively. There are existing tools in the industry but lack of advanced integrated system to communicate H&S planning of construction project. The proposed system will focus on assessing the risk on the construction sites occur due to workspace conflicts in order to avoid accidents/injuries on the construction sites. This will contribute towards successful development of an innovative methodology focusing on H&S awareness on the construction sites.

2.2 Advanced Visualisation Technologies

A number of technologies have been reviewed to identify the use of IT technologies for the advance visualisation planning. Li et al. (2003) described that the lack of innovative IT tool for the construction planner to assess and validate his planning can result into false operation planning, which will cause a lot of rework in the construction phase. Therefore, authors suggested that VR technology is the solution to the above problem. The authors developed knowledge base system called VCE (Virtual construction laboratory experiments), which enables the planner to examine virtual experiments of advance construction technologies, operation and process. Dawood et. al. (2005) proposed innovative advanced planning VIRCON (VIRtual CONstruction) tools in order to investigate sequential, spatial, process conflicts and temporal aspects of construction schedules before commencing the work on the site. It allowed planners to rectify and trade off the temporal sequencing of tasks with their spatial distribution to rehearse the project schedule.

Huang et al. (2007) argued that 4D-CAD system lack design and construction specific components such as scaffolding or other temporary facilities including storage area, carpentry shop, integrated with the system. Such 4D model also does not specify the space requirements of temporary infrastructures, which might result into space congestion, productivity loss and safety hazard. The author proposed a framework that allowed the project planner to check the safety, activity operation sequence, temporary infrastructures based on Dessault Systems solutions (DS). The system assisted to visualize 3D animation of a construction plan before actual start-up of a construction work and aid planners to analyses, simulate and model given prototype.

Zhou et al. (2009) proposed methodologies that support interactive, collaborative communication prototype. The proposed approach achieves the transparency by allowing an interactive and collaborative communication, to review construction plan and 4D-simulation model directly from 3D unique model. Author proposed distributed environment 4D prototypes to rehearse the real time construction operation sequences and verified the model through industrial case studies. Effective user interaction and Computer Supported Collaboration Work (CSCW) were the important factor for the proposed novel approach. However, it has further research scope such as Building information modelling (BIM) adoption for more efficient Product breakdown structure (PBS) collection using the reliable conflict detection system. So it could produce a more robust and reliable construction plan. FORBAU is a virtual construction site project that focused on distinct infrastructure projects to improve planning and management of construction sites. One main objective was to rehearse the process flow from planning to execution phase (Borrmann et. al., 2009).

Kuan-Chen and Shih-Chung (2009) supported that the construction processes are getting more complicated due to the number of objects including structural elements and equipments in Virtual construction. The proposed algorithm VC-COLLIDE to identify conflicts on static or dynamic construction sites and determined distance between large dynamic 3D objects in virtual construction sites by different scenarios. This algorithm would rehearse the operation sequence efficiently to detect the collision status in the real-time virtual construction processes. To determine collision and different scenarios, an algorithm will identify the geometrical object shapes such as cylindrical, spherical, etc.

Conducting a real time experiment on the construction operation sequences are expensive and hazardous, the construction industry is looking for an alternative approach to rehearse different construction operations to sustain effective project planning and safety control. Although many digital technologies have developed to visualise the innovative construction design, some virtual prototypes were developed to enhance effective communication of design, integrated planning and visualisation of the construction processes. The MineVR (Virtual Reality Safety Model, 2000) is Virtual Reality (VR) based simulation model of reconstructing a mining accident simulation, which have successfully used to educate people in preventing H&S hazards. Santa Clara University Library (NMC Virtual worlds, 2008) built in “Second Life” (SL) in the early phases of the construction to explore innovative ideas for interior spaces. The virtual construction site is used to visualize dynamic navigation of the construction site however, the rich interactivity function of VR is not used (Li, H. et. al., 2003) effectively. The VR’s ability to visualize dynamic operation sequence enables the construction planners to identify any possible H&S problems of the site layout before actual construction begins (Boussabaine, A.H. et. al, 1997). It can demonstrate different “What-If” scenarios with limited resources and efforts. The visualisation and control of the construction site operations will become prominent in the next generation 4D/5D tools. Serious Game Technologies is an innovative approach of presenting the construction planning to the professionals and users with less-knowledge (Sawyer and Smith, 2008). Pui Ho et. al., 2000, Carter and Smith, 2001 and Cameron and Hare, 2008 concluded that there is still a lack of an advanced integrated safety approach in planning and visualisation to rehearse real time construction scenarios.

This research will develop novel methodology that integrates H&S issues with construction project planning using Serious Game engine Technologies such as XNA game engine coupled with object-oriented technology such as C# (.NET environment), to develop an integrated interactive tool for the construction professionals such as site supervisor/safety mange/planner. It will assist them to visualise, analyse and evaluate the construction process at the detailed level to improve their decision-making process (Waly, A. F. and Thabet, W. Y. 2003). The proposed system will identify conflicts in schedule, workspace and safety on the construction projects. This will give an opportunity to amend it before the actual construction starts. The outcome of this research will be an application of Serious Game engine tool used by the construction planners, designers and safety managers to improve H&S on the construction sites.

2.3 Research Matrix

The Research matrix builds up a grid to identify gaps and review the scope for improvement. It reviews previous key researches in H&S and Advance visualisation planning. It classifies the planning, visualisation, database and the research constraints including physical, workspace, policy, resource and contract (See Table 1 for Matrix of key research in H&S planning and Advance visualisation system).

The Research matrix demonstrates technological dependencies and time constraints are the important factors to be considered in all projects. The Research matrix has been carried out to deduce how the H&S issues can be embedded into construction planning. The research has a scope of improvement for integrating H&S issues on serious game engine technologies. There are also some other constraints such as people, space, safety policy and environment taken into consideration. However, very few researches support all specified constraints. In regards to workspace constraints, many researchers have considered different variables such as resource, H&S, schedule and workspace area. However, there is only one research that considers most of the type variables.

Table 1: Matrix of key research in H&S planning and Advance visualisation system

Constraint, database, visualisation, optimisation and planning techniques	Fischer et. al. (1999)	Rowlinson and Hadikusumo (2000)	Cartert and Smith (2001)	Waly and Thabet (2002)	Sriprasert and Dawood (2002)	Li et. al. (2003)	Elbeltagi et. al. (2004)	Soltani and Fernando (2004)	Dawood and Benjaoran(2005)	Ciribini and Galimberti (2005)	Mallasi and Dawood (2006) ; Mallasi (2009)	Kazi et.al. (2006)	Jang et. al. (2006)	Liapi and Paschoudi (2007)	Hang et.al. (2007)	Cameron and Hare (2008)	Sacks et. al (2009)	Lai and kang (2009)	Zhou et. al. (2009)	Benjaoran and Bhokha (2009)
Constraint																				
Physical Constraint																				
People		X		X				X	X	X		X				X	X			
Space			X	X	X		X	X	X	X	X	X	X		X		X	X		X
Environment									X								X			
Technological dependencies	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Policy																				
Safety policy		X	X				X	X	X	X		X			X	X				X
Workspace																				
Resource					X			X		X	X	X	X				X			
H&S issues							X	X	X	X		X			X		X			X
Schedule					X		X				X						X			X
Work-area							X		X		X	X	X		X		X			
Contract																				
Time	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X
Cost	X													X						
Construction planning																				
Planning and scheduling	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Monitoring and Controlling					X					X										X
“What-If” modelling	X					X		X			X	X						X		
Algorithms																				
Numerical algorithms	X							X		X		X		X	X		X	X	X	
AI and Knowledgebase algorithms					X		X		X		X		X							X
Database		X	X	X	X						X	X		X						X
Visualisation																				
2D/3D view								X												
4D model					X		X		X	X	X	X	X		X		X	X	X	X
Web Interface		X	X		X															
VR model		X		X	X	X					X	X			X			X		

Modern construction planning techniques required more than just planning and scheduling. It requires an interactive planning that combines the planning, execution and control of a construction project and provides iterative feedback to improve the construction plan. There are different types of algorithm such as computational, artificial intelligence (AI) and knowledgebase algorithms, which can incorporate into system prototype in order to put some constraint. In terms of defining the construction site rules, knowledgebase algorithm can be very useful. In the other end, there are various visualisation techniques from 2D to nD/VR modelling to assist construction professionals to demonstrate and manage construction site processes. In conclusion, these constraints such as physical and logical should be coordinated in order to produce safer, efficient and productive system by exploiting Serious Game engine Technologies. The next section 3 describes about development of system framework. It discusses about the main research components.

3. DEVELOPMENT OF THE SYSTEM FRAMEWORK AND FUNCTIONALITIES

The aim of this section is to introduce a conceptual system framework for this research. It demonstrates the framework of the proposed system and presents the important components of this research.

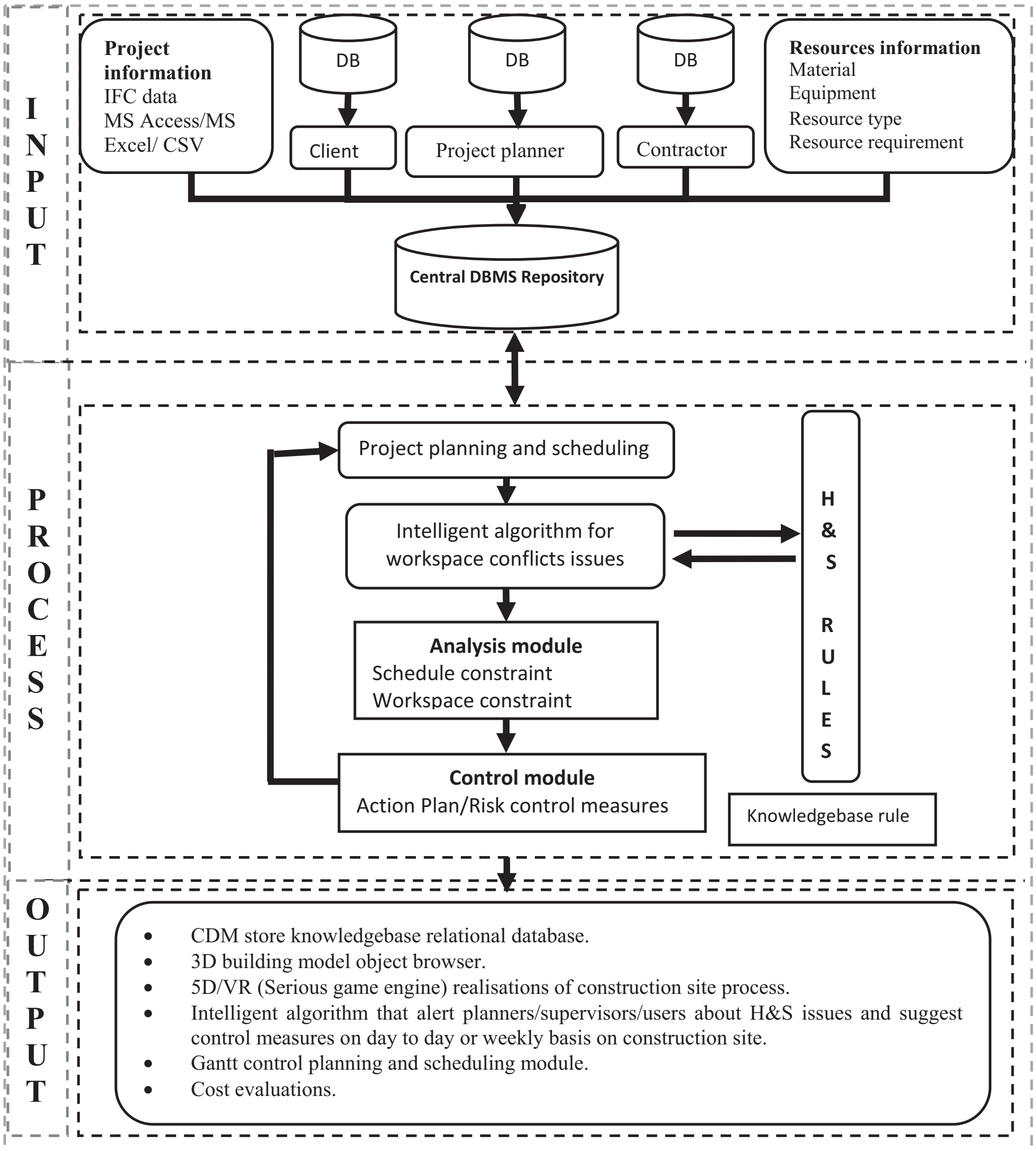

Figure 1: System Framework

The figure 1 illustrates the overview of the proposed system framework. This framework divides into three phases including Input (Data structure), Process (Integrated core system module) and Output (Final outcomes). The system process defines the business logic in order to make intelligent planning by identifying schedule, workspace and safety conflicts. The intelligent algorithm will communicate with Knowledgebase module to specify the site rules related to H&S, workspace or resources. The knowledgebase module stores the risk assessment information and workspace classification details to allocate workspace type. The analysis module will define the constraint in order to check schedule and workspace conflicts. If the intelligent algorithm finds any conflicts, the control module will propose an action plan or Risk control measures in order to resolute the identified conflicts. The control module will suggest the possible solutions to improve the existing planning and provide iterative feedback to users to improve planning decision based on knowledgebase module.

3.1 Input (Data structure)

An input data layer stores the detail information of project planning and design, users and resources into the database. All data input will store into the DB Repository. DB Repository will establish the communication of database with the integrated software prototype.

- **User's data information**- It stores user database information to plan construction project collaboratively. It allows interacting different stakeholders including owners, contractors, planner and project designer to improve the better decision-making process at different phases of the construction project including designing, planning and controlling.
- **Resource information** – It stores the resource information into the database. Various resources will have different characteristic and type.
    - Materials, Workers, Equipments.
- **Project information**- It presents a file information into one of the following formats : IFC Data/ MS Project/MS Access/ MS Excel/ SQL/Text/CSV
- **Central Repository DB**- It has input from various databases and unified into the central database. It will establish db connection with core model.

3.2 Process (Integrated core system modules)

A knowledgebase core layer creates business logic for an integrated system.

Integrated system logic - It iterates the interaction between the intelligent algorithm, knowledgebase module (H&S issues), analysis module and control module. It will provide recursive feedback to improve the future plan and schedule of the construction project.

- **Intelligent algorithm** – It analyses the different constraints including schedule, workspace and safety.
    - **Schedule constraint**- It defines the criteria for different activity to prevent the conflicts.
    - **Workspace constraint**- It classifies the workspace type and the causes of conflict in a specified workspace. Workspace types include installation space, transfer space, safety space, fabrication space and loading space (Moon et al., 2009). Conflicts in installation space occur due to over allocated resources or a lack of installation space area. Conflicts in transfer space occur because of transferring the equipment and materials in restricted work space. Fabrication space conflict occurs when another workspace moves towards the fabrication space. Conflict occurs in safety space due to accidents or injuries happened by falling objects. Conflicts occur in loading space due to fall or collision while moving the equipment or materials. The main causes of workspace conflicts are materials, equipment, workers and workspace itself.
- **Knowledgebase Module**- It integrates the knowledgebase H&S rules into the workspace conflicts algorithm. It defines a procedure based on set of rules to check the problems and proposes a solution. The defined procedure is carrying out by some steps i) Identify the conflicts, ii) Check the type of conflicts iii) Determine the cause of conflict iv) Suggest different solutions for indicated problem v) Propose a final solution. It also stores information related to Risk assessment of different activities. It will create a Risk template where user can configure risk information related to activities.

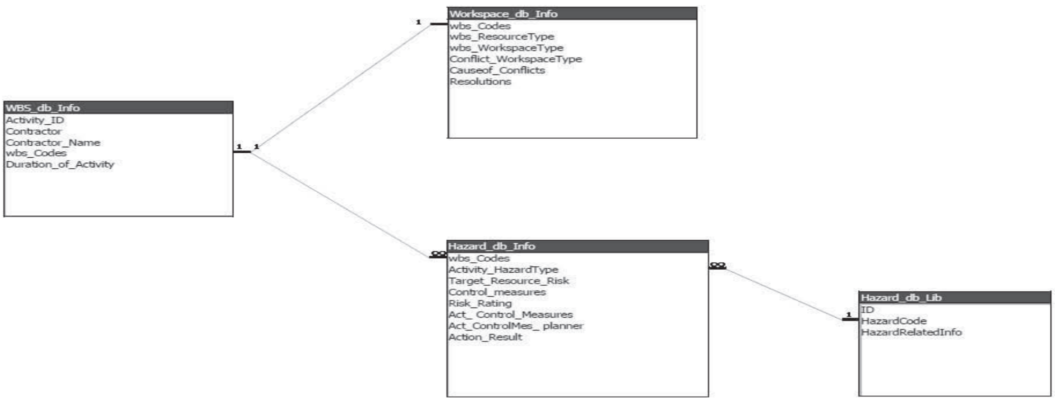

Figure 2 : Data structure of Knowledgebase module

The above figure illustrates the data structures of the CDM store database. This database incorporates knowledge of the H&S issues, workspace and resource types.

- **Control module** –It will constraint the decision variables (equipment, material, workers and workspace) to propose safety and congestion free solutions by innovative interactive planning technique that provides the workable backlog to improve the project plan. It will suggest guideline of different control risk measures on day to day or weekly basis on construction site.

3.3 Output (Final Outcomes)

It is an interactive layer which presents the expected final outcomes of the model prototype (See figure 2). User can rehearse different scenarios of a real time construction process as "What-If" and interact with the software prototype to explore the project experience with several dimensions including safety, space, time and cost.

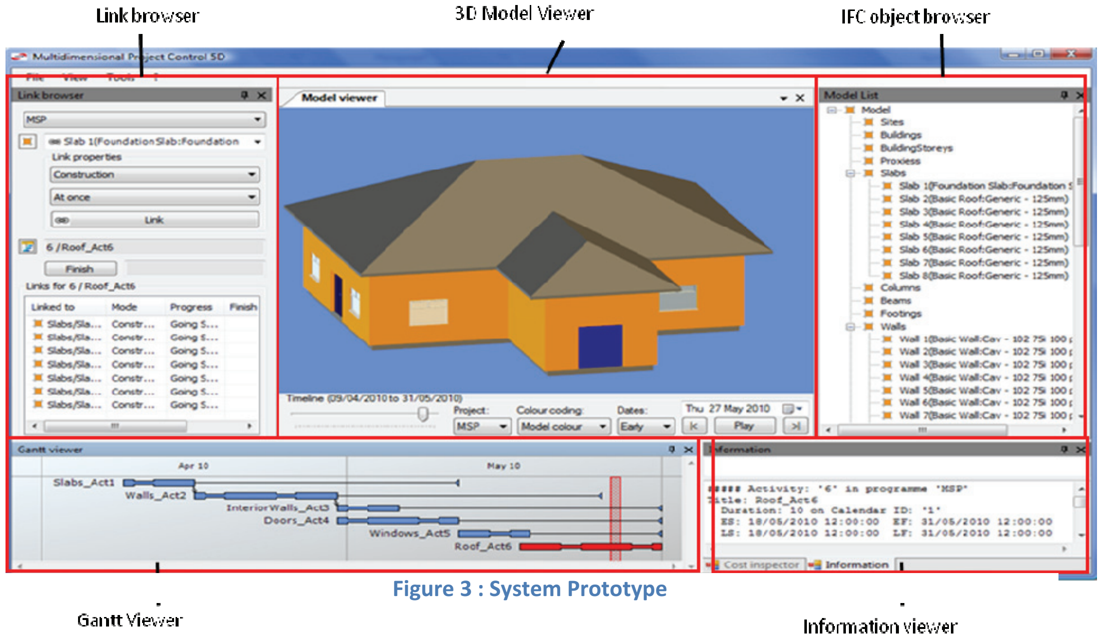

Figure 3 : System Prototype

- nD prototype – the outcome of the system prototype will be as following:
  - 3D model + safety, space, time and cost visualisation.
  - Planning and scheduling module.
  - Configuration module I) Workspace allocation II) Risk assessment
  - Cost evaluation.
  - Rehearse different "What-If" scenarios of real-time process in the game engine environment.

This framework demonstrates the outline of the system prototype. It assists to create data structure for this prototype and develop an intelligent algorithm to satisfy the objective. This framework proposes a conceptual framework to develop an innovative interactive reviewer tool to bridge a gap between construction H&S issues, construction planning and advance visualization techniques by exploiting Serious Game engine Technology.

3.4 System Functionalities

The system will carry out following functionalities.

- CDM Storage database – It develops a Relational-database system to formalise the structured activity data information and associated risk with it. It also specifies the workspace classification and allocation information.
- Develop 4D (3D + Schedule) model by assembling building objects to rehearse the construction site progress in a game engine environment.
- Create a Risk assessment template where user can input Risk related information to each activity and incorporate the risk information into activity planning.
- Create a Workspace template where user can input Workspace related information to each 3D object into model viewer.
- Analysis module- integrates an intelligent algorithm to identify the risk level of the construction sites. Add Metadata information to the activity planning.
  - Schedule, workspace and safety constraints.
- Assess the probability of risk in workspace area on construction sites (only identified hazards can be planned for H&S control measures).

    - Assess Risk information using Custom templates related to each activity.
    - Derive Risk-level Grid in order to assess the criticality of workspace area.
    - Define activity codes- To measure the severity of accidents/injuries on site.
        - High, Medium, Low (It changes as the project progress).
- Resolution module: - H&S Control measures.
    - The system will suggest the possible solutions to improve the existing strategy and provide iterative feedback to users to take decision based on knowledgebase module.
    - Resolute the workspace conflicts and congestion issues by optimising workspace or resources.
- Report Module: - Prepare H&S file to comply CDM regulations.
    - H&S report that includes identified and existing H&S issues.
    - H&S report also address action plan to prevent H&S issues on sites. It also Keep the track of progress data.

The development of the Serious Game engine tool will contribute towards increasing an awareness of the H&S issues on construction sites for construction planner/Safety manager/project coordinator to manage the consistent H&S planning. Therefore, the users can be more confident when using 5D visualisation for communicating the construction project plans.

4. CONCLUSION

Co-ordination of H&S issues throughout the construction planning at each stage of the project is mandatory requirements for construction project. In this paper, the research matrix has been prepared to identify the research scope and gaps by investigating the several key researches. It is concluded from review that there is a need of integrated solution that can bridge the gap between construction site H&S issues and advance visualisation techniques. It needs to move forwards towards the integrated module based knowledge management system where H&S, support infrastructures and workspace information can be integrated. The system needs to support advance visualisation techniques for users with less knowledge such as Serious Game engine Technologies.

In order to add value to the existing practices and researches, need an integrated knowledge management algorithm that incorporates H&S, workspace and support infrastructure information. The system will focus on assessing the risk on construction sites occurs due to workspace conflicts and support infrastructures in order to avoid accidents/injuries. The research proposes a conceptual framework assists to develop an innovative interactive system to bridge a gap between construction H&S issues, construction planning and advance visualization techniques by exploiting Serious Game engine Technology. This will contribute towards successful development of an innovative methodology focusing on safety awareness on the construction sites and assist planner to review the construction plans and amend it before the construction work commence.

5. FUTURE WORKS

The development of the intelligent algorithms to configuration, classification and allocation of site workspaces. It will check the schedule, workspace and safety conflicts to plan monitor and control the construction projects. The system will develop a resolution strategy in order to resolve the identified conflicts using optimisation algorithm such as Genetic algorithm and prepare an action plan or control risk measures to manage the construction sites. The system will validate and verify through the real time case-studies.

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VISUALISATION OF SEMANTIC ARCHITECTURAL INFORMATION WITHIN A GAME ENGINE ENVIRONMENT

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ABSTRACT: *Because of the importance of graphics and information within the domain of architecture, engineering and construction (AEC), an appropriate combination of visualisation technology and information management technology is of utter importance in the development of appropriately supporting design and construction applications. Virtual environments, however, tend not to make this information available. The sparse number of applications that presents additional information furthermore tends to limit its scope to purely construction information and do not incorporate information from loosely related knowledge domains, such as cultural heritage or architectural history information. We therefore started an investigation of two of the newest developments in these domains, namely game engine technology and semantic web technology. This paper documents part of this research, containing a review and comparison of the most prominent game engines and documenting our architectural semantic web. A short test-case illustrates how both can be combined to enhance information visualisation for architectural design and construction.*

KEYWORDS*: 3D, BIM, construction industry, game engines, information, semantic web, virtual environments , visualisation.*

1. INTRODUCTION

1.1 The extent of interoperable three-dimensional AEC information

One of the most notable efforts of recent years in the context of semantic information modelling for construction industry, is the Building Information Modelling (BIM) approach (Eastman et al., 2008). This approach is often combined with the Industry Foundation Classes (IFC) as a language to establish an appropriate level of interoperability (Liebich et al., 2010). In a BIM application, one is able to build up a 3D building model that represents the building design at hand and describes all information considered relevant to this building design, including to a certain extent material information, cost information, planning information, etc. Using the neutral IFC format to serialize this information, one should ideally be able to communicate this information to other applications that may reuse and/or interpret this information.

A parallel research and development effort towards interoperability of information is led by the World Wide Web Consortium (W3C) in the World Wide Web (WWW) domain, albeit targeting a less specialised and wider field of information. By increasingly changing the WWW into a semantic web (W3C, 2010), this effort aims at describing and connecting all WWW information so that its semantics are made explicit and the described information becomes reusable both by humans and machines. The usage of semantic rule engines and query environments accessible by semantic web agents, for instance, may then target an improved automatic processing of information.

Whereas the IFC standard provides a means to describe information for one domain only, namely the AEC domain, the semantic web effort targets interoperability in a wider range of domains, namely all domains that may be described in the WWW. As the semantic web effort thus provides a more general and more widely supported and applied approach, we investigated how the building information described with the IFC standard could be brought into this semantic web and how it could be extended with other information in this semantic web, including more detailed material information, cultural heritage information, library information, etc. A large part of this research work is presented in Pauwels et al. (2010), and will only be documented briefly in this paper. The result of this research is that building information can be converted or directly modelled into a semantic web representation, allowing anyone to extend it with information that falls out of scope for the IFC standard, to (re-)edit this information and to re-use it efficiently in domains and environments that were not available in the narrower context of BIM and IFC.

1.2 Offering semantic information through a 3D virtual world

A second part of our research focuses on the visualisation of this semantic information in a 3D virtual world. The semantic web version of the building information allows the addition of information that is not part of the IFC standard, nor of the BIM environment (e.g. geography, cultural heritage, material details, etc.). This information is hard to visualise in traditional AEC applications as it is not part of the native data structure and functionality of these applications.

We therefore started an investigation in advanced visualisation environments, including Virtual Reality (VR) and Mixed Reality (MR) systems, specifically focusing on their ability to visualise the semantic web of information behind the building model. We compare the general visualisation possibilities of VR and MR visualisation systems in this respect. When considering the AEC domain, MR systems seem to focus on inspection and construction progress management because of their incorporation of real world objects, whereas VR systems rather focus on the earlier design phases, in which the building design is still mainly virtual. We also experience a contrast between dedicated VR environments built up using specialised VR software (e.g. VR Toolkit, etc.) and hardware components (e.g. data gloves, CAVE, etc.), as opposed to fast VR environments built up using an out-of-the-box game engine that provides a whole range of standard components with diverse complex functionalities.

Following the outcome of this general comparison, we consider the usage of game engines as they could provide us with a fast and intuitive way to generate a VR world connected to the available semantic web information. We briefly test and review several game engines, thereby taking into account parameters such as intuitiveness, API quality, graphical visualisation quality, relation with AEC applications, and interactivity. Results of this study show advantages and disadvantages throughout the engines for each of these parameters. One game engine is eventually considered as the more appropriate choice for the visualisation of a building model together with its underlying semantic web of information.

In a short test-case, we finally investigate how a three-dimensional building model visualised in a game engine may be connected to semantic web servers for an advanced and interactive 3D visualisation of this semantic information. For this test-case, we have built an architectural semantic web for an architectural design in Antwerp, Belgium. Through a semantic query interface, queries can be constructed and run on this architectural semantic web, resulting in the specifically requested information. We connect the game engine with the query interface, so that the architectural semantic web may be queried at runtime from within the game engine environment.

This paper gives a brief overview of this end-to-end investigation. We start the paper with a brief discussion on semantics in the AEC domain, a discussion concerning visualisation strategies for AEC information and a comparison of underlying game engines. We then indicate how a good combination of an information management and visualisation environment could produce an effective and realistic visualisation with the appropriate respect for the underlying information.

2. AEC INFORMATION IN THE SEMANTIC WEB

Management of information in the AEC domain seems to evolve into an appropriate usage of BIM applications. Within the context of construction design, these BIM applications prove to be a very valuable tool. However, as soon as building related 3D information is to be accessed from within any other knowledge domain, such as architectural design or cultural history, the range of powerful BIM environments does not suffice. Our research therefore concentrated on how the amount and the kind of information available in traditional BIM models may be extended with information from within these other knowledge domains.

2.1 Information management relying on BIM environments

The AEC domain involves all kinds of information, covering material characteristics, elementary architectural design notions, legal regulations, three-dimensional parameters, etc. Within a BIM platform, a designer is able to model a three-dimensional BIM model containing the most essential parts of this information about the building designed, including concrete information as 3D geometry, cost information, material information, etc. (Eastman et al., 2008). This improves the interoperability of information as AEC specialists presumably need to maintain only one central information model, which can then be referenced by diverse other applications for automation in construction.

This interoperability is further enhanced by the IFC format (Liebich et al., 2010). The standardized IFC schema aims at providing AEC specialists and application developers with an agreed upon information structure, fit for describing any building or architectural 3D structure. Although important limitations persist in the development of IFC (Yeong et al., 2009), it provides a solid basis to rely upon within construction industry applications. Example applications relying on IFC information can be found in various corners of the AEC domain, including for instance applications for energy performance calculations or project cost analyses. As these can become rather specialized applications, these calculation and simulation applications most often require remodelling information or adding extra information next to the information coming from the BIM environment. Certain knowledge domains, covering not only energy performance simulation or cost analysis, but also cultural heritage or architectural history domains, may benefit from additional information linked to the IFC information (Pauwels et al., 2010).

2.2 Connecting building information to information in relevant other knowledge domains

As we indicated in Pauwels (2010a), relying on the IFC schema has its advantages, but also its prices. Whereas it provides a certain level of interoperability, which is in itself an issue that still needs substantial research work (Yeong et al., 2009), it restrains users to a certain level of expressiveness. One cannot focus on designing the most unique building elements, including sloped walls, three-dimensionally curved roofs with window elements, etc., and still expect this atypical information to be describable in an international standard. As the semantic web allows anyone to construct his or her own vocabulary and link it to existing information, this may encompass this situation and allow designers to step out of the IFC schema when necessary and design the information in a vocabulary of choice, while to a certain extent maintaining the link with the standardized tools.

Semantic web technology enables the description of any information using mere logical terms. The discussion of semantic web technology is out of scope for this paper, but references and a brief discussion in the light of the AEC domain can be found in Pauwels (2010a). Using semantic web technology, one may describe near to anything, including for instance the spatial topology of a building, building element information, historical design information, geographical information, material details, etc. These descriptions can be made using custom vocabularies or ontologies, that might for instance be considered the ‘vocabulary’ of an architectural design firm or of a certain period in cultural history.

Semantic web technology additionally promises, or at least targets, the possibility to connect all these vocabularies and different kinds of information into one semantic web. By providing links to the underlying vocabularies and to other related information, semantic web descriptions thus always include their inherent semantics. As such, it might enable the description of information in several distinct, but nonetheless connected graphs, for instance explicitly connecting a building representation in the IFC schema to representations of the same building according to any geometric schema (e.g. X3D, STL, etc.), or to completely different information not available in the IFC schema. Applications may rely on this web of information as a central information source to provide services as needed for each of the members of a design team ánd to people outside the AEC domain but nonetheless interested in building information.

3. ARCHITECTURAL VISUALISATIONS IN VIRTUAL 3D ENVIRONMENTS

The information in a semantic web is not that easy accessible by any human user. Because of the importance of an intuitive interface in handling any kind of information, we start an investigation on how to present this information in an appropriate visualisation environment capable of relating it to the respective 3D objects. We investigate the diverse environments and their inherent strategies to visualise information related to the 3D objects. Several environments already exist for the visualisation of construction-related information. These environments differ mainly in the following characteristics: the quality of graphics, the level of interactivity, the information flow and re-use from within modelling environments for the AEC domain and/or the semantic web, the availability and quality of scripting functionality for the implementation of extended functionality, the intuitiveness of the resulting 3D environment, and the targeted benefits for the AEC domain.

We distinguish between VR and MR environments within this investigation. We consider VR environments as environments that consist completely of virtual objects and of no real objects, whereas MR environments are understood as environments that combine both virtual and real objects in a certain degree.

A first class of VR applications related to the AEC domain provides users with an online 3D environment in which users can lead a 'second', virtual life through their personalised avatars. Two main examples of such environments include Second Life (Khemlani, 2007) and SketchWorlds (SketchWorlds, 2010). These environments typically focus more on fast geometric modelling of an attractive 3D environment and less on the information modelling typically found in AEC applications. The standard functionalities, including for instance easy collaboration possibilities over a network, intuitive 3D modelling and basic visualisation functionality, provide nonetheless for a solid basis for collaborative design exploration. The main limitation in these environments seems the missing import/export functionality with respect to AEC applications. SketchWorlds provides the possibility for importing Ogre meshes, which may be exported from AEC applications using third party plug-ins, but this does not compare to the typical information exchange found in the AEC industry.

A second class of VR applications seems to focus on providing an appropriately functional virtual world for building design inspection. Examples of such applications include NavisWorks (Autodesk, 2010), Virtual Building Explorer (VBE) (Graphisoft, 2010) and goBIM (Keough, 2009). These applications typically focus on an optimized information exchange with major BIM environments, as opposed to the online worlds brought up above. These applications provide easy support for calculations and simulations mainly considered in a final design stage, including 4D construction planning, interference or clash detection, design reviews, 3D model checking, etc. The applications tend however not to provide an equally intuitive virtual world as is experienced in Second Life or SketchWorlds for instance. Instead, focus is put on an interactive third person overview and on the possibility to create animations with a certain lesser degree of freedom. The ICEvision application (ICEvision, 2010), for instance, focuses on the creation of such more presentation-oriented animations. These applications present a third person view that is not as intuitive and interactive as the first person view experienced in Second Life for instance.

MR applications always rely on a certain percentage of real objects. Two common examples of MR applications are the Layar Augmented Reality Browser (Layar, 2010) and the Wikitude World Browser (Wikitude, 2010). Both applications are typically used on a smartphone and present information retrieved from the web as a dedicated virtual layer on top of a view recorded by the built-in camera recorder of the smartphone, based on GPS information and on the view direction of the camera. In the AEC domain, MR applications seem typically useful in the later stages of the design process, including for instance the stages in which part of the site is already under construction. A large part of the suggested applications include construction site inspection (Shin et al., 2009). Another important application domain is project management, more specifically for construction progress monitoring (Golparvar-Fard et al., 2009). Even more extremely, MR visualisation can prove a useful addition in the context of facility management (FM), building maintenance and renovation (Webster et al., 1996), and building damage evaluation in the aftermath of disasters (El-Tawil et al., 2006).

4. SUGGESTED STRATEGY FOR THE VISUALISATION OF SEMANTIC ARCHITECTURAL INFORMATION

4.1 Strategy

MR applications are thus typically developed for contexts in which real objects matter for the building design. In an early design context, this includes in many cases only an empty construction site. In these cases, this MR visualisation does not seem such a valuable addition to the design process, because design decisions rely almost exclusively on the virtual parts of the design. Certain, more exceptional design tasks may profit from the usage of an MR visualisation, including the design of underground structures (Roberts et al., 2002) and exterior architectural design (Thomas et al., 1999) for instance, but in mainstream design projects the percentage and value of real objects, e.g. the site, tends to be rather low in comparison with what is imagined and is essentially virtual. Because VR visualisations, on the other hand, typically involve only virtual elements, they tend to be far more useful in the early stages of the design process, in which the complete design is still mainly virtual in the designer's mind. VR visualisation environments thus typically focus on visualising as much of this internal mental image of the design to generate an improved image of the state of the design at hand.

In our research, we target the improvement of the initial stages of the design process. Following the above considerations, we focus our research on VR visualisation systems and will handle only these systems in the remainder of this paper. VR visualisation systems can typically be subdivided in two types, depending on the software deployed to build the virtual environments. On the one hand, we distinguish more traditional VR systems that rely on more low-level software libraries for optimizing the interface between the application logic and the VR hardware, including tracker systems, stereoscopic displays, interactive input devices, etc. Alternatively, we distinguish VR environments that rely on standard game engines that focus on an out-of-the-box environment for a fast and intuitive development of virtual worlds that may subsequently be optimized for certain VR hardware.

A brief and comprehensive comparison between game engines and 'virtual reality engines' is given in Al-Najdawi (2007). This overview indicates the most significant reasons why one typically chooses for a visualisation based on a game engine. Comparing to other research efforts (Marks et al., 2008; Wünsche et al., 2005; Moloney et al., 2003), we extract the following main reasons.

- Solid, high-level, and out-of-the-box functionality enables a considerably fast development of functional virtual worlds
- Low cost
- Mature tools for the development of extra functionality: networking utilities, physics engine, AI engine, etc.
- More compelling results in terms of interactivity and 3D graphics
- Designed for a remarkably good minimal performance on a whole range of operating systems and hardware configurations

Comparing this strategy overview with our focus on the initial architectural design stages, we decided to focus first on VR visualisation environments based on game engine technology. Considering the large number of available game engines, it is nearly impossible to give even a brief overview of all game engines. We therefore focus on the most promising game engines in relation to visualisations in the AEC domain. An overview and qualitative analysis of such engines was recently given in Koehler et al. (2008). Following developments in game engine technology, we give a short overview of the game engines Unity3D, Quest3D, Shiva, Virtools and Creator. We analyse to what extent they are appropriate for the visualisation of semantic architectural information in a virtual interactive 3D environment, and in how far they compare or compete with the visualisation environments discussed earlier. Traditionally very popular game engines, such as Doom, Unreal, etc., are not considered as they do not provide the required interoperability with the CAD tools typically deployed in the AEC industry, and usually require users to (re-)model all 3D in an in-house game editor to obtain sufficiently qualitative graphics.

4.2 Comparison of game engines

4.2.1 Creator

Esperient Creator is one of the newly emerged 3D engines explicitly targeting architectural design processes. The product's whitepaper indicates how the product fits perfectly into the typical architectural design process, indicating the position of the application in relation with major architectural design tools such as Google SketchUp, Autodesk Revit, GraphiSoft ArchiCAD, Bentley v8i and Autodesk 3DS Max (Esperient, 2009). A closer look at the workflow from CAD tools in the AEC domain to Esperient Creator, however, shows a not so intuitive process, involving a link to the relational database underlying the original CAD tool or connecting trough Microsoft's Distributed Component Object Model (DCOM) (Esperient, 2009a). Alternative file-based processes seem to require a detour via 3DS Max, which is a specialized 3D visualisation tool and not a standard CAD tool possessed by any AEC specialist, and the usage of the Right Hemisphere (.rh) file format, which seems not to produce the best visual graphics when testing.

On the other hand, Esperient Creator provides a significant and useful set of standard GUI components to its users, and looks a fairly intuitive tool to use (Esperient, 2009a). Apart from the two available built-in scripting languages, it also provides an extensive C++ API for the development of advanced functionality in the visualisation. Extended with the availability of ODBC database connectivity and the necessary networking functionality, Esperient Creator provides a solid basis for the advanced information visualisation environment we targeted earlier.

4.2.2 Virtools

The 3DVIA Virtools visualisation engine of Dassault Systèmes has evolved into a complex, but highly functional platform for 3D authoring and 3D visualisation. The presented process "Import - Create - Publish" (Virtools, 2010) gives an appropriate idea of the visualisation process typically gone through when using Virtools for building a virtual world. Extensive functionality is provided for the creation of the eventually resulting world, extending the main platform with many additional functionality libraries, including a Physics Library, a Multiuser Library, a VR Library, etc. Combined with a highly functional and well-documented Software Development Kit (SDK), any user is thus provided with all the required functionality to build compelling 3D worlds.

Virtools primarily focuses on the connection with Dynamic Content Creation (DCC) applications, thereby mainly targeting with animation software such as Autodesk 3DS Max. The bridge towards Product Lifecycle Management (PLM) and BIM software is provided through the 3D XML plug-in for Virtools (Virtools, 2010). This plug-in is, however, mainly available for PLM applications by Dassault Systèmes, thereby somewhat excluding the easy usage of Virtools outside the Dassault Systèmes product suite. Combined with the high purchase cost, we tend not to consider the Virtools platform as an appropriate tool for developing the targeted information visualisation.

4.2.3 Unity3D

The Unity3D game engine is a recent game engine under development by Unity Technologies. The engine focuses on a fast and intuitive game development for diverse hardware and software environments, including iPhone and iPad applications, immersive installations, etc. (Unity3D, 2010). After testing, it was considered as one of the best game engines in terms of usability, intuitiveness, and resulting quality in graphics and interactivity. The game engine relies mostly on import through the FBX file format, analogous to other, similar game engines. Unity3D provides a useful API that is accessible through C# scripts and JavaScript for basic game engine functionality (Unity3D, 2010). The more advanced API components, such as a VR library, a physics engine, a multiuser library, etc., are not available out-of-the-box, resulting in a compact, functional API for fast application development.

In our investigation of Unity3D, we experienced a remarkable support, elaborate documentation and an active user community, indicating a high level of user satisfaction. The fact that other initiatives for VR visualisation, including goBIM for instance (Keough, 2009), rely on the Unity3D engine, indicates the appropriateness of the game engine. The availability of a free version adds to these advantages.

4.2.4 Quest3D

The Quest3D engine, developed by Act-3D, differs considerably with the other game engines described here. This difference is mainly caused by the heavy reliance on 'channel graphs' to express interactivity in the resulting virtual world (Quest3D, 2010). Channel graphs are graphs that are continuously called when running the virtual world, and depending on the 'channels' contained in the graph, one or another action / interaction is triggered.

The connection with existing CAD tools relies heavily on import/export/conversion plug-ins developed by third parties. As Quest3D information is described in an in-house format, any external 3D description needs to be converted into this data structure. An important information loss is experienced in this conversion, not to mention the hard balancing exercise between advantages and disadvantages of the several conversion alternatives. After experimenting, the Quest3D engine proved not as intuitive as was originally expected. Notwithstanding the promising character and the nice results of the Quest3D game engine, we found the game engine inappropriate for the targeted fast and intuitive visualisation of 3D building models and their information.

4.2.5 ShiVa

The newly emerging StoneTrip ShiVa game engine (Shiva, 2010) focuses on compatibility with a whole range of existing DCC applications through the DAE and FBX file formats, including Blender, 3DS Max, Maya, Cinema4D, etc. In order to get a building model from a BIM modelling environment into the ShiVa visualisation environment, one is thus required to get the model in any of these DCC applications and export it again in a DAE or FBX format, which might cause a certain amount of information. The provided import/export functionality via DWG provides an alternative workflow, but this is not the ideal approach considering the richness of the IFC format, for instance.

Furthermore, ShiVa seems to provide all the basic functionality one could expect from a game engine nowadays. Scripting possibilities via Lua are provided, an API provides developer access to the engine, and the environment can be published into a myriad of environments, including mobile hardware systems such as an iPhone and iPad. To conclude, ShiVa can provide a solid basis for an information visualisation environment. Being a young and small company compared to the companies considered above, a somewhat lesser support and maintenance may nonetheless be expected for the moment.

4.3 The best choice?

Purely based on the functionality provided by each of the game engines, only relatively small differences were found between the engines, of which the extent can only be experienced through a far more detailed study *and* usage of each of these engines. Every game engine can to some extent be used as a basis for implementing a visualisation environment for the architectural information linked to the building models on a semantic web, and none of them seems perfectly fit. Based on the extra characteristics of the game engines, such as cost, development support and popularity, we found the Unity3D engine most promising. We therefore chose to use this engine for building an example virtual environment in which a 3D building model is visualised and the semantic architectural information can be interactively accessed in real-time for each of the elements of the building model.

5. ACCESSING THE ARCHITECTURAL SEMANTIC WEB FROM WITHIN THE UNITY3D GAME ENGINE

5.1 Information exchange

For testing the visualisation of a building and the information available on the semantic web for this building, we modelled a design built in Antwerp by architects R. De Meyer and F. Van Hulle, using Revit Architecture 2010. Building information concerning the building design was added to the model as in every usual BIM model using the Revit BIM environment. This information was exported using the IFC export utility standard provided in any mature BIM application, including Revit Architecture 2010. The information in this IFC file was then converted into an online RDF graph using our in-house IFC-to-RDF converter (UGent MultiMediaLab, 2010). References were added to other information in the online open linked data cloud, including more detailed material information and geographic information (Pauwels, 2010). This information is now accessible through an online SPARQL endpoint. Through this endpoint, any information processing system may access the information described.

We did not found any game engine able to build a virtual world based on an IFC description. As the IFC format targets interoperability mainly in construction industry, it is near to useless for a game engine. As an alternative approach, one could choose to exchange the 3D information using the triangulated mesh representation made available through the API of the modelling application, as was done in Keough (2009). We however chose to rely on a well used file format, ideally a formal or informal standard. Industry standards in animation industry include formats such as FBX and DAE. As Unity3D provides standard 3D exchange through FBX, this was chosen as the communication medium of the 3D information. Note that the amount of information that can be described using the IFC format exceeds that of FBX, which focuses solely on graphical information.

5.2 Creation of the virtual world

After import of the 3D model in FBX into Unity3D, a few actions enable the creation of an interactive virtual world. The mere inclusion of a terrain, a global directional light and a First Person Controller enable a fast production of a basic virtual world. After the import of the FBX file, every building element that was modelled in Revit Architecture is available as a separate object, identified by the original CAD object ID. As this CAD object ID is also present in the IFC description and thus also in the semantic web graph (Fig. 1), a connection between the object in the virtual world and the information in the semantic web graph is available.

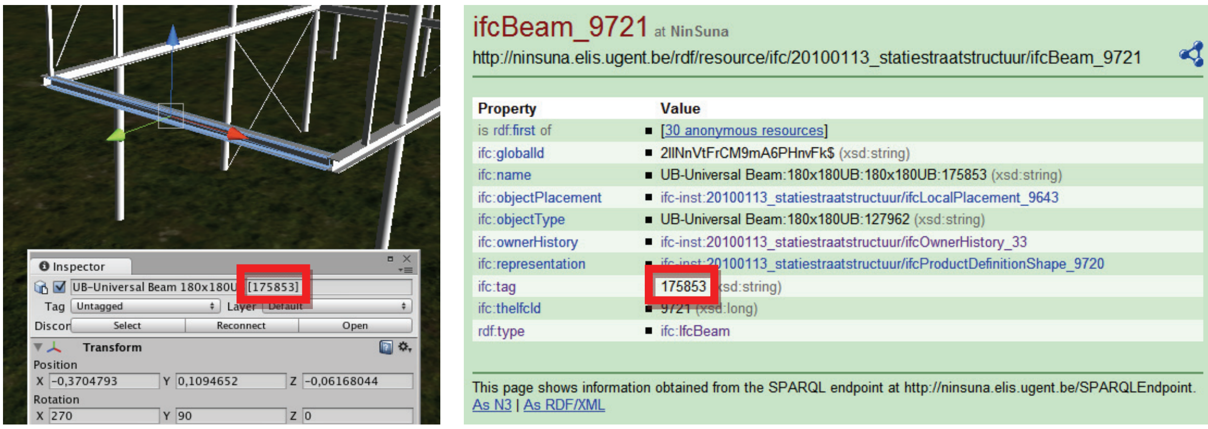

Fig. 1: The unique CAD Object ID is available in Unity3D (left) and in the semantic IFC/RDF graph (right).

5.3 Implemented functionality

Several additional scripts allow a connection from within the Unity game environment with the SPARQL endpoint on the server. When connected with this endpoint, any possible query can be sent through over HTTP. The query result received by the script can be processed or visualised as wished or required in the virtual world. At the moment we implemented functionality so that any AEC specialist can intuitively walk around in the virtual 3D world (Fig. 2, left) and select any object using the available pointer. Upon selecting an object, a query is fired towards two parallel semantic web servers, the one containing a number of IFC models in one semantic web graph, and the other containing extra architectural information (e.g. topological information, material information, etc.) added to these original IFC models. The user view changes into a separate focus view that isolates the selected element from the rest of the building and merely displays the information available for this element (Fig. 2, right). This information is displayed as a three-dimensional graph that can be further explored by selecting the nodes in this graph.

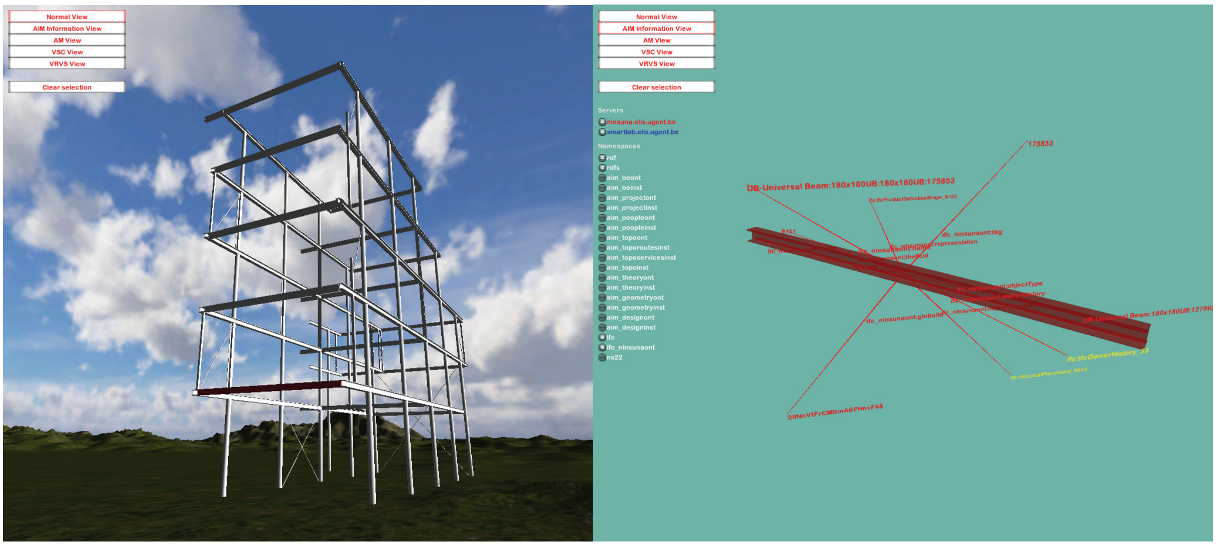

Fig. 2: Virtual world with the building structure of the visualised design, both in an overall First Person View (left) and in an isolated view for the building element highlighted earlier in Fig. 1 (right).

5.4 Evaluation

The main objectives of this research was to find an appropriate virtual environment allowing easy visualisation of 3D building models typically developed within the AEC domain *and* the information adhered to these models using semantic web technology. The Unity3D game engine has indicated this functionality, and an initial implementation of the targeted functionality was implemented.

However, because research primarily focuses on the connection between a game engine and this semantic building information, we did not elaborate on the interface displaying the information. As most AEC specialists are not familiar with a 3D graph representation in a virtual world, it proved not the most intuitive interface for the targeted functionality. As an alternative, the information might be better visualised in a form-like view, similar to existing CAD applications. We also recognized the importance of selective views on the information of the building elements. No one benefits from an 3D information 'explosion', so further interface optimisation is needed also on this topic. As this is ongoing research, further reports on these topics are to be expected.

6. CONCLUSION

This research shows how the combination of game engine and semantic web technology may enable an advanced visualisation of design information in an attractive, possibly very realistic and interactive environment. Considering further enhancements, such an environment may well be an appropriate extension of the designer's workspace, better than a combination of two-dimensional drafting technologies and a set of disparate databases. We also believe that the usage of game engine technology may provide the domain of semantic web technology a way to visualize information in a more intuitive and more attractive environment, especially when considering building and architectural information.

We are aware that this end-to-end research requires more in-depth research at certain critical points in the decision-making, but we argue that it represents useful considerations on the topic. A more in-depth investigation of game engines, of VR and MR in general, and of 3D modelling functionality in these environments would improve the system considerably, but were out of scope for this test case research. Further research could also focus on the usage of query systems or rule engines in the visualised environment to enable the appropriate visualisation of an automated checking of the building designed.

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USER-CENTERED DESIGN AND EVALUATION OF E-HERITAGE: A VIRTUAL REALITY PROTOTYPE FOR LEARNING ARCHITECTURAL HERITAGE IN INFORMAL EDUCATION

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ABSTRACT: *The importance of user-centered design and evaluation of virtual reality application (VR) cannot be underestimated, especially for the development of applications that involved massive users. Based on an ongoing effort to develop a usable and meaningful VR to learn cultural heritage through architectural monuments, a series of user evaluation is required to identify usability issues and design improvements from user perspective. Museums have been selected as representatives of informal education settings, based on their role in the dissemination and popularization of knowledge of cultural heritage to the general public and the acquisition and preservation of heritage to be displayed and disseminated among public. The objective of this paper is to deliver the results of such evaluation through gauging and analyzing the feedback and subjective opinions of the actual users of the system. This is to subsequently allow for a better implementation of modifications aimed at improving fidelity of the user interface and ease of use of the system in informal education. Progression and performance is evaluated as this is determined by users' ability to navigate in the VR environment and then recall historical as well as architectural information embedded in the virtual reality application. Visual and auditory information is provided during the navigation in order to impart architectural knowledge to the users. Results will provide a systematic approach of the evaluation of the VR system, information for guidance on system refinements and hence allow for comparison of usability levels with other types of learning systems.*

KEYWORDS*: User-centered design, Virtual reality, Usability, Architectural heritage, Informal education.*

1. INTRODUCTION

The importance of involving real users in the process of design and evaluation for real-world virtual reality (VR) applications is being emphasized despite the difficulties of such a choice (Swan II et *al*., 2003; Bowman et *al*., 2002). Implementing such a user-centered approach requires collecting and analyzing as much information about users as possible, through a detailed user requirements process and a deep understanding of how they work (Drettakis et *al*., 2007).

Virtual reality applications have increasingly been used for disseminating historical and cultural information as well as knowledge to public despite of its high cost and maintenance. Successful stories of VR installations are the Foundation of Hellenic World in Greece (Gaitatzes, 2000) and Natural History Museum, Japan (Kondo et *al*., 2007). User evaluation is therefore important to determine whether the museum exhibits really provide an exceptional level of learning to its visitors. It is also impossible to allocate curators to each and every exhibit as visitors come and go in different timeframes with undetermined intention. The use of VR is perhaps one of the solutions in addressing this problem despite its high cost and rigorous maintenance. Considering these issues, user evaluation on the museum exhibits has to be implemented to ensure that they are worth being displayed and to some extent, providing a good learning experience to the visitors. Previous evaluation studies on both VR installations and applications in cultural heritage institutions suggest that VR delivers enjoyment, immersion, interaction, learning capability, and engagement (Forte et *al*., 2006; Pujol-Tost & Economou, 2007) and the potential is huge and hard to be refused, taking into account that it should not replace the real objects (Alzua-Sorzabal et *al*., 2005). In most cases, these exhibits are blends of VR, augmented reality, and other ICT technologies such as multimedia, animation and 3D visualization and user evaluation was done after such systems were installed and running at museums. Therefore, it is difficult to know how such user evaluation improved the design of these VR applications.

To exclude the influence of memorizing real experience, Fatehpur Sikri, one of the gazetted world heritage sites in Agra, India, is selected as the case study for the VR application development. Other reasons are due to the cultural values it possesses where it was once the capital city of the Mughal Empire and how it is well known for its urban planning, massive use of red sandstone in construction and indigenous craftsmanship. Figure 1 demonstrates the overall map of Fatehpur Sikri and the red boxes indicate important monuments to be included in the VR application.

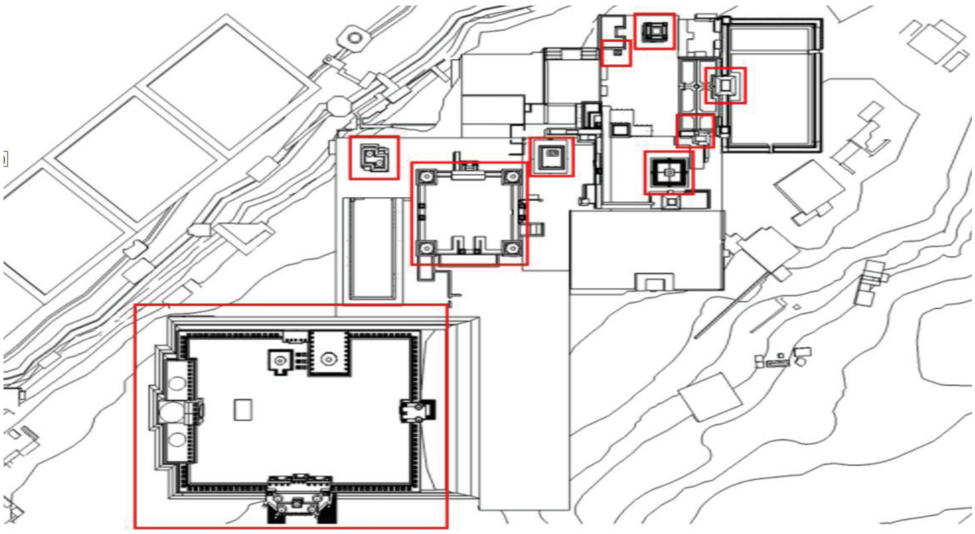

Fig. 1: The overall map of Fatehpur Sikri imperial complex.

This study proposes UCDE framework to be incorporated in the development stages of a VR application for learning architectural heritage in informal education settings. Museums have been selected as case studies based on their role of cultural heritage acquisition and preservation to be displayed and disseminated among public. Among the challenges are the vast background of audiences and how to engage museum visitors to do the experimental procedure from start to end. However, the advantages of such framework are the ability to reveal usability and accessibility issues and to demonstrate the conformity of the overall design which may not be able to be covered by developers.

2. RELATED WORK

User-centered design and evaluation (UCDE) aims to create software, a system or an application that can match users' ability to perform intended tasks. UCDE in general performs the central theme in human-computer interaction (HCI) and usability engineering (UE) to ensure the developed systems generally would meet not only functional requirements yet can be used and reused with effectiveness, efficiency, and satisfaction. There are well-published guidelines and principles for designing systems that propose valid user-centered methodologies such as Logical User-Centered Interactive Design Methodology or LUCID (Smith & Dunkley, 1998) and others (Shneiderman, 1998; Mayhem, 1999). LUCID is basically an early prototype development coupled with Taguchi philosophy of total quality management and targeted to optimize the interface design by shorter prototyping phase and overall development time (Smith & Dunkley, 1998). These methods however are meant for traditional graphical user interfaces (GUI) where users are already familiar with the two-dimensional (2D) interface metaphor. Virtual reality is normally in three-dimensional (3D) interface metaphor and requires three-dimensional interaction devices which naturally increase the complexity of such system in terms of user interaction and system functionality.

Virtual environment (VE) evaluation methods were developed because the existing graphical user interfaces (GUI) based evaluation methods were not able to address broad variety issues in VEs (Bowman et al., 2002; Hix & Gabbard, 2002). These methods, known as VE usability engineering methods were derived from usability engineering methods for GUIs and normally use one or more usability evaluation methods whereby evaluation here usually is associated with inspection aims to identify problems in user interaction design (Hix & Gabbard, 2002). VE usability engineering methods employ user task analysis, expert guidelines-based evaluation, formative usability evaluation, and finally summative evaluation which involve users and experts. The iterative development and evaluation cycle was employed in terms of experimental design and procedure (Gabbard et *al*., 1999) where users are selected in advance. The selection of users is useful in application-specific and/or domain-specific levels as users normally shares common education background and interests.

The user-centered design and evaluation approach was successfully adopted in application domain such as battlefield visualization system (Swan II et *al*., 2003) which in its summative evaluation involved 32 users such as civilians as well as military and retired military personnel. The same project has demonstrated the extensive use of UCDE approach and how the results have been incorporated into subsequent development stages. However, the nature of this system differs from the application developed in this study in terms of its targeted audience and also the learning modules and outcomes of its content that become central for VR not only to be usable and useful but delivers a meaningful content for museum visitors.

3. METHODS

The user-centered approach used in this study is evolved around sequential evaluation framework – user task analysis, expert guidelines-based evaluation, formative user-centered evaluation, and summative comparative evaluation – proposed by Bowman et *al*. (2002) which initially developed for generic VR research and later adapted by Hix and Gabbard (2002) and Swan II et *al*. (2003) in the battlefield visualization system development and whom the targeted users were military personnel. In this study, it differs in terms of application domain which mainly focuses on learning architectural heritage and targets a vast audience of museum visitors. The following sections describe the design and evaluation stages and procedure during the development of the VR application.

3.1 User Task Analysis

The goal of user task analysis is to identify a complete description of tasks, subtasks, and actions required to use a system as well as other resources necessary for user(s) and the system to cooperatively perform tasks (Hix & Hartson, 1993). In order to perform the analysis, generic user requirements were identified during our preliminary study using face-to-face interview with museum visitors (Murni et *al*., 2009) and series of roundtable discussions with a museum expert.

Following are notable findings from this preliminary study:

- The demographic information of 371 respondents shows computer competency of majority respondents is intermediate (49.7 valid percent), novice (33.2%), expert (9.0%), and not exposed (8.1%). However, majority (70.5%) are not exposed to online or video games, 12.8% plays on the basis of one to five hours per week and only 8.7% are always engaged in an online or video games.

- Museum visitors (40 respondents) in an architectural museum perceive ICT in general ultimately can help in several ways: to provide easy access to information (20), visualizing past items or scenarios (17) and learning in a fun way (10).

- When asked on how can learning history and cultural heritage be interesting on display, it is found that museum visitors in architectural museum provide comments that may tap the potentials of VR such as "*visual (exhibit) can make me understand things easier*" and *"(museum should provide exhibits where) people can interact and view the content*". Another respondent wished that "*places and landmark that they put bars and we can just see from outside, as far as possible we can go there and experience*". For social interaction, particularly among family members, one respondent suggested to "*have more* *interactive display especially for children (who) do not want to come to museum and just look, they want to experience and experiment, that's the way they learn*".

In general, museum visitors would like to have some interactive exhibits in the architectural museum in order to learn and experience historical sites and monuments. Those in family trips would be relieved to see their children enjoy the museum visit by experiencing and experimenting things by their own. This contributes to the design requirements of the VR application.

Nonetheless to get more specific requirements, series of roundtable discussions were conducted with a museum expert and architectural historian. A low-level functional VR prototype was presented to the expert and the expert made comments during the presentation. Finally, a set of requirements was established where among others: the VR application should be able to cater for two distinct and extreme groups of museum visitors – normal visitors and experts such as researchers, historian, and archeologists; it should support at least two major spoken languages for wider accessibility; it should provide some interactive elements; it should be intuitive and easy to use by the general public; and it can support social interaction that may initiate conversation among family members or groups.

From the literature, there are few visitor studies focusing on the use of ICT as an interactive exhibits that allow learning-by-doing (Roussou, 2000), the effectiveness of ICT as museum exhibits, and the usefulness of immersive VR for learning in cultural settings (Pujol-Tost & Economou, 2009). From these studies, very general guidelines of exhibit design emerged: suitable for learning (contains different link elements with appealing contents), enjoyable (interactive), engaging, easy to use (intuitive, clear affordances so visitors can concentrate on content), and suitable for groups (allowing group exploration). Most researchers agree that ICT exhibits, if to be located in the same room with the rest of exhibits, should integrate well with other interpretation methods (i.e. artifacts, replicas, posters).

These requirements were incorporated into our initial interface and interaction design. In VR environment, the users may navigate freely; an icon that indicates information is available when a user is in a range of proximity to a particular attraction or monument. By triggering the icon (i.e. user collides with the icon), the user may view extended information regarding the attraction or monument. The information can be shown to the use in the following formats: text, still images or movie files, as shown in Figure 2. In this VR environment, users' navigation in the 2D graphical user interface (GUI) was facilitated by sidebars and drop down menu. These navigation features were incorporated in the VR interface. It is speculated that 2D GUI may yield a more efficient navigation due to familiarity and simplicity. The navigation features are available upon demand (i.e. by clicking the sidebars and/or pressing keyboard buttons); such design decision is to avoid cluttering in the virtual environment with irrelevant substances and features which may lead to user confusion and loss in the environment.

Fig. 2: The initial design of the interface during navigation inside Diwani Khas (Hall of Private Audience).

Based on the background of the museum visitors, it is decided to use traditional keyboard and mouse for the input devices as it is assumed those novice users are familiar with these input devices. Another reason is the robustness of these devices to be used by the general public from all levels.

3.2 Expert Review

Expert guidelines-based evaluation is also known as heuristic evaluation and usability inspection that aims to find usability issues based on established guidelines at the early stages of the development (Hix & Gabbard, 2002). It is decided at this stage to confirm the design of the interface and also the content of the system. Therefore, two experts – museum expert and usability expert – were invited in this review stages.

In fulfillment to the requirement of information rich environment, we developed an alternative of a 2D metaphor as the main interface where VR application can be triggered upon clicking a menu button (refer Fig. 3). Using this 2D metaphor, historical information can be reached in few clicks and more facts and figures can be embedded in the system. Users may then navigate around the 2D interface metaphor by clicking the menu button.

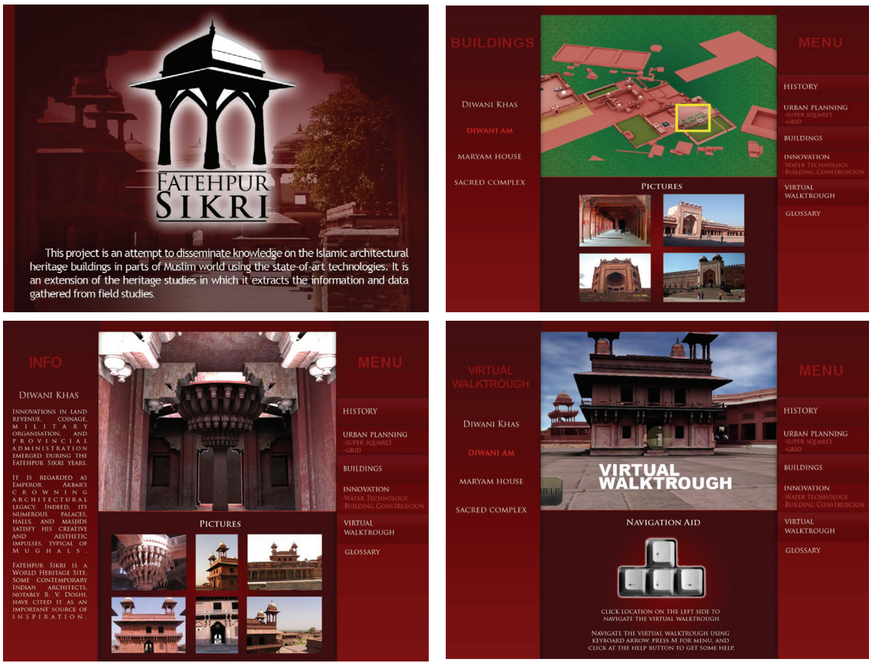

Fig. 3: The alternative 2D interface metaphor to allow more information to be embedded into the system.

3.2.1 Feedback and Recommendations

During the first expert review, the 2D interface metaphor and its functional prototype as shown in Figure 3 was presented in front of a museum expert by means of expert walkthrough. He completely disagreed with the 2D interface metaphor and instead emphasized on the uniqueness of VR application that can provide a sense of presence despite its 2D counterpart. Therefore, it is decided that VR should be the main interface of the application rather than normal 2D interface metaphor.

During the second expert review, the initial design of a functional VR application as in Figure 2 was presented in front of the usability expert. The usability expert has never encountered VR heuristics before but has numerous experiences on Web site heuristics and usability. Thus, she suggested few recommendations based on her previous experience: to put navigational map into the system to inform user on current location; to provide easy access to help whenever user requires; and to use short titles for each embedded items to describe contents. Due to technical restrictions, the navigational map could not be incorporated into the virtual environment.

3.2.2 Improvements

Based on these reviews and recommendations, it is decided to work upon designing the user interface and improving the user experience. At this stage, the content video files have been developed and ready to be embedded. However, the heavy detailing of the 3D model, particularly the unitary pillar inside the Diwani Khas as shown in Figure 2 has contributed to large computing power and huge memory consumption. It is then decided to optimize the 3D model as much as possible and at the same time retain the shape of the structure. The initial plan to transform each monument to VR navigational experience had to be restricted to two major buildings namely Diwani Khas and Diwani Am (Hall of Public Audience), and the others were compensated by 3D animated video.

It is then crucial to focus on the user experience of the VR application particularly in terms of storytelling and the flow of navigation. The introduction video to Fatehpur Sikri was inserted to put users into the right context. Virtual portal was used to bind the VR navigational experience of the two major buildings with other monuments. We then changed the initial colliding icons into clicking the rotating cubes to allow user to choose which information they want to know. Along this line, series of previews were done among the team members to ensure all contents are acceptably appealing and the transition from one scene to another is considerably smooth.

3.3 Formative Evaluation

The objective of formative evaluation is to identify usability problems as well as to assess the ability of the interaction design to support user exploration, learning, and task performance by means of iteratively placing representative users in task-based scenarios to assess, refine, and improve user interaction (Hix & Hartson, 1993). Typically, formative evaluation begins with development of user task scenarios that specifically designed to explore all identified tasks, information and workflows (Hix & Gabbard, 2002).

3.3.1 Methods

This study performed this evaluation by means of experimental design in field deployment to observe how museum visitors used this application in real-world settings. The experiment employs direct observation, usability questionnaire, and post-interview.

The selected museum is a two-storey heritage building with its nature of exhibition combining arts and sciences under a single roof and was selected because it is the only museum in this country that delivers VR content in astronomy projected using a half-dome system. The drawback is that it has no architectural heritage display and our VR application is only associated with Islamic arts exhibition gallery in the ground level. Nonetheless, our VR application was installed in an auditorium at the upper level that can fit up to forty people and projected onto a large screen display (see Figure 4).

3.3.2 Procedure

During the experiment, at least two evaluators were there, one was to respond to respondents' enquiries and another was to mark time stamps and did the video recording, and both observed the respondents and gathered other qualitative data such as respondents' expressions and conversations if they did the session in pairs or in groups. In most cases, respondents were free to navigate the virtual environment and complete predesigned tasks themselves. Evaluators would help them only upon request and at critical incidents that halted respondents to complete their tasks.

Fig. 4: Museum visitors during the experiment sessions.

Visitors were invited to participate in this study upon signing their informed consents, meaning that they volunteered to participate and may withdraw from the experiment at any point of time without penalty. Demographic information on age, gender, occupation, computer competency, VR experience, familiarity with 2D and 3D input devices as well as the content of application (i.e. Fatehpur Sikri) was collected. Respondents were then given five to ten minutes to get familiar with the application before doing the designated tasks and later the recall session. The tasks were designed to allow visitors to experience walking through the monuments and appreciate the craftsmanship of structural elements. These would also help respondents discover information that led to answers for the recall session afterwards.

Respondents were then asked to complete 27 usability questionnaire in Likert scale 1 (strongly disagree/very unsatisfactory) to 5 (strongly agree/very satisfactory) derived from VRUSE (Kalawsky, 1999) and finally answered post-experiment interview questions on their learning experience while using this VR application as well as gauging their feedback and suggestions for improvement. A small token of appreciation was given to respondents upon completion. The designated time to complete the experiment is 40 minutes but due to the nature of a museum visit, most respondents took about 30 minutes.

3.3.3 Observations

There are 46 participants: 20 male, 26 female, and majority (70%) of them are below 20 years old involved in this study. It is observed that teenagers were enthusiastic to explore the VR application rather than adults. In most cases, when they were accompanied by parents, their parents normally asked the children to participate while the parents observed or wandered in nearby area. Table 1 demonstrates the demographic information of respondent: 40% participants rarely used computers and 29% respondents have previously encountered virtual reality applications.

Table 1: Demographic information of respondents

				Frequency	Valid %.	
Gender		Male		20	43	57
		Female		26		
Age	below 20	20	32	11		70
	– 39	40 and		3	24	6
		above				
Computer use		Rarely	19	13	40	28
	Often	Very		14		32
		often				
VR experience	Yes	No	13	33		29
						71

It is observed that participants have no difficulties in using keyboard arrows to navigate forward, backward, right, and left. However, pressing the mouse's wheel button to turn around was not easy for some respondents. It also took some time for participants to navigate to the upper level of the building as the staircases were originally built in between the walls as a security measure and hidden from the participants' view. We did put the label indicating the way to the stairs but majority participants clicked at the label instead of going to the shown direction.

Majority participants did not read the navigational instructions page shown right after the virtual environment loaded. They would then ask the evaluators how to navigate instead of finding it using the menu tab. It is also natural for participants to click the rotating cubes in the order of where they are located. A critical incident that may halt the user navigation was identified at a point along the stairs where few participants reported that they suddenly plunged into the ground level and could not navigate further. To proceed, the evaluator had to restart the application and they had to begin from the introduction page. At this point, they wanted to skip all introduction videos as they had watched them before but could not find any skip button. It is our intention initially not to reveal the skip button so that users would watch the introduction video to gain contextual understanding about the history and place.

For groups of school excursions, one or two of the group members were invited to use the application (we addressed them as 'pilot') while others were watching. It is observed that peers naturally would direct the way for them and more observant to the information shown on the large screen. The 'pilot' would then seek advice from peers rather than the evaluators should they encountered any difficulties. This suggests a social interaction among visitors – in this case, among peers – has been taken place.

For groups of families, it is observed that parents would ask the children to be the 'pilot'. In one case, there was family of four members and their two children were in control of the application. Both parents, while watching, kept questioning the evaluators on the technology of the application e.g. 'how did you do that (the virtual environment)?', 'what it takes to develop this (the 3D models)?', and so forth. Both then helped their children answered the recall session and usability questionnaire. The father lamented that they were amazed by the video showing the architectural details of the buildings that they forgot to listen to the narration and read what was written.

Findings from our observation did suggest usability issues that might be overlooked by developers during the development stages. These issues together with results for usability questionnaire discussed in the following section were analyzed and prioritized based on their bold appearance and frequent comments from users.

3.3.4 Usability Evaluation

Table 2 describes the results gathered using usability questionnaire. Respondents were satisfied that overall our VR application provides sense of presence (mean=3.50, s.d.=.860). This application also provides satisfactory learning experience (mean=3.82, s.d.=.951) and satisfactory overall usability (mean=3.58, s.d.=.929).

Table 2: Usability evaluation

Item		Mean	Standard deviation
1	I felt a sense of being immersed in the virtual environment	3.79	.833
2	I did not need to feel immersed in the virtual environment to complete my task	2.48	1.122
3	I got a sense of presence (i.e. being there)	3.76	.830
4	The quality of image reduced my feeling of presence	3.19	.962
5	I thought that the field of view enhanced my sense of presence	3.93	.474
6	The display resolution reduced my sense of presence	2.97	.981
7	I felt isolated and not part of the virtual environment	2.44	.768
8	I had a good sense of scale in the virtual environment	3.92	.744
9	I often did not know where I was in the virtual environment	2.58	1.027
10	**Overall I would rate my sense of presence as:**	**3.50**	**.860**
11	I thought the system provides a good learning experience	4.29	.772
12	I can easily access information I want through the system	3.88	.928
13	The system improves my learning capability	3.71	1.105
14	I found the system contains too much information	3.29	1.160
15	I hardly recall the information from the system	3.35	1.222
16	I can easily recognize elements/structures shown in this system	3.75	1.000
17	**Overall I would rate my learning experience as:**	**3.82**	**.951**
18	I thought that the system worked against me	2.96	.999
19	I would be comfortable using this system for long periods	3.75	.645
20	I did not have a clear idea of how to perform a particular task	2.62	1.134
21	The overall system response time did not affect my task	3.22	.892
22	I found it difficult to learn how to use the system	2.69	1.158
23	I felt in control of the system	3.85	.834
24	The system did not work as expected	2.57	1.034
25	I found it difficult to work with the system	2.74	.944
26	I enjoyed working with the system	4.07	.900
27	**Overall I would rate the system usability as:**	**3.58**	**.929**

Overall, respondents rated this VR application as satisfactory. The results however reflect the overall usability and user experience and do not help much in identifying which components of the application need to be improved.

Nonetheless, these results will be a benchmark for comparison with other learning media systems.

3.4 Refinements

Based on the findings of the formative evaluation, necessary refinements have been made to our VR application. Among others are the navigational instruction page was redesigned to be bold and noticeable; the skip, pause, and replay functions were added to the introduction video and other videos that exceeded 30 seconds; and the keyboard navigation controller was moved to game-like AWSD buttons. Figure 5 depicts the screenshots of the earlier version of this application (on the left-hand side) and after refinements (on the right-hand side).

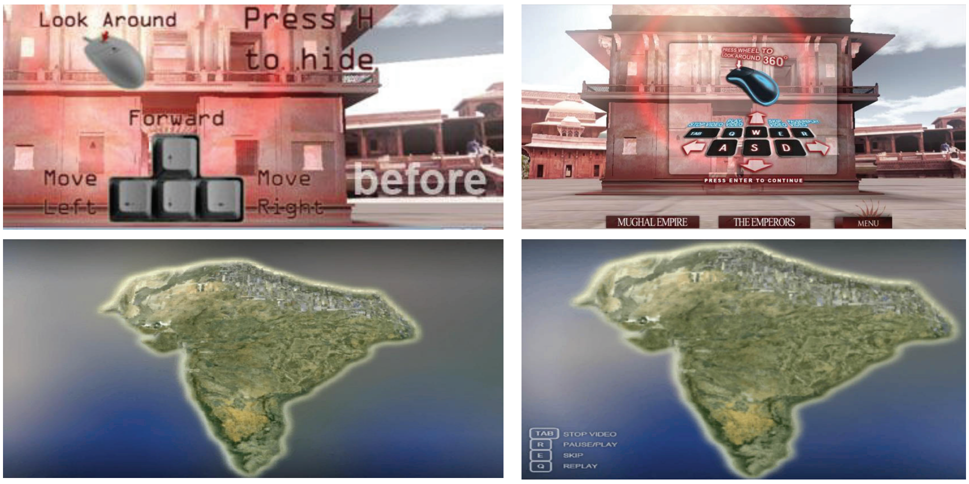

Fig. 5: Screenshots of our VR application showing the earlier version (left-hand side) and after refinements (right-hand side).

The redesign of mouse navigation was attempted whereby pressing the wheel button was replaced by clicking left or right button. Unfortunately, this redesign conflicted with our earlier object selection of clicking rotating cubes by using left-button mouse and hence could not be implemented.

In summary, considerations of various design and redesign options may consume time and development effort. The user-centered design and evaluation through findings from observations as well as gauging and analyzing user feedback and comments may contribute to a level of consensus on the design of the VR application.

4. CONCLUSIONS AND FUTURE WORK

This study emphasizes the importance of UCDE to be incorporated into the development stages of a VR application for learning architectural heritage. This paper describes the UCDE experience – user task analysis, expert evaluation and formative evaluation – that involved domain experts and real users in real-world settings. It further discusses findings resulted from these evaluations and how these findings were then contributed to the interface design and later were used to refine the VR application.

It is best however to get an architectural museum as one of the evaluation settings and it is good to conduct another user evaluation at such museum. Future evaluation may include comparison among other learning media to this VR application and hence determine to what extent museum visitors can recall information from this VR application.

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V. OPERATION AND TELE-EXISTENCE

AUDITORY FEEDBACK FOR VR-ASSISTED CONSTRUCTION ROBOT TELE-OPERATION

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ABSTRACT: *This paper explains the idea and the realization of a study to enhance tele-operators' skills and situational alertness by using auditory feedback. Safety and reliability are the most important issue in construction robot tele-operation. Tele-operators have a tendency to lose visual focus due to overloading task at hand. This makes it very stressful for operators to control the construction robots, especially since they are heavy and expensive to be repaired on site. Basically, information is presented visually in tele-operation, by including multi-display monitors, virtual reality, and camera images. Recent developments also include force and auditory feedback to improve performance in tele-operation. Both multi-sensory approaches have been proposed for tele-surgery and ground-to-space tele-manipulation. In general, audio signals can be used to reinforce alertness. Thus, if applied correctly, the signals should increase performance by channeling valuable information to the ears. Human operators are very sensitive in segregating information disparity by hearing patterns in sound. Hence, they can quickly notice changes in the task, and proceed with appropriate new inputs to the system. Therefore, in this research, audio signals have been utilized to enhance force feedback during heavy construction tele-operation. The objective is to supply the operators with safe and sustainable grip to minimize random tele-manipulation error. The study focuses on the effect of auditory feedback on construction robot tele-operators' workload, gripping and manipulation task performance. Combined force and auditory feedbacks have been found to improve gripping performance, by introducing safe and sustainable grip.*

KEYWORDS: *Multi-sensory feedback, master-slave tele-operation, construction robot, virtual environment.*

1. INTRODUCTION

There are few reasons why auditory feedback is useful in VR-assisted tele-operation. According to Brown et al. (1989), the most common reason is that auditory feedback, in the form of audio signals, can help in reducing visual overload; since visual interfaces tend to be busy due to overloading task and information at hand. He suggested that channeling the information in the form of audio signals to the ears could reduce the load. In general, information that is visually presented, either in the form of multi-display monitors or virtual display images can contribute to overloading task. The problems of overloading are consistence with the remote-controlled post-disaster reconstruction, where heavily monitored tele-operated construction robot may unpredictably collide with other equipments, or accidentally crushes important workpieces. Such mishap can attribute to costly accidents, and often cannot be easily resolved on site. This makes it very stressful for operators to control the robots. The use of auditory feedback is also useful when eyes are elsewhere, for example, when giving to much attention to gripping an object, while forgetting the proximity of the fork with the ground. It is the same as using auditory feedback to assist in a condition where someone's visual attention should be entirely devoted to a specific task such as surgically operating on a patient or driving a car (Recarte and Nunes, 2003).

Auditory feedback can also be more informative since humans are very good at hearing patterns in sound. This means that at times it is easier to understand information when it is sonified. Bly (1992) suggested that as similar to an x-y plot that reveals relationships in data, sound can also be use to reveal such relationships. The sound can be use to represent many type of information, in many different ways. Thus, in this paper, the goal of the auditory feedback at this stage is not just to give warning alert to the operators about the proximity of the grapple to the ground, but also support the operators awareness about when to grip or how hard to grip the object. The goal is not to simulate or imitate existing auditory behavior but to provide useful information for the user interaction. The current research presented in this paper focuses on auditory feedback effect on operators' performance, gripping control and workload, in handling various types of construction materials. Possible post-disaster reconstruction materials are bricks, stones and concrete, which is heavy and hard to manipulate, and ceramics, aluminums, mud bricks and glass blocks, which are brittle and delicate to handle.

2. AUDITORY FEEDBACK FOR SAFE AND SUSTAINABLE GRIP

In general, joysticks provide gripping perception of the grapple during tele-operation. In the case of VR-assited construction robot tele-operation, it is necessary to overcome the limitation of the operators' ability to control the system. In our previous studies, virtual reality successfully improved the visual feedback of the system (Yamada et al., 2009), and force feedback-assisted tele-operation system improved task efficiency and performance (Yamada and Muto, 2003). Velocity control that monitors the error between the joystick displacement and cylinder velocity is an effective way to obtain stability when remotely controlling the robot. However, it is noticeable that kinesthetic senses in human body are lacking the adequate sensitivity to sense gripping force feedback, especially for soft and fragile work pieces. This happens because small load does not cause big displacement for heavy construction machineries, which proved to be difficult to detect. The delay effect in sensing the force feedback through the use of joysticks have little effect for hard objects, since the objects have the tendency to withstand heavy pressure from the hydraulic force. However, for soft and brittle objects, mishaps could increase exponentially. Therefore, the contribution of auditory feedback is considered to be useful during a sustainable gripping process, since audio signals can enhance the operators' understanding on the visual and force feedback delivered during the gripping process. Gripping perception could be reinforced through sound tempo, which could also be used to provide supplementary signals to adjust the position and orientation of the robot's boom, arm and grapples. Nagai et al. (1999) reviewed that auditory feedback had been used successively in ground-based tele-operation of a space robotic arm, for manipulating space antennas. The usage of different sound tempo in the interaction of robot end-effector with an antenna attachment had been tested in the actual space telemetry operation. The magnitude of force and torque on the end-effector was converted into tone signals and transmitted to the audio sampler. A sound source of motor noise was stored in the audio sampler, and the audio sampler generated the motor noise according to the force and torque magnitude. Results showed that the system decreased both the total operation time and the amount of time the operators spent looking at the display while attaching the end-effector to the antenna. In other words, the use of auditory feedback can be a powerful tool to help operators make decisions, which can help to prevent accidents during space robot tele-operation. In a recent discovery, auditory feedback was also found to influence the haptic perception during a tele-operation of robot-assisted surgery by using the Da Vinci Surgical System (Kitagawa et al., 2005). A suture tension measurement device was designed by installing a load cell, which detected the force feedback signals during tele-surgery operation. The force feedback was represented visually by using a horizontal indicator, which was projected on the television screen. Auditory feedback presented additional audio signals for the system. Subjects were asked to do the test based on different suture materials, by using all feedbacks. Kitagawa et al. (2005) found that the feedback helps them in reducing the amount of broken suture during tele-surgery, and the performance is equal to a normal surgery. Moreover, the combined visual, auditory and force showed great variability in controlling the tension force required during the tele-surgery experiments.

3. TELE-OPERATION TEST BED AND FEEDBACK SYSTEM

3.1. Construction robot system

Figure 1 illustrates the tele-operation test bed for the research. The construction robot is based on modified Hitachi EX5 Landy Kid mini-digger, manufactured by Hitachi Construction Machinery Co. Ltd. It weights up to 0.5 tonnes, and has swing capability of 150 degrees. The bucket is replaced by a grapple attachment, suitable for manipulation and pick and place operation. The robot is equipped with 4 Kayaba Stroke Sensing Cylinders

(KSSC), as part of the I/O devices for the test bed. The sensors are placed at the rod end of the cylinder, and accurately detect the displacement of the cylinder. Four servo valves through a PC-based controller control the four hydraulic actuators. The control PC is also used as the main computer for data acquisition, using c++ as the main programming system. The test bed utilizes the use of master-slave controller, where two joysticks are used as the master, while the construction robot acts as the slave. The piston velocity is set to zero when the joysticks are at the middle position.

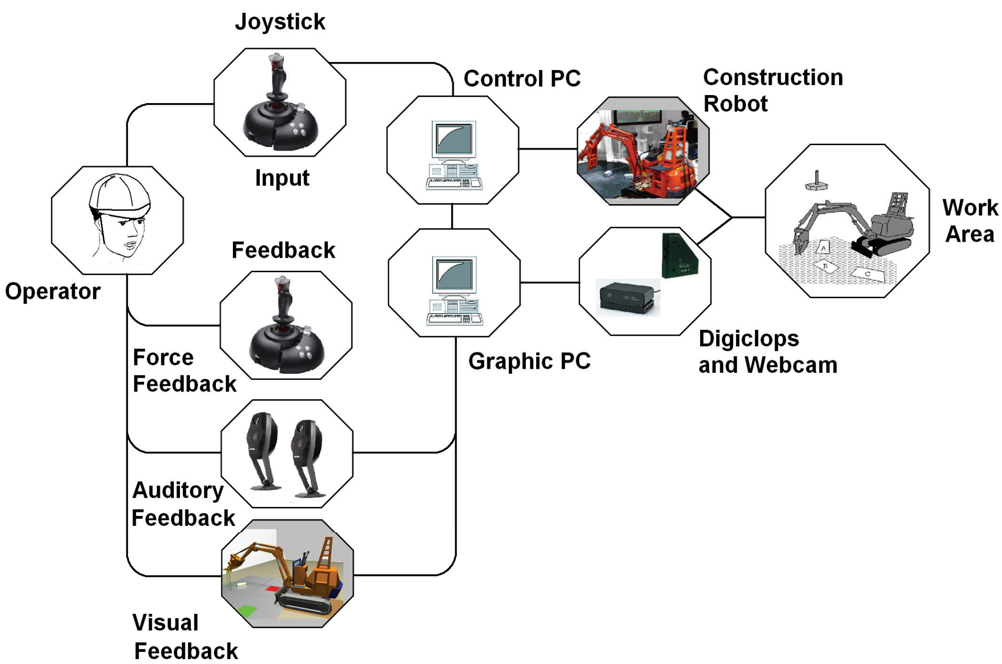


Fig. 1: Construction robot tele-operation with virtual reality

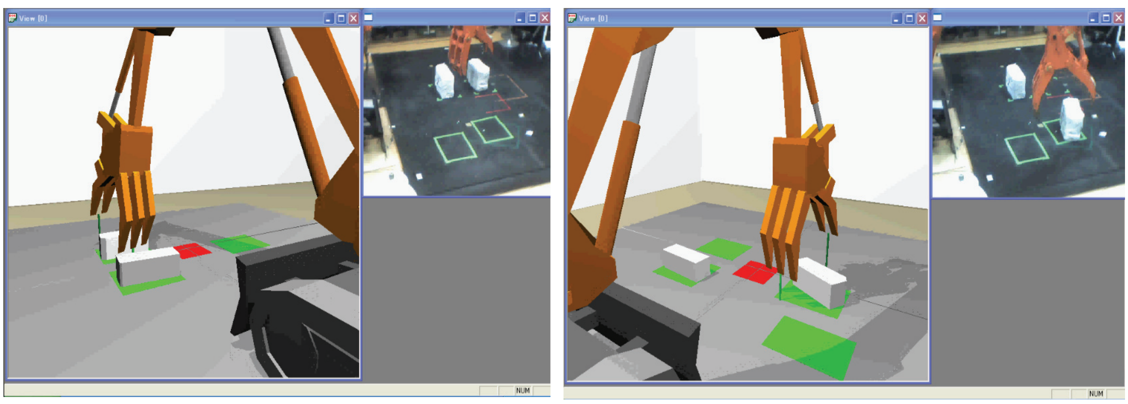


Fig. 2: Visual feedback system

3.2 Visual feedback system

Figure 2 illustrates the setup of the work piece in real and virtual images. The information is represented simultaneously in the form of virtual and real images. The virtual images of the workpieces are created by using *Digiclops* camera, a product of Point Grey Research, Inc. The camera is a color-stereo-vision system, linked to the graphic PC to provide real-time image by using stereo vision technology, which acquires the position, the color and the shape information of the workpieces on the operation site in its field of view and create virtual images of the workpieces at a speed of about 30 frames/second. The virtual reality images of the construction robot are also generated by the graphics PC. The motion of the virtual robot is generated according to the operation signal from the joysticks. Cylinder displacement data from the KSSC is sent to the computer, which is later transferred to graphic PC to synchronize the movement of the construction robot with the virtual robot. The camera is set up just above the construction robot, and the optical axis of the stereovision camera is made to intersect with the floor perpendicularly. A webcam is also used to provide real image for the operators during the simulated tele-operation.

3.3 Force feedback system

Figure 3 shows the force feedback system (FFS) based on velocity control method. The FFS is generated by the interaction of master-slave system (Yamada et al., 2003), where the control is based on the concept of velocity control method (Yamada et al., 2006). The equation for the velocity control FFS is represented in equation 1.

$$t_r = T\{k_{pm}(Y_m - V_s) + k_{tm} f_s\} \qquad (1)$$

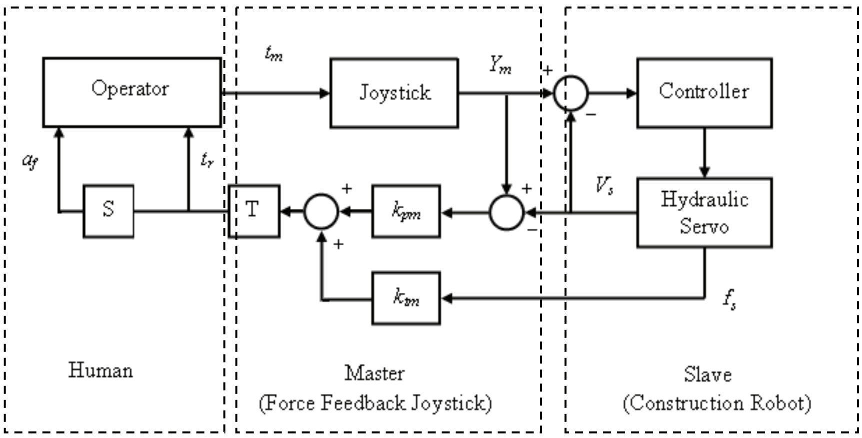


Fig. 3: Auditory and force feedback system

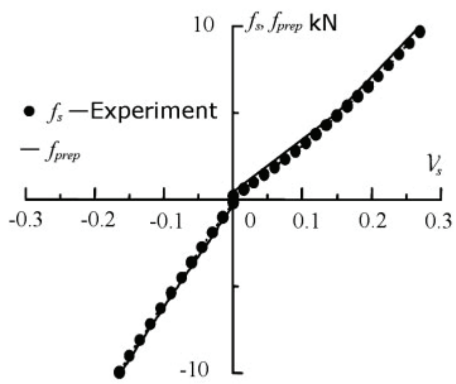


Fig. 4: Velocity-dependent motion relationship

Upon gripping, the force feedback is represented by reaction torque, t_r [Nm]. Operators later provide suitable input by providing relevant torque to the joystick, t_m [Nm], in order to obtain sustainable grip for suitable driving force, f_s [N]. In the velocity control method, the difference of non-dimensional piston velocity, V_s [-] and the non-dimensional joystick displacement, Y_m [-] are used as the control error. This error, (Y_m-V_s) is used to provide crucial information on the joystick feedback's in order to produce velocity control FFS. The larger the joystick displacement the faster the piston velocity is. The proportional and torque gain of the master are represented by k_{pm} [Nm] and k_{tm} [m]. In order to assist soft objects manipulation, a velocity-dependent motion is created by plotting a relationship between variable threshold force, f_{pre}[N] and cylinders velocity, V_s [-], as shown in Figure 4. By using the least square methods, the plotted relationship can be represented by equation (2).

$$f_{pre} = \begin{cases} 35.7V_s^2 + 25.5V_s + 0.4 & (Vs \geq 0) \\ -19.8V_s^2 + 56.0V_s - 0.4 & (Vs \leq 0) \end{cases} \tag{2}$$

The threshold force f_{pre} [N], is used in gain parameter, T, in order to create gripping condition that is sensitive to soft objects. The gain is expressed in equation (3), where the maximum extension force is f_{e_max} [N] while the maximum compression force is f_{c_max} [N]

$$T = \begin{cases} 0 & (|f_s| \leq |f_{pre}|) \\ 0 < \dfrac{f_s - f_{pre}}{f_{e\_\max} - f_{pre}} < 1 & (f_s > 0 \cap f_s > f_{pre}) \\ 0 < \dfrac{f_s - f_{pre}}{f_{c\_\max} - f_{pre}} < 1 & (f_s < 0 \cap f_s < f_{pre}) \end{cases} \tag{3}$$

3.4 Auditory feedback system

Auditory feedback system or AFS can be represented by three simple parameters, which are pitch (frequency), amplitude (volume) and tempo (tone repeat frequency). These parameters are represented by sound parameter S. In the experiment, the tempo is used as the main auditory feedback parameters to the operators, since repeating sound tone provide good information to the operators. The pitch of the feedback is set at constant frequency of 445 Hz. The volume of the feedback is kept free, so the operators could adjust the sound volume according to his comfort. In single tempo AFS, the corresponding audio signal, a_f, is realized by a single tempo of 40 BPM of sound. From the gain T, we can calculate the reaction torque, t_r, and at the same time create a relationship between the sound and the force feedback. The operators will hear the audio signals when gain T is bigger than 0.02. Equation 4 shows the relationship of the auditory feedback used in the test.

$$S = \begin{cases} 0 & (T = 0) \\ 40 \ BPM & (0 < T < 1) \end{cases} \tag{4}$$

4. METHODOLOGY

Six students, ages between 24 and 33 participate in the experiments. Experiments are conducted in an isolated room, and each participant is comfortably seated to remotely control the construction robot in another room. The participants remotely operate the robot by viewing visual feedback from a large screen in front of them. There are two visual feedbacks available, the real images from a webcam, and virtual images, which is provided by the *Digiclops* camera and graphic PC. The visual display set-up is shown in the previous section, in section 3.2. The force feedback is available by using two *Microsoft Sidewinders Force Feedback II* joysticks and the auditory feedback is presented to the participants through a *Creative Inspire T6200* speakers. Participants are instructed to transfer two workpieces within a designated area, using three different feedbacks during the gripping process. These feedbacks include the force feedback, auditory feedback and combined feedback (simultaneous force and auditory feedback). Prior to the test, a small training session is given to each participant to ensure that they are familiar with the system and experimental protocol. The tele-operation also involves the use of two types of workpieces, which are categorized as the soft and hard objects. The soft objects refer to the use of non-rigid aluminum cans, which will perish when subjected to high force. The hard objects in this case are the rigid construction bricks that can withstand the crushing force of the construction robot. The experiment validates the influence of all feedbacks on task completion time, gripping risk index and workload. Descriptive statistics are used to describe the mean and standard deviation of the data, while *Paired Samples t* test is used to compare cases by groups. Normal distribution is analyzed by using Normal *Q-Q* plot, with *Blom* and *Tukey* method.

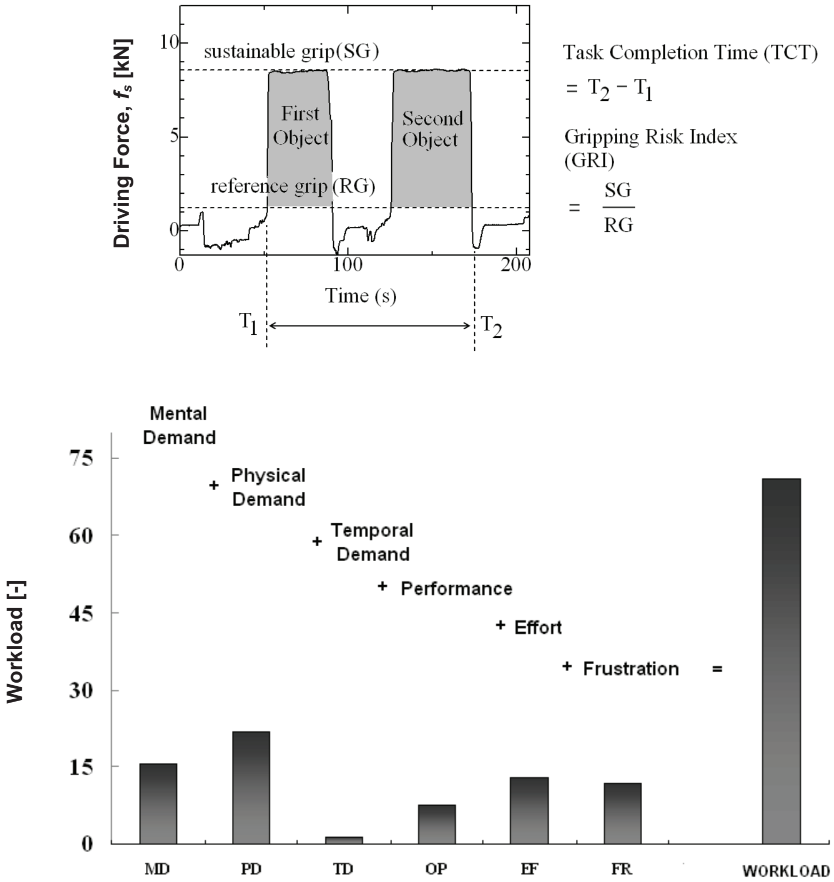


Fig. 5: Task completion time, Gripping risk index and NASA task load index evaluation

4.1 NASA task load index (Workload)

The workload is evaluated by using the *NASA Task Load Index (TLX)*, a subjective workload-rating technique. It is the most commonly used subjective evaluation technique, and has been applied in numerous settings including civil and military aviation, driving, nuclear power plant control room operations and air traffic control (Gawron, 2008). In *NASA-TLX*, the workload is defined as the "cost incurred by human operators to achieve a specific level of performance". The test concentrates on human perceptions of task demand, which influences the behaviors and subjective responses, and which include emotional, cognitive, and physical demands (Hart and Staveland, 1987). Task demands can be objectively quantified in terms of magnitude and importance. In the test, the subjective workload is defined as the combination of weighted evaluations of behavior and weighted subjective responses. There are six factors that contribute to the *NASA-TLX* subjective workload: Mental demand (MD), physical demand (PD), temporal demand (TD), own performance (OP), effort (EF), and frustration level (FR).

4.2 Gripping risk index (GRI)

Gripping risk index measures the different of average sustainable grip in which the operators are able to hold a secure grip of the workpieces, and without damaging them. As shown in figure 5, sustainable grip (SG) refers to the condition where the operators hold the objects without crushing or accidentally releasing them during the transfer. The reference grip (RG) refers to the position in which the operators hear the auditory feedback, at which the reaction force begins to rise due to the gripping process. Gripping risk index is calculated as SG/RG, which means that the higher the index the higher the risk of crushing and damaging the objects. Experiment data shows that for gain $T > 0$, for example at 0.02, the amount of driving force at the presence of auditory feedback is about 0.85 kN. Thus, the reference grip force is set at 0.85 kN, while the sustainable grip is calculated based on the average value of the driving force, during the manipulation of both objects. The averages of the GRI from 12 trials are used to measure the operators' performance based on the three feedbacks.

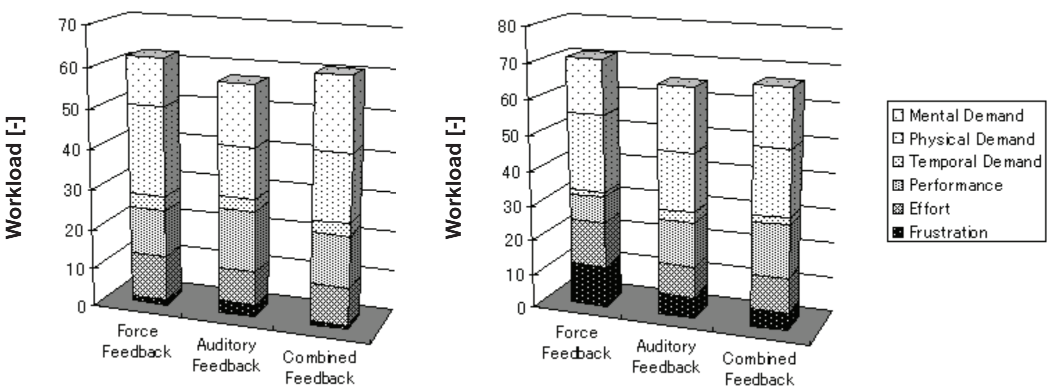
4.3 Task completion time (TCT)

In figure 5, task completion time refers to the different of T_1, where the first work piece is gripped and transferred, and T_2, where the second work piece is finally released and transferred. The averages of the TCT from 12 trials are used to measure the operators' performance based on the three feedbacks.

5. RESULTS AND DISCUSSION

5.1 NASA-TLX workload

Figure 6 shows the results for the subjective measures of workload during the manipulation of both types of objects. Figure 6(a) shows that for hard object manipulation using force, auditory and combined feedback, the mean and standard deviation are (62.0 ± 12.1), (57.1 ± 14.7) and (60.5 ± 12.1), respectively.



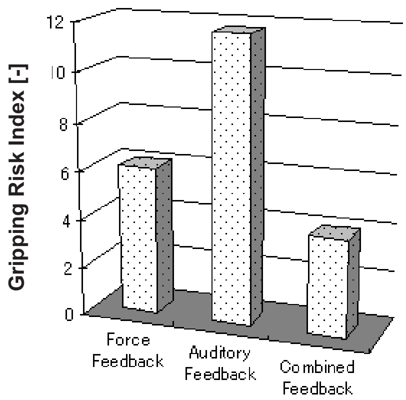
(a) Hard objects manipulation (b) Soft objects manipulation

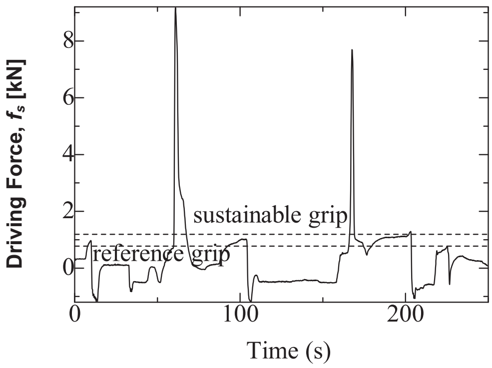
Fig. 6: Workload based on different manipulation feedbacks

Workload for soft objects manipulation are (70.7 ± 12.1), (65.0 ± 16.9) and (66.7 ± 13.7), respectively. The results show that for both types of objects, auditory feedback delivers minimum workload for the operators. The results of soft objects manipulation also suggest that frustration is at minimum when the operators use auditory or combined feedback, instead of using force feedback. The combined feedback even provides 16% decrease in frustration, as compared to the use of auditory feedback alone. Performance during soft object manipulation using combined feedback also increases to a maximum level, with a 50% increase compared to using force feedback alone. The use of force feedback alone increases frustration level to a maximum, due to the ineffective gripping perception that is caused by the delay in sensing the force through the use of joysticks. For hard objects manipulation, similar effect on frustration is noted when auditory feedback is used in gripping hard objects, instead of combined or single force feedback. It is noted that the use of single tempo auditory feedback fails to support manipulation of hard objects, since the operators do not have clear guidance on how to steadily control the grapple. Overall results also show that workload during the manipulation of soft objects is significantly higher than hard objects manipulation, in all type of feedbacks. (*(t (17) = 3.23, p <.05; Paired Samples t Test*).

5.2 Gripping risk index

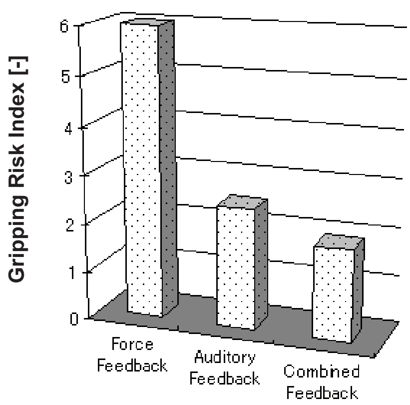
Figure 7 (a) shows the results of the gripping risk index (GRI) during the hard objects manipulation as described in 4.2. The vertical axis in the figure indicates the value of risk index; here a higher value indicates higher risk in crushing the objects.

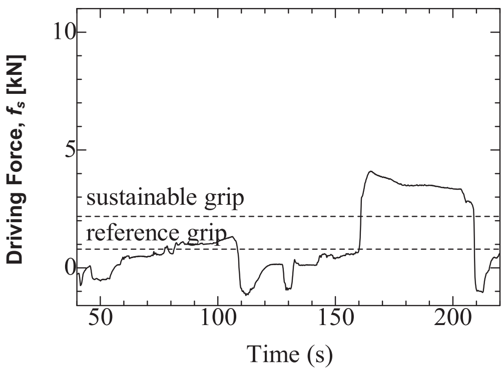




(a) Gripping risk index (b) Driving force during combined feedback manipulation

Fig. 7: Gripping during hard objects manipulation





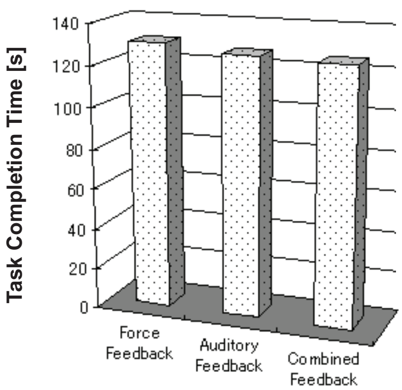
(a) Gripping risk index (b) Driving force during combined feedback manipulation

Fig. 8: Gripping during soft objects manipulation

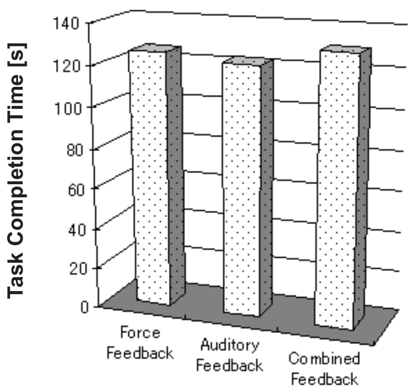
In hard object manipulation, combined feedback manipulation (4.0 ± 2.7; mean ± one standard deviation) shows a lower risk than force feedback manipulation (6.1 ± 3.7) and auditory feedback manipulation (11.7 ± 0.7). Here, combined feedback has a significant effect in reducing risk, than using only force feedback. ((t (11) = 3.8, p < .05; *Paired Samples t Test*). The results in figure 7 (a) also concludes that grasping hard objects by using only auditory feedback with single tempo parameter is dangerous because of the inability of the operators to effectively reduce their gripping force to a safe and sustainable rips. The operators know that they are overgripping, but fail to pinpoint the exact location of the reference grip, due to the lack of force feedback to guide them. In general, during the manipulation of hard objects, many operators push the joystick too fast, resulting in a faster gripping process, and thus a higher driving force. It is possible that in the operators' state of mind, the safety and concern over the work piece status is not important, since hard objects should be easy to be manipulated without extra cares. Based from figure 7(b), the operators' grip is clearly overshot, but all of them manage to reduce the driving force effectively later on, by the guidance of the force feedback. This is clearly shown by the reduction of risk in the combined feedback manipulation results. The combination of force and auditory feedback helps the operators to realize that they are beyond the limit of safe and sustainable grip. Figure 8(a) shows that combined feedback provides lower gripping risk (1.9 ± 0.7), as compared to auditory feedback manipulation (2.5 ± 0.8) and force feedback (6.0 ± 3.6), during the manipulation of soft objects. In soft objects manipulation, most operators handle the joystick slowly, which give them the ability to stop pushing the joystick on time, when they hear the beeping sound, as shown in figure 8(b). Gripping risk during the manipulation of soft objects is significantly lower than hard objects manipulation, in all type of feedbacks. (*(t (35) = 4.43, p <.05; Paired Samples t Test*).

5.3 Task completion time

Figure 9(a) shows the mean and standard deviation of task completion time during hard objects manipulation using force, auditory and combined feedback are (130s ± 50s), (127s ± 46s) and (125s ± 47s) respectively. The results suggest that the use of auditory feedback increases manipulation speed performance by 2% than the use of only force feedback, and increases by 4% when combined. The results however, are not significant, since the time differences between the feedbacks are small. (*(t (11) = 0.842, p = .418; Paired Samples t Test*). In the case of soft objects manipulation, figure 9(b) shows the mean and standard deviation for all feedbacks are (126s ± 38s), (122s ± 40s), and (131s ± 35s) respectively. The figure shows that combined feedback has the highest task completion time, followed by force feedback manipulation. Auditory feedback shows the lowest task completion time. However, the results are still statistically insignificant, due to small differences between the feedbacks. (*(t (11) = 1.175, p=.265; Paired Samples t Test*). The insignificant results for time completion time can be caused by several reasons. This might be due to the learning effect, where all the participants might have mastered the task during practice hour, which makes the task feedback effect redundant to the operators' sensory perception needs. Other reason is that each participant reacts in different way during the manipulation of both objects during the experiment. This resulted in unique holdup during the movement of construction robot's boom, arm and grapple.



(a) Hard objects manipulation



(b) Soft objects manipulation

Fig. 9: Task completion time based on different manipulation feedbacks

6. CONCLUSION

We have evaluated the use of auditory feedback for construction robot tele-operation. Initial experiment by using single sound tempo has been studied. The use of auditory feedback verifies the most reduction in workload, in both soft and hard objects manipulation. It is also noted that manipulation with force feedback alone increases overall workload. The workload is reduced when auditory feedback is integrated during the manipulation process. Results also show that the use of auditory and combined feedback improves the performance by introducing safe and sustainable grip during the experiments. This is based on the low gripping risk index during the manipulation. However, it is noted that single tempo sound parameter is only suitable for early detection of contact, and not suitable for a sustained grip, without additional support of force feedback. In the future, a variable tempo parameter will be used, instead of a single tempo sound parameter, in order to see the effect of auditory feedback on construction robot tele-operation. The results of task completion time are insignificant for all the feedbacks used in the manipulation. Further test will also be conducted for task completion time, by changing the manipulation procedure of the experiments.

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EFFECT OF SIMULATION TRAINING METHODS ON OPERATOR ANXIETY AND SKILL DEVELOPMENT

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ABSTRACT: *Construction equipment is becoming increasingly technologically advanced with operators using computerized controls requiring more skill to manipulate materials at construction sites. Operator training typically consists of using the physical equipment in a training environment while receiving instruction about performance and machine controls. The industry has begun using simulators for training operators in order to save fuel, equipment wear, and the inherent risks of damage and injury, while providing repetitive training in a safe and controlled environment. Operating equipment for the first time can be intimidating and the large magnitude and range of motions can produce operator anxiety.*

A study was performed to examine the rate at which skills are developed, the degree to which simulator skills transfer to actual equipment, and the degree to which operator anxiety levels when operating the physical equipment are decreased. Simulation based training was provided with the Volvo Advanced Training Simulator (ATS), which simulates a Volvo L120F wheel loader and provides multiple operating scenarios. Simulation training was provided in varying types and durations. Operating skills were measured during training and afterwards though a field performance evaluation. The level of anxiety experienced was quantified by measuring heart rate and self-reporting using the STAI.

Based on the results obtained during the study, no statistically significant difference in operator performance was found between those trained using full motion simulation and those trained using static simulation. While the levels of anxiety experienced by participants receiving static simulation training were consistently greater than those receiving full motion simulation training, the differences were not found to be statistically significant.

KEYWORDS*: Construction Equipment, Simulation, Training, Operator Training.*

1. INTRODUCTION

Construction equipment is becoming increasingly technologically advanced with operators using computerized controls requiring more skill to manipulate materials at construction sites. Operator training typically consists of using the physical equipment in a training environment while receiving instruction about performance and machine controls. Training provides some basic operating experience and allows for familiarization with equipment controls, maneuvering, efficiency, and safety. Training is often inconsistent and expensive due to operating costs and lost productive time of the machine. There is also an increased risk of injury to other workers and damage to surrounding property.

The industry has developed an interest in equipment simulators for training operators. Simulators save fuel, equipment wear, and the inherent risks of damage and injury, while providing repetitive training in a safe and controlled environment. Operators are introduced to equipment, operation, and machine controls within a virtual environment. Familiarization with the machine and its operation reduces the anxiety of operating large equipment. However, there is some question as to the extent the skills developed from simulation transfer to operating the actual machine. Many question whether trainees learn to operate the simulator, but not the machine.

A study was performed to examine the rate at which skills are developed, the degree to which simulator skills transfer to actual equipment, and the degree to which operator anxiety levels when operating the physical equipment are decreased. The data collected was used to answer the following research questions:

1. Is there a difference in the rate at which skills are developed through full-motion simulation training and static simulation training?

2. Do operators receiving full-motion simulation-based training perform field tasks better than those receiving static simulation-based training?

3. Is there a difference in the level of anxiety experienced when operating the physical equipment by operators that have received full-motion simulation training and those that have received static simulation training?

2. BACKGROUND

Simulators are used to provide a safe and inexpensive practice environment for persons who operate complex machines such as airplanes, trucks, cars, and construction equipment. They are particularly useful for researching problems in which the real environment is too hazardous, costly, or difficult to control. Simulation has been widely applied to the vehicle driving environment to explore the effects of cell phones on driving performance (Schneider and Kiesler 2005), conditions that lead to better in-vehicle performance (Bullough and Rea 2001), and devices to help mitigate accidents (Enriquez et al. 2001). Studies have established correlations between participant behavior in driving simulators and behavior in real vehicles (Godley et al. 2002, Panerai et al. 2001, Tornros 1998).

Simulators are effective training tools that replicate a real environment and the realistic behavior of simulation participants. Two recent studies regarding the use of simulators in training snowplow operators have been sponsored by state departments of transportation (Strayer et al. 2004, Mashiocchi et al. 2006). In both reports, simulation-based training was well received by participants and found applicable to operators at all levels of experience.

Simulation-based training has also been used to train operators of construction and other similar equipment. Wang and Dunston (2005) surveyed virtual training technologies for equipment operators and Gokhale (1995) describes the development of a directional drilling machine simulator for training. Typically the training objectives are to familiarize operators with the controls, train the operators to steer the machine, and enable evaluation of operator performance. The US Army has begun to use simulators in the preparation of military construction equipment operators (Fisher et al. 2009).

The effectiveness of simulation in training equipment operators is not well documented in the literature. Training operators of haul trucks, excavators, and surface drill rigs in a mining application has resulted in improved operator performance and reduced equipment damage (Anon. 2005). Kamezaki et al. (2008) quantified the effect of simulation training for operators of double front work machines and found substantial improvements in task completion time and positional accuracy. Hildreth and Stec (2009) evaluated the effectiveness of simulation training for wheel loader operators and reported statistically significant improvements in loading time and production rate.

Hildreth and Stec (2009) address the question of whether full motion simulation is better for training than static simulation, but conclude only that both are viable options to on-machine training. Fisher et al. (2009) note that the integration of motion platforms results in higher fidelity simulation, which will reduce the need to augment simulation with hands-on training. They also note that operating equipment for the first time can be intimidating.

In addition to this intimidation, the large magnitude and range of motions experienced while operating heavy equipment can produce operator anxiety. The level of anxiety experienced by an individual can be measured using the State-Trait Anxiety Inventory (STAI). Cattell (1966; Cattell & Scheier, 1961, 1963) first introduced the concepts of state and trait anxiety and Spielberger (1966, 1972, 1976, 1979) elaborated on them. Trait anxiety refers to the proneness of an individual to experience anxiety, while state anxiety refers to the level of anxiety experienced at a given point in time (Spielberger et al. 1983). The STAI consists of questionnaires that allow an individual to self-report both state and trait anxiety, which can be used to calculate an anxiety score that can be compared against published norms for various populations.

3. METHODOLOGY

Simulation based training in the operation of a wheel loader to load articulated haulers was provided with the Volvo Advanced Training Simulator (ATS). The ATS simulates a Volvo L120F wheel loader and provides multiple operating scenarios, including a training scenario and performance evaluation scenario in which stockpile material is loaded into an articulated hauler. The ATS includes an operator station containing OEM controls and is mounted on an electrically activated motion platform to provide pitch and roll motions during operation. The motion platform can be engaged to provide full motion simulation or disengaged to provide static simulation.

Figure 1: Volvo Advanced Training Simulator

The ATS is controlled by a standard personal computer operating in a Linux environment. The ATS software application developed by Oryx Simulations AB is used to select from a large number of simulation scenarios. The application interfaces with motor controllers used to drive the motion platform. Visual and audio feedback is provided to the operator through a large-format monitor (LCD television) mounted directly in front of the operator and on the platform. The motion platform and display system is shown in Figure 1

In the training scenario, the hauler is positioned opposite the stockpile and loader movement is constrained by concrete barriers on the left and right. This scenario requires trainees to load the bucket, carefully execute a tight three point turn, and place the load into the hauler. Real-time feedback is provided during the training simulation in terms of amount of material loaded into the hauler (as percentage full), time of operation, number of collisions with fixed objects, and damage resulting from collisions. Training continues until the hauler is 100 percent full.

In the performance evaluation scenario shown in Figure 2, the hauler is positioned to the right of the stockpile and loader movement is not restricted. No real-time feedback is provided to the trainee and the scenario continues until either the hauler is completely full or 3.5 minutes has elapsed. Operational performance is measured by the amount of material loaded, number and severity of collisions with fixed objects, performance time, and amount of fuel consumed. At the conclusion of the scenario (hauler full or 3.5 minutes elapsed), these metrics are reported to the trainee and used to calculate an overall performance score.

Figure 2: Volvo ATS Hauler Loading Performance Evaluation Scenario

3.1 Operational Training

University students enrolled in the Department of Engineering Technology and Construction Management were solicited and volunteered to participate in the study. Participants were required to have no previous wheel loader operating experience. A total of 21 participants were randomly assigned to training groups as shown in Table 1.

Table 1: Research Study Groups

Group	Simulation Type	Training Duration	Number of Participants
A	Static	20 mins	8
B	Motion	20 mins	7
C	Motion	60 mins	6

Groups A and B trained for 16.5 minutes in the training scenario and then performed the 3.5 minute performance evaluation scenario, for a total of 20 minutes of training. Group C completed the same 20 minutes of training three separate times, for a total of 60 minutes of training.

Each participant was briefed on the operation to be performed and the controls for operating the wheel loader prior to training. During the training scenarios, the researcher observed and provided verbal feedback and instruction. In the first training session, instruction was focused on loader controls, maneuvering (three point turns) and approaching the stockpile and hauler. Group C also completed second and third training sessions in which instruction was provided on bucket loading technique, load placement, and simultaneous motions (e.g. leveling the bucket and lowering the boom simultaneously).

The overall performance score from the performance evaluation scenario was recorded for each training session as a measure of skills development and to document improvements resulting from additional training sessions for participants in Group C.

3.2 Field Performance Evaluation

A field performance evaluation was used to measure participants' ability to operate the physical loader following simulation based training. A Volvo L150F wheel loader was used to load stockpiled material into Volvo A25 and A30 articulated haulers. To emulate the performance evaluation scenario, 3.5 minutes was given to three pass load a hauler and each participant loaded three haulers. The field performance evaluation is shown in Figure 3. Payload was determined by weighing and recorded along with load time and number of collisions. The rate of fuel consumption during the three loads was measured by the instrumentation on-board the loader and was also recorded.

The rate of fuel consumption was roughly equivalent to the amount of fuel consumed reported by the ATS during the performance evaluation scenario. Thus, an overall field performance score was calculated, but could not be directly compared to scores from simulation based training.

Figure 3: Field Performance Evaluation

3.3 Operator Anxiety Measurement

The level of anxiety experienced by operators was measured during simulation based training and operation of the physical equipment. Heart rate provided a physical measure of anxiety and participants self-reported anxiety level by completing the State-Trait Anxiety Inventory for Adults (STAI). Heart rate was measured using a wrist watch with a heart rate indicator. Participants self-reported trait anxiety prior to simulation training and self-reported state anxiety during both training and operation.

Heart rate was recorded and state anxiety reported:

- immediately before each simulation training session;
- immediately after each simulation training session;
- immediately before loading the first hauler in the field performance evaluation;
- immediately after loading the first hauler; and
- immediately after loading the third hauler.

A state anxiety score was calculated in accordance with the methods recommended by Spielberger et al. (1983).

4. RESULTS AND DISCUSSION

4.1 Rate of Simulator Skills Development

The difference in rate at which operator skills are developed was investigated by comparing the simulator scores achieved in the first training session for participants receiving full motion simulation training with those receiving static simulation training. Differences in scores correspond to differences in skill development rate since training time was equal. Simulation score results from the first training sessions for Groups B and C were combined and compared to those from Group A. A box plot of simulation performance scores is provided as Figure 4 and shows that the average score from full motion simulation was slightly less than that from static simulation.

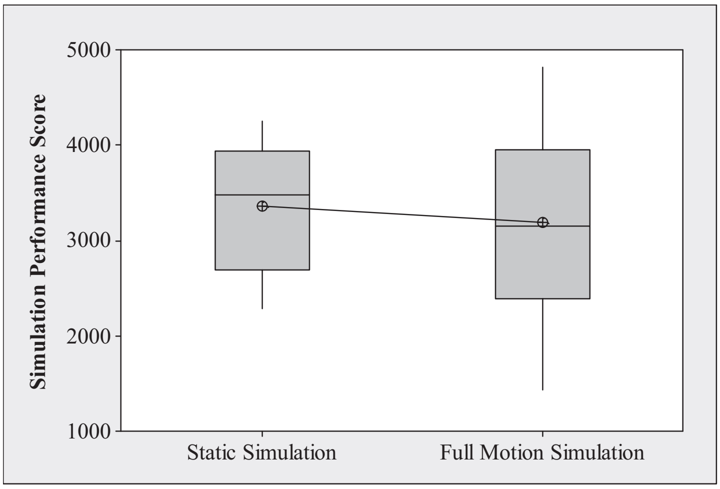

Figure 4: Simulation Performance Score Box Plot

The simulation scores were analyzed for differences in skill development rate. Data was tested for and found to be normally distributed and there was no basis for assuming equal variances between the two datasets, so a t-test assuming non-equal variances was used to test for differences at the 0.05 confidence level. Table 2 provides a summary of the simulation score data.

Table 2: Simulation Performance Score Data Summary

Simulation Method	Count	AD Normality Statistic	p-Value	Mean	Variance
Static	8	0.233	0.701	3,357	490,636
Motion	13	0.104	0.993	3,195	947,272

The observed p-value was 0.633, which is substantially greater than the 0.05 confidence level. Thus, it was concluded that simulation type has no effect on skills developed in 20 minutes of simulation training.

4.2 Field Performance

Field performance scores were used to investigate whether the type of simulation training influenced the development of skills in operating the physical equipment. The field performance scores for Group A were compared to those for Group B, since both groups completed 20 minutes of simulation based training. Scores were calculated for each of the three loads performed by participants. It was necessary to determine whether the scores could be combined for each group or whether differences existed as a result of learning during the performance of the field evaluation.

Each of the six datasets (static and full motion for loads 1, 2 and 3) were found to be normally distributed. Paired t-tests were used to test for differences between the datasets. Table 3 summarizes of the paired t-test results. It was found that for Group B, scores from the load 1 differed from load 3. Thus, scores from loads 1 and 2 were combined for each group and compared. Box plots of the field performance scores are provided as Figure 5.

Table 3: Summary of Paired t-Tests for Differences in Field Scores

Study Group	Data Comparison	t Observed	p-Value
A – 20 min Static	Load 1 v. Load 2	-1.40	0.205
	Load 1 v. Load 3	-0.83	0.436
	Load 2 v. Load 3	0.06	0.957
B – 20 min Full Motion	Load 1 v. Load 2	-1.36	0.223
	Load 1 v. Load 3	-7.45	0.000
	Load 2 v. Load 3	-1.41	0.208

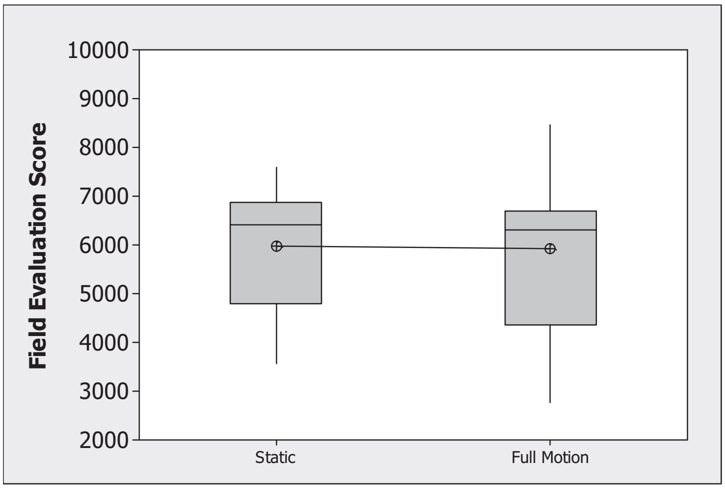

Figure 5: Box Plot of Field Performance Evaluation Scores

The combined datasets were tested for and found to be normally distributed. A summary of the datasets is provided as Table 4. A t-test assuming non-equal variances was used to test for differences at the 0.05 confidence level. The observed p-value was 0.927, which is substantially greater than 0.05. Thus, it was concluded that simulation type has no effect on field performance scores.

Table 4: Summary of Combined Field Performance Score Datasets

Study Group	Count	Mean	Variance	AD Normality Statistic	p-Value
A - 20 min Static	16	5,970	1,594,946	0.568	0.117
B - 20 min Full Motion	14	5,923	2,272,881	0.552	0.125

4.3 Operator Anxiety

Anxiety measurements were used to investigate the influences of the type and duration of simulation training on the level of anxiety experienced by the operator when operating the physical equipment. To determine whether the state (situational) anxiety scores of participants could be properly compared, differences in the trait (general) anxiety levels between the groups was investigated. The average trait anxiety scores for the groups were nearly identical, with Groups A and B having an average score of 33 and the average for Group C being 31. Further statistical analysis confirmed their similarity with t-test p-values ranging from 0.511 to 0.927. Thus, the groups did not differ in their general anxiety levels and state anxiety scores could be compared across groups.

State anxiety level was self-reported by participants at three points during the field performance evaluation: before the first load, after the first load, and after the third load. The box plots of reported scores are provided as Figure 6. It is apparent that the anxiety levels of Group A were consistently about 5 points greater than Groups B and C, and levels in Groups B and C were similar. Further analysis revealed that there were no statistically significant differences between the groups, which lead to the conclusion that simulation type and duration do not affect self-reported levels of state anxiety.

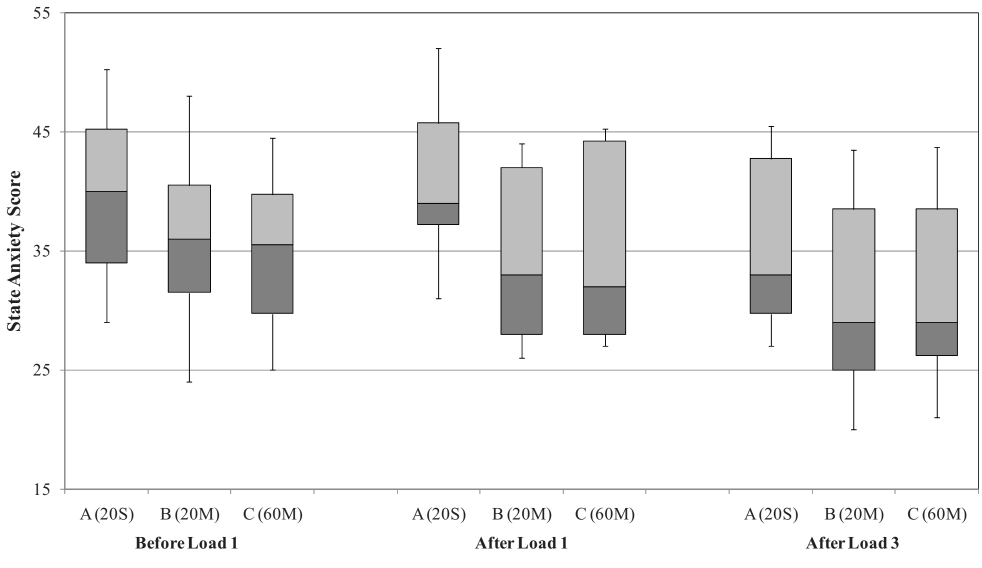

Figure 6: Box Plot of State Anxiety Scores during Field Performance Evaluation

Heart rate data was also recorded as a physical measure of anxiety at the same points in time as the state anxiety was reported. However, there is significant potential for the data to be influenced by factors that could not be controlled (physical fitness of participant, temperature, etc.). Therefore, in depth analysis of the data was not appropriate. The mean heart rate for each group was calculated and is presented in Figure 7. It can be seen that the mean heart rate of participants in Groups A and C increased substantially, as much as 15 to 20 percent, during the field performance evaluation. It appears that participants in Group B were "cool, calm, and collected" as heart rates did not appreciably change throughout the study. It is interesting to note that Group A, which received static simulation training, experienced the greatest heart rates immediately prior to operating the physical equipment. This would appear to support the hypothesis that static simulation, in which trainees do not experience the motions associated with equipment operation, provides trainees with little comfort with the equipment.

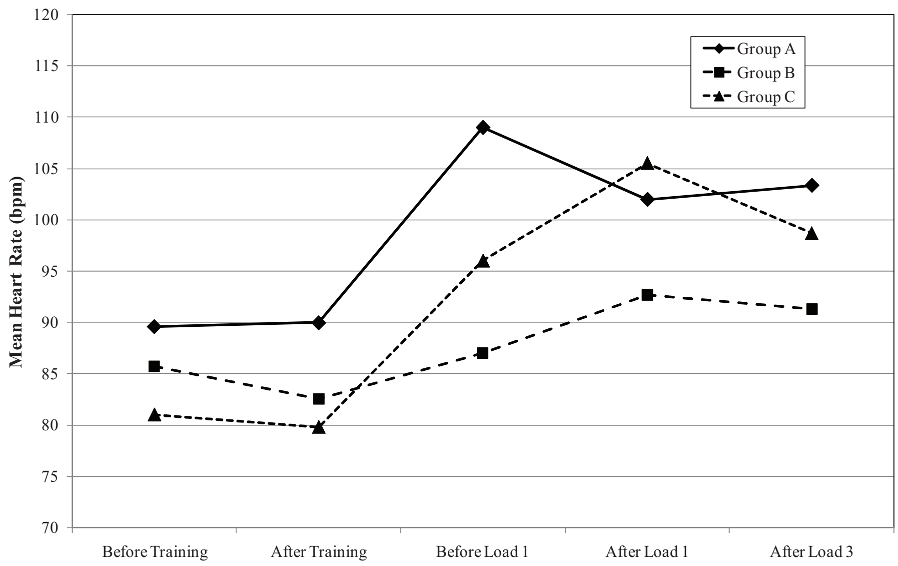

Figure 7: Mean Heart Rate of Trainees

5. CONCLUSIONS

The purpose of this study was to evaluate the effect of the type of simulation training on the rate operator skills are developed and the level of anxiety experienced when operating the physical equipment. Based on the results obtained during the study, no statistically significant difference in operator performance was found between those trained using full motion simulation and those receiving an equal duration of static simulation. Based on data obtained from participants receiving 60 minutes of full motion simulation training, the magnitude of additional skills that can be obtained from additional training appears to be substantial. While the levels of anxiety experienced by participants receiving static simulation training were consistently greater than those receiving full motion simulation training, the differences were not found to be statistically significant. However, the substantial increases in heart rate observed indicate that participants were stressed during operation of the equipment.

It was concluded that simulation type did not affect the participants' abilities to perform a simple field operation. While 20 minutes of simulation training was sufficient time to become familiar with the controls and operation, it is not a sufficient amount of training to produce a field ready operator. After 20 minutes of training, it was safe to allow participants to operate the equipment, but they were clearly not ready to perform in a production operation.

It is postulated that full motion simulation training is more effective than static simulation for refining fundamental skills and that this difference will be manifested in the field task performance metrics. In this study, the effect of simulation training type was investigated based on groups completing 20 minutes of training, and no difference was found. It is believed that this small amount of training only progressed trainees a short distance along the learning curve and that this training duration did not progress trainees beyond developing fundamental skills.

Additional studies are recommended in which participants receive several hours of training further evaluate the effects of simulation type on performance. It is also recommended that future studies specifically focus on operator confidence rather than anxiety. Operator anxiety is more appropriately associated with developing fundamental skills, while confidence is more appropriately associated with refining fundamental skills.

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DEVELOPMENT OF TELE-OPERATED ROBOTICS CRANE FOR IMPROVING ERECTION OPERATION IN CONSTRUCTION

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ABSTRACT: *The purpose of this research is to develop a tele-operated crane system which integrates augmented reality and motion planning technologies for improving crane operations at current construction sites. We build a prototype system called Zebra as the operation platform, which consists of a robot arm and environment cameras, and multi-screens and a controller as the remote control cabin. We also conduct a usability test to evaluate the efficiency and effectiveness of this developed system. The feedback from test participants shows that Zebra has great potential for ease of use and it can be used to assist crane operators efficiently during the erection task. The system can further integrates more guiding information to make more effective on real construction cases.*

KEYWORDS*: tele-operation, augmented reality, motion planning, crane operation*

1. INTRODUCTION

Safety and efficiency play key roles in construction projects. As time, budget, and technologies are limited, the success of modern construction projects usually depends on how well the resources are used during the life cycle of construction. Among these resources, many construction projects involve using cranes. In particular, cranes are essential for lifting and transporting materials and equipment. These machines are critical and one of the most commonly shared resources at the site. For example, the cost of erection-related activities represents an average of 27% of the total cost in steel structure construction (Carter, et. al., 2005). Therefore, efficient and safe operation of cranes is important in the safety, schedule and overall success of a project. Similarly, efforts for improving crane operation have become necessary.

Recently studies have aimed at improving crane operation performance in three aspects: (1) construction management, (2) hardware stabilization and (3) operation assistance. In terms of construction management, researchers have focused on how to solve the operation problems by improving erection plans in the planning stage of construction. For example, optimizing erection paths and crane selections help engineers to predict efficient operations and also prevent potential collisions during the actual erection (Kang, et. al, 2009; Al-Hussein, et. al, 2005). Physics-based simulations developed based upon kinematics and dynamics theories are also used to create a virtual environment in which crane operation can be simulated. (Hung and Kang, 2009; Kamat and Martinez, 2005) The operator of a real crane can get realistic feedback on the simulation results and follow instructions to complete tasks safely.

In the aspect of hardware stabilization, the findings of previous studies have targeted at stabilizing movements of crane machines including cable swings (Chen, et. al., 2007), hoisting vibrations (Masoud, 2009) and body motions . In an attempt to precisely control cranes' behaviors precisely and also increase the speed of operation, many control theorems like fuzzy control (Chang and Chiang, 2009) are used to reduce the nonlinear properties caused by the flexibility of crane cables and deformable crane components. Hardware improvement is another topic which many studies have focused on. With the assistance of sensors, a crane operator has more information to base on when manipulating the machine (Teizer, 2008). Tele-operation systems, which have been widely used in flight and train simulators, continue to hold a significant role as an appropriate platform for cranes (Kim, et. al, 2009). By combining with sensors mounted on real crane, tele-operated construction equipment (Shapira, et. al., 2008) can be a developing trend on improving crane operations.

Finally, about operation assistance, many researchers have focused on providing computer-planned guidance and visually assisted toolkits for crane operators as extra information during manipulation. Active visualization technologies help to extend humans' perception system (Klein and Murray, 2007) and these technologies can also benefit crane operations. For example, Augmented Reality (AR) has many applications in industrial (Fang, et. al, 2009) and educational (Wang, 2008) fields, especially in training environment (Wagner, et. al., 2010). This technology has also been proved efficient to guide operators of construction machines (Rezazadeh, et. al, 2009).

Although extensive research has been carried out on considering these three aspects, all developed based on traditional or nearly traditional form of crane machines. It would seem that further studies are needed in order to introduce new crane mechanisms for the efficiency purpose and to integrate previous improvements from the three aspects.

The purpose of this research was to develop a tele-operated system based on a robotic arm-liked machine, a new type of crane, and to use augmented reality as remote guiding interface for improving operation performance. By providing remote images and taking advantage of augmented reality technology, operator can operate the crane machine in a safe environment and make efficient decisions during operation. It is hoped that information provided by this research would be useful in identifying better operation experiences of crane activities.

2. SYSTEM DESIGN

For considering the aspects mentioned in previous sections in order to improve crane operation, we developed a guiding system, which consists of three key elements: motion planning, augmented reality and tele-operation. The detailed architecture of the developed system can be seen in Figure 1. Unlike traditional crane equipment, this system contains two sets of components, one in the control field and the other in the operation field. The control field, which contains control and display devices, and the processing units of these devices, represents the manipulation place of crane operators. The operation field, also called construction sites or fields, represents the working place, where actual crane machines and mounted sensors function to perform construction activities.

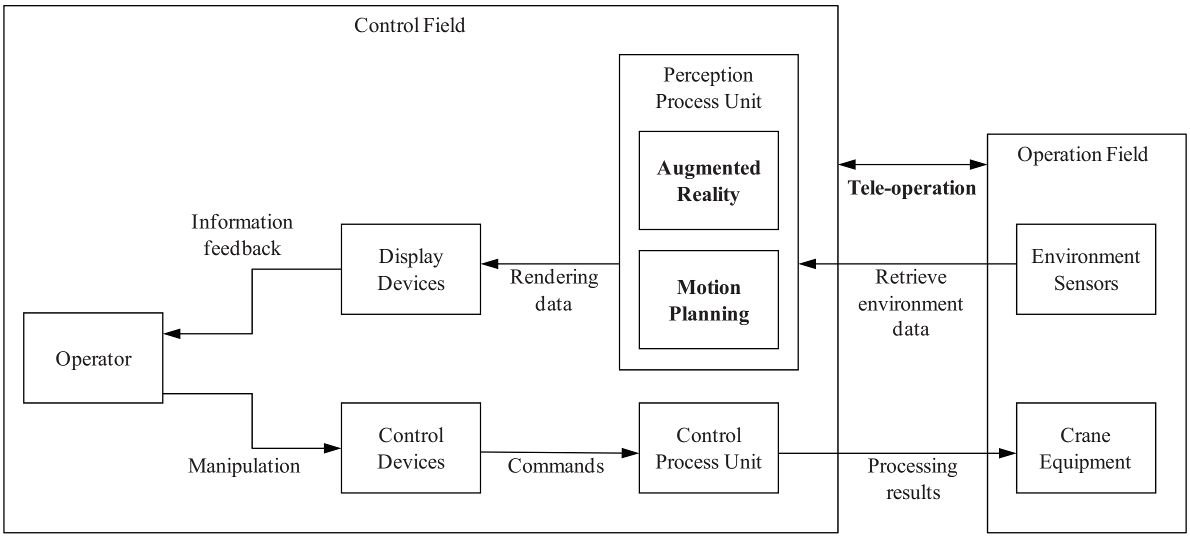
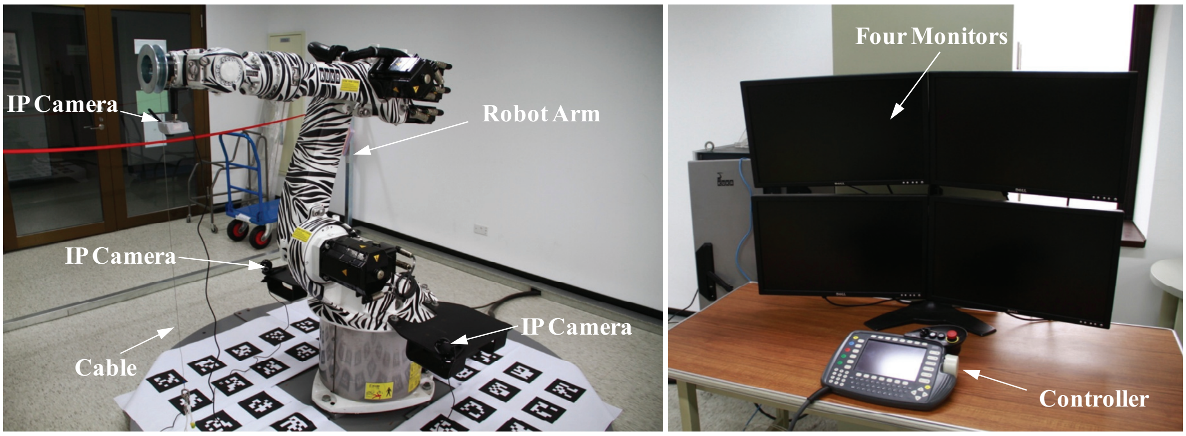


Fig. 1: The architecture of the operator guiding system.

In both fields, the first key element, tele-operation, is used as a communication technology to pass processed control messages and at the same time retrieve environment data for perception uses. Once the operator uses control devices to manipulate the motion of a remote crane, the control commands will first be sent to the control processing units to check if the motors are able to handle this movement. Then the processing results are sent to activate the motion of the crane in the operation field if the results are feasible. In parallel, the sensors mounted on the crane keep retrieving environment data and sending the information back to the perception processing units. In these units, the environment data can be used directly to show on-display devices or to reconstruct the geometry properties of the operation field for registering virtual object on it. The second key element, augmented reality, allows us to put ongoing construction plans as virtual information onto display devices. By knowing the geometry properties through the augmented reality technology, the third key element, motion planning, can also be used to calculate auto-generated rigging paths and provide it with on-display devices. The operator can thus adjust their manipulation or make a judgment according to this information.

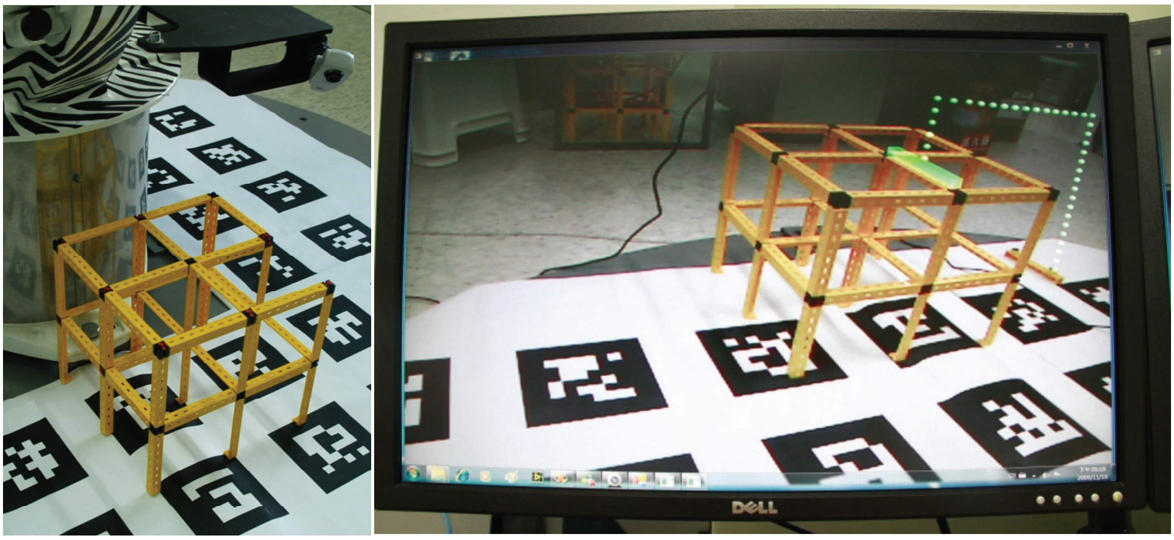
3. IMPLETEMENTATION

By following the architecture of the guiding system, we built an experimental platform called Zebra, which uses an industrial robot arm as crane prototype, IP cameras as environment sensors, and multiple monitors as tele-operation interface. The system is divided into control and operation field. As can be seen in Figure 2(a), we integrated an industrial robot arm, KUKA KR 16 CR, in the operation field, which has rigid body components and six degree-of-freedoms (DOFs) to simulate current structures and movements of cranes. By mounting a pulley on the end-effector and three AXIS 207MW IP cameras on the left, right and top of the robot arm, this equipment is able to collect environment data and be operated by tele-operated control commands at the same time. Besides the three mounted IP cameras, we also placed another one camera as a global side to capture everything in the operation field. The captured environment data can be also sent back for increasing global geometric concept to the system users.



(a) Operation Field (b) Control Field

Fig. 2: The environment settings of the (a) Operation Field and (b) Control Field.



(a) (b)

Fig. 3: The virtual erection path is: (a) registered on real scenario and (b) shown on the monitor.

As shown in Figure 2(b), the environment setting of control field contains four 24" LCD monitors at 1900×1200 resolution which are arranged in a matrix style for displaying the operation status retrieved from operation field.

The controller is provided to user for operating rigging activities remotely. In the control field, there are also processing units including a PC running Windows 7 (3.2 GHz 8-Core Intel Xeon with two nVIDIA Geforce 8800GT graphics cards and 2GB RAM) for providing perception information, and an embedded system for dealing with the controller signals. These components are combined as a remote cabin of crane so that the users of this system can monitor the feedbacks from the four LCD and at the same time use controller to make adjustments during simulated erection tasks.

About the content of the interface, the four LCD are used to display images captured from four IP cameras individually. Besides providing the real scenario images to users, we also developed a program to register the virtual information onto the real scenario images. As shown in Figure 3(a) and Figure 3(b), the motion planned erection path is put onto the monitor for further guiding the users in identifying the securing/releasing positions and possible erection solutions. We developed a positioning program which integrated an augmented reality library, AR Tag (Cawood and Fiala, 2007), to register the virtual erection path according to the markers around the real scenario, and show the paths on the monitor. Other than obtaining virtual paths visually, we also provide elevation information for users to overcome the visualization problems due to limit of view angles. Like the view captured from the top of camera, the elevation information of rigging object and destination are needed because user cannot get them from the geometric properties. The elevation information is displayed in digit form for accuracy and collisions avoidance purposes.

4. USABILITY TEST

For evaluating the efficiency and effectiveness of Zebra system, a usability test is conducted. In this test, we focus on identifying how the three technologies, tele-operation, motion planning and augmented reality, integrated in the developed system influence the performance of erection tasks. The interface of the system is the main evaluation topic we concerned. Similarly, the interface of this system is developed base on multiple computer technologies different form the design concepts of traditional control dashboard. Therefore, the participants of this test require basic knowledge on making use of computer programs. Considering the understanding of visualization technologies and easy of familiarity with the developed system, we collected the undergraduate and graduate students who took relating visualization courses to be our participants. We have collected users' evaluations and opinions from 30 participants.

(a) (b)

Fig. 4: The usability test: (a) the scenario of a steel frame building and (b) the overview of simulated rigging task in the usability test.

In this test, the participants are asked to complete simulated erection tasks in order to observe the performance of using Zebra system. As shown in Figure 4(a), a simulated steel frame building made by plastic blocks is used in the test. By assigning securing and releasing position on the building, participants need to manipulate the controller and finish the erection activities remotely (Figure 4(b)). The participants have to finish the tasks three times with three different type of operation interfaces: (1) traditional top view plus oral guidance, (2) multiple views (including top, right, left and global view), and (3) multiple views plus virtual information guidance.

Traditional top view plus oral guidance: In the first operation interface, participants are asked to monitor only the top view of the crane. The top views' images are captured by an IP camera which is mounted on the end of robot arm and directed downward to the top of the building. This operation interface is used to simulate the traditional view of tower crane operators whose view angles are limited and far from the erection objects. In addition to visualization information, the traditional operation method includes the oral guidance of the workers through radio at construction site. We also provide such assistances in the test. The test host gives directions to the participants when they operate the hook approaching the erection object or the object is being released during the tasks.

Multiple views: About the second type of operation interface, four monitors are used to provide top, right, left and global view of the crane. These views are all captured by the IP cameras mounted on the robot arm in the operation field. The participants can monitor these views which have covered every view angles of rigging objects, and then finish the assigned tasks. In this operation interface, no more oral guidance be provided, and participant need to use other visualization information, such as views from left, right and global side to understand the elevation between rigging objects and the building in order to avoid collisions.

Multiple views plus virtual information guidance: In the third operation interface, we provide not only multiple views but also the virtual information for participants during erection tasks. The virtual information includes augmented rigging paths (like Figure 3(b)) and digit formed elevation status on the top view. Both are refreshed in real time by following the changes of the view angles and rigging objects. This type of interface is the developed solution we try to propose in this study. The main purpose of this usability test is try to compare this operation interface with the other two types and to evaluate how efficient and effective if this kind of operation being used during erection activities.

After accomplishing the tasks by three operation interfaces, the performances of the participants are recorded by following three test items: (1) time spent on finishing tasks, (2) task loading score for participants, and (3) utility rate of views.

Time spent on finishing tasks: We recorded the time spent on finishing three erection tasks (by using three different operation interfaces) in order to compare the efficiency among them. The time duration includes how long the participants secure the rigging objects, move the objects to the destination, release the objects and return to the original position. It is a complete cycle for erection activities.

Task loading score for participants: For evaluating the loading of the participants when they are operating Zebra system, we utilized NASA Task Load indeX (NASA-TLX) questionnaires to collect the self-evaluation results from participants. NASA-TLX is a standard questionnaire developed by NASA Ames Research (Biferno, 1985). It is a self-rating procedure for participants, which provides an overall workload score based on six weighted factors: Mental Demands, Physical Demands, Temporal Demands, Effort, Performance, and Frustration. In the beginning of the test, the participants are asked to decide the weight of these six factors according to their own opinions. Then they proceed to finish the simulated erection tasks by three different operation interfaces. Each time the participants finish one task, they need to rating in term of six weighted factors to evaluate the operation interface they used. In the end of the test, there are totally three overall workload scores which represent the rating of three operation interfaces by participants themselves. It may help to understand the user experiences and quantify the effectiveness of the developed system.

Utility rate of views: In addition to loading evaluation, we try to verify the utility rate of different views used in the test. It is for identifying the users' perception patterns and further improving the multi-views interface of the system. When the participants doing erection tasks by using the second and the third type of operation interface, we tracked to the views where the participants' eye located at each second and formed the utility distribution of each views during the test.

5. RESULTS

In this test, we try to identify the efficiency and effectiveness of the developed system for improving crane operations. The results of the test are summarized in the following figures and tables. Figure 5 shows the time of 30 participants spent on completing the three simulated erection tasks. By eliminating the samples out of 95% confident interval, the time spent on using the second and the third operation interface (multiple views, and multiple views + virtual information guidance) to finish tasks are faster than that by using the first operation interface (top view + oral guidance). According to the average time for participants to finish erection tasks, using top view with oral guidance spend 376 second while using multiple views and multiple views with virtual information guidance spend 341 and 350 seconds respectively. Despite the average time spent on the second interface is slightly faster than that on the third interface. The time distribution of participants' performance shows that the results are more coverage in the case of being assisted with virtual information guidance.

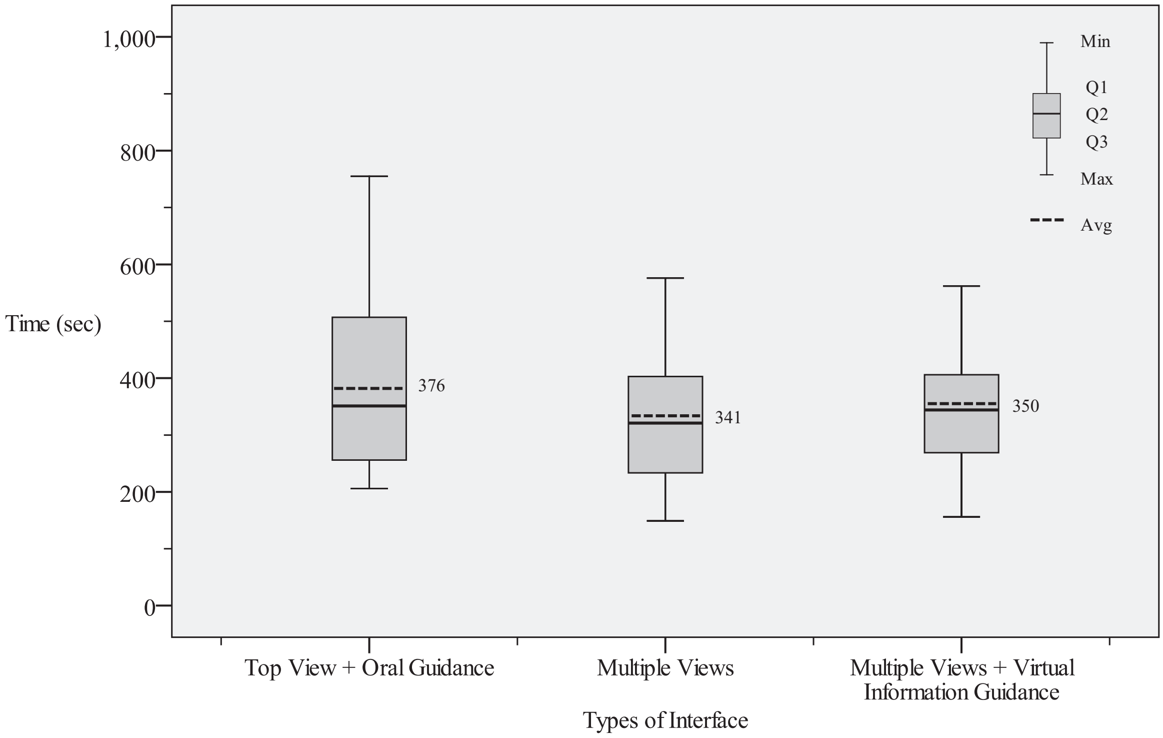
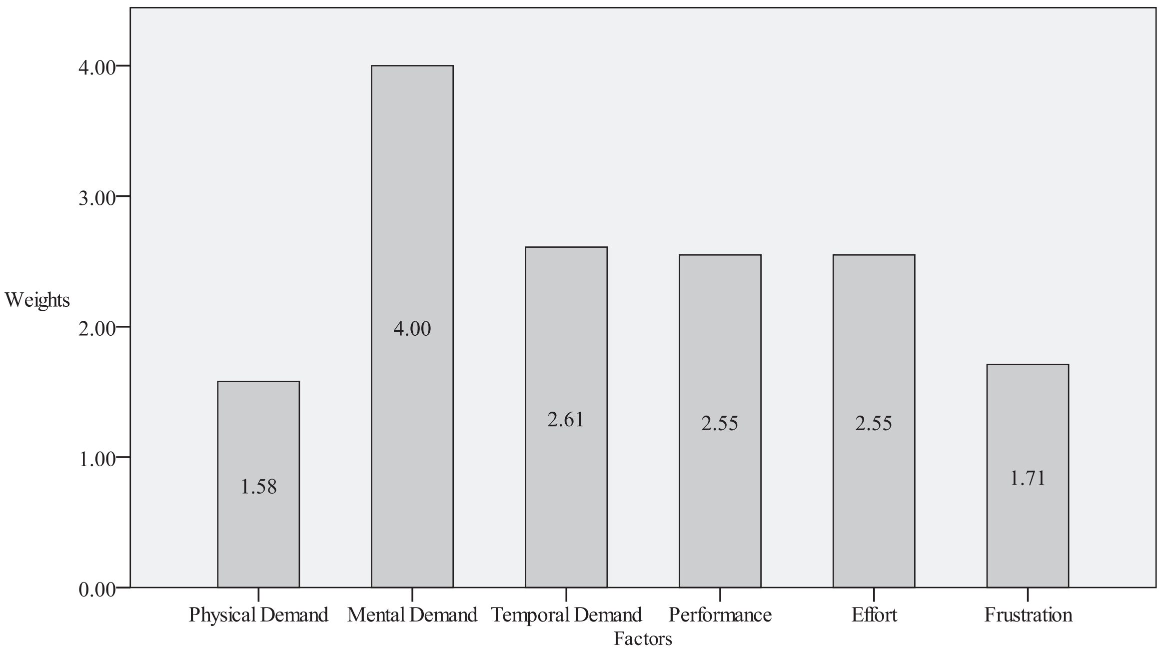


Fig. 5: The average time spent on finishing the three scenarios.

Figure 6 shows the average weights of the six factors evaluated by participants. In general, mental demand is the most important factor for participants to decide whether a task is easy or difficult to complete. The difficulty of the erection tasks in this test depends on how participants dealing with their perception system. The weight of this factor is 4.00. Other than mental demand, the three factors: temporal demand, performance, and effort which have similar weight according to participants' opinions. The values of them are 2.61, 2.55, and 2.55. Among all of the factors, frustration and physical demand are considered the last important factors comparing to the others. They are 1.71 and 1.58 respectively.



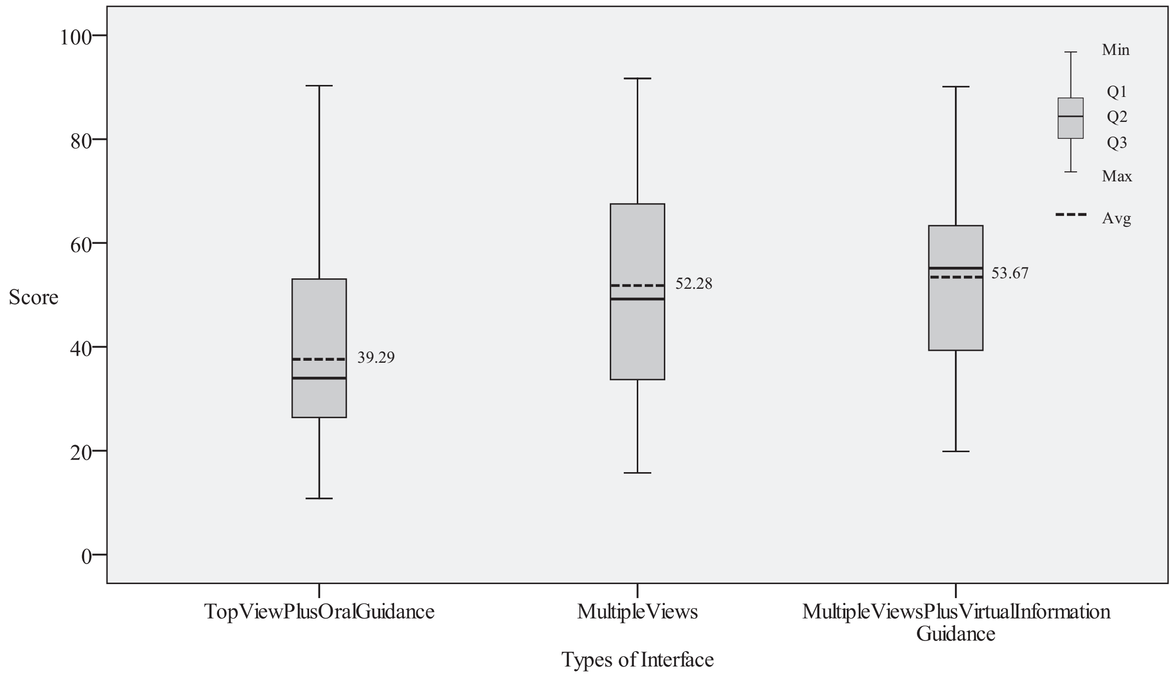


Fig. 6: The average weights of the six factors evaluated by participants.

Fig. 7: The average and distribution of the system scores for the three scenarios evaluated by participants.

Figure 7 provides the average and distribution of system scores given by participants according to operation interfaces of the three tasks. The scores made by each participant are graded within a range of 0 to 100 in term of the six factors and then averaged by multiplying the weight they decided. In general, these scores are based on different participants' opinions and different baselines so that the grades themselves are meaningless but show significant relationship by comparing with each other. As can be seen in this figure, the score of the second (using multiple views) and the third operation interface (using multiple views plus virtual rigging paths) are better than the score of the first operation interface (using a single view plus oral guidance).

Table 1: The utility rate of different views from three operation interfaces.

	Utility Rate of Views			
Scenarios	Left View	Right View	Top View	Global View
Top view + Oral Guidance	N/A	N/A	100%	N/A
Multiple Views	32.16%	8.63%	36.89%	22.31%
Multiple Views + Virtual Information Guidance	13.13%	24.45%	39.04%	23.38%

About the utility rate of views, Table 1 shows that top view frequently used for participants when they operate by using the second and the third operation interfaces. The utility rates of them are 36.89% and 39.04% individually. Global view is also utilized very often for participants to view by using these two interfaces (22.31% and 23.38%). Comparing the rate of top view global view, the results of right and left view are fluctuate depend on different assigned tasks (32.16% and 8.63% in multiple views cases, 13.13% and 24.45% in multiple views with virtual information guidance cases).

6. DISCUSSION

In evaluating the efficiency and effectiveness of the developed system, the result of the usability test shows that an erection task done by using multiple views and virtual information guidance is more efficient than traditional operations. It can thus be suggested that the developed system would be able to increase current erection speed at a construction site by providing more information to operators compared with the transitional method of offering traditional view from crane cabin and instructions by workers through the radios. We discuss the details of the findings in the following paragraphs separately:

Time spent on finishing tasks: According to the results of complete times, the participants spent less time on the second and the third operation interface than the first one. This may be because the participants are able to see the horizontal information from the left, right, and global of the camera, and monitor the remote environment completely. From the observation of the test and interviews, the participants can save time when they are operating in object securing and releasing stages. The detail visualizations including right, left, and global view can provide enough information to participants to slightly tune the hook and finish the movements efficiently. When they are operating by using the first interface, they become more cautiously and tentatively follow the oral guidance, and the operations they did tend to be conservative.

Besides, the assistance from virtual information may not significantly better than just using multiple views in this test. Based on the opinions of participants, it may be because the complexity of the simulated tasks is not high enough to show more benefit on virtual information guidance than without using them. However, the time distribution of the third interface is more centralized than the second interface; it demonstrated that the results of completing time on the third interface are more reliable than that on the second interface.

Task loading score for participants: About the grading of the three operation interfaces, the benefit on using the second and third operation interface for simulated erection tasks is significantly superior to the first interface. As shown in Figure 6, the most important factor for participants to evaluate the load of the tasks is mental demand. This factor is directly influenced by the design of the operation interface which we try to evaluate in the usability test. Overall, the system scores show that the loading of the tasks are influenced a lot by mental demand factor, and the second and the third interface do reduce the loading (Figure 7). In fact, most of participants mentioned that it is more comfortable to operate according to what they see rather than following oral instructions. Although few of the participants (about 10%) have opposite opinions, this may due to the lack of operating experiences and confidence for participants on the developed system.

Utility rate of views: According to the results of Table 1, top view is heavy-used view on which the participants depend during the tasks. Through this view, participants may be able to interpret the plane information of the construction site and at the same time identify the position of the hook or rigging objects. So this traditional view keeps playing a significant role on the developed system. Since it is difficult for the participants to understand the whole situation of the erection equipment, the global view also becomes relevant by providing extra opportunities to adjust the attitudes of the equipment and avoiding possible collisions between equipment and surrounding elements. This may make the operation more safely. About the left and right view, the fluctuated results can be thus explained by different assigning missions on different interfaces. For example, the participants are asked to secure the objects on the left side of the building on using multiple views interface so that the utility rate of left view is higher than that of right view. Overall, the left and right view also provide useful information depend on the geometric relationship between erection objects and construction environment.

Qualitative feedbacks: Overall, the participants in this test show great interests on developed system and provide positive feedbacks. Although the virtual information we implemented in this test may not significantly utilized by participants, they provide valuable improving suggestions. For example, the augmented reality and motion planning technologies should be used by showing critical erection instructions rather than global reference paths. From their opinions and the observations of this test, we can realize the information provided by multiple views is enough for participants' perception system. It is not necessary to increase these kinds of information by using augmented reality and motion planning technologies. When the participants operate the developed system, it is more important to info direct and critical information, such as where to move at next step, or the alignment of rigging object with destinations, for them to solve current problem instead of global information which they already can get by multiple views. So it turns out that the elevation information is more useful than virtual erection path. Besides this topic, the participants also suggest the system should provide critical information like collision warnings.

7. CONCLUSION

In this study, the aim is to develop tele-operated cranes based on a robotic arm-liked machine, and use multiple views and virtual information as a remote guiding interface for improving operation performance. The three aspects for improving crane operations - augmented reality, motion planning and tele-operation - have been covered in developing this system, and the architecture of the system has been presented.

An industrial robot arm has been integrated as a prototype crane. By mounting IP cameras on the left, right and the top of this robot arm, the environment information around the arm can be retrieved and multiple view angles of the rigging objects can be covered. Also, this work utilizes augmented reality and motion planning technologies to generate a virtual path, which is then registered on the images taken from the cameras. With the guidance information and multiple screen display, operators are expected to operate the prototype crane more effectively during erection task simulations.

The usability test conducted in this study shows that the developed system has potential benefits in improving efficiency and effectiveness of erection activities. The completion time and system scores of the simulated erection tasks using this system are better than that of traditional operations. Despite the test results of virtual information guidance on the operators is not significant. Participants in this test provide positive feedback and valuable suggestions on providing effective virtual information, such as active instructions, for improving this system. It is recommended that multi-disciplinary technology integration for construction cranes could be a worthy research direction to pursue in the future.

8. ACKNOWLEDGMENT

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BOUNDARY GENERATING METHOD FOR COLLISION DETECTION IN VIRTUAL CONSTRUCTION

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ABSTRACT: *The recently introduced 'Virtual Construction' allow engineers to envision the construction process, plan construction strategies, and identify potential problems. However, a construction site consists of thousands of objects, which can be very scattered and must be assembled in a complicated manner. This makes the process of generating collision boundary for virtual construction more difficult and tedious. This paper presents a method called the "Propagation Clustering Method" (PCM) to automatically generate collision detection boundaries by grouping the objects. It utilizes the k-mean clustering method to classify the objects in the virtual construction site according to their geometry and position. It can generate a hierarchical boundary tree, which allows for collision checks ranging from rough collisions to detailed collisions. The proposed method was tested in three scenarios: diverse, uniform, and composite (including both diverse and uniform objects). We found that the PCM can effectively group objects in all the three scenarios.*

KEYWORDS*: clustering, collision detection, grouping, virtual construction.*

1. INTRODUCTION

The recently introduced idea of virtual construction allows the simulation and visualization of construction progress, testing and verification of construction plans on computers, and is becoming a popular and important research topic in the field of construction (Waly and Thabet, 2003). Engineers are able to preview the detailed construction process in order to find potential problems, and provide plausible solutions using virtual construction simulations before the start of the actual project. Virtual construction can provide a low-cost and fast-prototype environment for development and testing. Many successful applications have shown the feasibility and advantages of utilizing virtual construction technologies (Wilkins and Barrett, 2000, Clayton et al., 2002, and Kamat and Martinez, 2003).

As modern construction projects become more complicated and difficult, the growing demand and quality of the virtual construction simulation rises. Detailed activities such as crane erections can be simulated so that unexpected accidents can be reduced (Chi, 2007). The recently introduced physics-based simulation for constructions can provide a more realistic and plausible construction simulation (Chi et al., 2007, Kang and Miranda, 2009). Researchers, such as Breland and Shiratuddin (2009), have integrated game engines into virtual construction. Game-based simulation emphasizes interaction and controllability in the virtual environment. This allows users to control and walkthrough a virtual environment to retrieve information or operate the construction machineries.

To develop both a physics-based and interactive virtual construction, Kang et al. (2009) and Hung and Kang (2009) integrated a physics engine to not only simulate the detailed physical behaviors of construction machineries, but also provide interactions. Physics engines involve a mathematical approach to reduce the computational cost, such that it can calculate the physical motions of machineries in real-time. It increases the possibility of simulating and testing entire cycles of the construction projects in a virtual world.

Other research related to virtual constructions such as collision detection (Lai and Kang, 2009), multiple coordination of cranes (Kang and Miranda, 2008), and path planning of cooperative cranes (Sivakumar, 2003, Ali et al., 2005) have raised the value of using virtual construction to improve the method in which construction is proceeded in the near future.

2. CHALLENGES OF INTERACTIVE VIRTUAL CONSTRUCTION

An interactive virtual construction consists of a virtual environment that can provide feedback and react immediately when users input data or information. The calculations of actions and animations in virtual construction must be finished in real-time. The challenges to fulfill this requirement are the simulations of the physical motion and reactions.

The simulation of physical motion in virtual construction can be downsized as the simulation of the rigid body, or multi-body, dynamics. The physical properties, such as position, velocity, or force, of an object during each time frame must be calculated. For a more complex mechanism in construction such as the rigging system, it becomes difficult to achieve a real-time computation and simulation. In the research carried out by Kang and Miranda (2009), a mathematical model was developed in order to simulate the dynamic motions of a crane. Although this method can generate the animations of crane activities efficiently, it is difficult to achieve the real-time interaction. To solve this problem, Hung and Kang (2009) and Kang et al. (2009) demonstrated the feasibility of using a physics engine to simulate in real-time the detailed crane motion.

Physical reaction is the behavior of two or more bodies colliding with each other. In a real construction site, collisions may happen between construction machineries and elements in the scene. Similarly, to simulate the behaviors of colliding in a virtual construction, the computer needs to perform the task of detecting the collision. It was pointed out that the computational cost of this can be a great drawback in the simulation process (Paulson et al., 1987, Halpin and Riggs, 1992, Martinez and Ioannou, 1999). Lai and Kang (2009) developed a real-time efficiency collision detection strategy for virtual construction simulations. However, as modern construction sites become larger and more complex, the number of the elements and components in a construction site increases enormously. This makes collision detection increasingly difficult because of the exponential growth in the computational costs when the number of objects increases. The irregular types of objects are also a critical problem that developers must cope with.

There is a trade-off between the efficiency and accuracy of collision detection. When collision boundaries of greater detail and complexity are used, more computational effort is required in the collision checking. In contrast, a simplified collision boundary may speed up the collision checking, albeit with less accuracy. Therefore, the problem of making an appropriate strategy to properly balance both sides of collision detection is also a critical and important issue.

Another challenge of interactive virtual construction is that in contrast to computer games, a general and well-designed virtual construction system must support the simulation of various construction projects, or a project under different progress stages. This means that it has to provide the functions of a changing dynamic model and importing in order to easily and rapidly build up virtual construction environments.

Collision detection is still a critical challenge in both the gaming industry and academic research. The collision detection method used in interactive virtual construction must be efficient and effective. The collision boundary used must also be constructed automatically. Hence, a suitable method for handling the problems in virtual construction is required.

3. PROBLEM STATEMENT

To perform collision detection efficiently, the model is usually separated into several parts. The objects can be grouped together to ignore some detailed geometry of the model in this preprocessing action. The objects are usually grouped according to their geometry and position. The objects that are selected for grouping can significantly influence the efficiency and accuracy of collision detection. For example, the more groups we selected, the more computing efforts is required, albeit with greater accuracy. Hence, it is very important to group the objects correctly and appropriately.

In practice, developers usually perform this task via modeling software such as 3ds Max Studio (Autodesk, 2010). They group the objects to construct a simplified 3D model for collision detection directly according to their own experiences and knowledge. In order to construct an appropriate collision boundary, developers usually develop the grouped or built model through repetitive work between modifying and testing the model. This procedure is tedious and time-consuming. When the models are modified or replaced, developers need to re-build the boundary according to these changes. Furthermore, in some applications such as 4D modeling, the 3D model of scene will be changed over time. It is difficult for developers to manually construct the collision boundary for every time step. A more intelligent and automatic method is needed for this problem.

Therefore, the aim of this study is to develop an object grouping method for the automatic generation of collision boundaries in virtual construction sites. The proposed method can classify the scattered and complex objects of the construction scene efficiently and effectively. They can also be grouped according to their geometrical and positional properties for collision detection. Hence, the generated collision boundaries are allowed to support the real-time collision detections.

4. METHODOLOGY

To classify the objects in a construction scene, all of the objects must be represented using the same format. Each object is converted into an axis-aligned bounding box (AABB), as shown in Fig. 2 (Van den Bergen, 1997). An axis-aligned bounding box includes six properties: x, y, and z from the position; w, h, and l from the dimension of the box. Therefore, we can transfer the construction scene into a list of bounding boxes as the input data of classification in order to simplify the model and generate collision boundaries.

4.1 Classification using k-mean Clustering Method

The problem with the classification of these defined boxes can be regarded as a traditional clustering problem. We represent a box using a data point with six dimensions (x, y, z, w, h, and l). All the boxes can then be transferred into a set of points in a six-dimension space as the input data for clustering. We utilize the most widely used clustering method, the k-means clustering method, to classify these boxes. Given a set of n data points in real d dimensional space, Rd, and an integer k, the problem is to determine a set of k points in Rd, called centers, to minimize the mean squared distance from each data point to its nearest center (Kanungo et al., 2002). Table 1 shows the pseudo code of the k-means clustering method. After the objects are classified and grouped, the efficient boundary for collision checking can be built.

The k-means method uses Euclidean distance between two data points as the measurement for deciding which group that data point belongs to. Each element in a set of data has the same level of influence to the distance. However, in some case, for example in Fig. 1(a), we are trying to cluster a scene that includes 1,243 objects into three groups. As the distance between dimensions has the same level of influence with the distance between locations, the k-means method may result in an unexpected boundary with lower accuracy, as shown in Fig 1(b). To improve the rationality and accuracy of the clustering result, weights are added to each element of the data point before clustering. The new distance calculating method is expressed as following equation:

$$\mathrm{d}'(g_i, g_j) = (g_{1\mathrm{x}} - g_{2\mathrm{x}})^2 \cdot \omega_\mathrm{x} + (g_{1\mathrm{y}} - g_{2\mathrm{y}})^2 \cdot \omega_\mathrm{y} + (g_{1\mathrm{z}} - g_{2\mathrm{z}})^2 \cdot \omega_\mathrm{z}$$
$$+ (g_{1\mathrm{w}} - g_{2\mathrm{w}})^2 \cdot \omega_\mathrm{w} + (g_{1\mathrm{h}} - g_{2\mathrm{h}})^2 \cdot \omega_\mathrm{h} + (g_{1\mathrm{l}} - g_{2\mathrm{l}})^2 \cdot \omega_\mathrm{l} \quad (1)$$

By increasing the weights of x and y, the degree of the influence to the distance by the location in the plane will increase. Therefore, the clustering process under these conditions can provide a more suitable result as shown in Fig 2(c). If we set all the weights of the dimension to zero, the k-means will cluster only according to the location of the objects.

TABLE 1: Algorithm of the k-means clustering method

G: a set of n data with d dimension.

$C_{initial}$: initialized k cluster centroids.

C: centroids of k cluster.

$P = \{p(i) | i = 1, \cdots, N\}$: the cluster label of B.

$d(g_i, g_j)$: the squared distance between data.

$Kmeans(G, C_{initial}) \rightarrow (C, P)$

Let $C = C_{initial}$

Repeat:

Let $C_{previous} = C$

For all $j \in [1, k]$: $c_j = average\ of\ g_i, whose\ p(i) = j$

For all $i \in [1, N]$: $p(i) = \arg min\, d(g_i, c_j), 1 \le j \le k$

Until $C = C_{previous}$

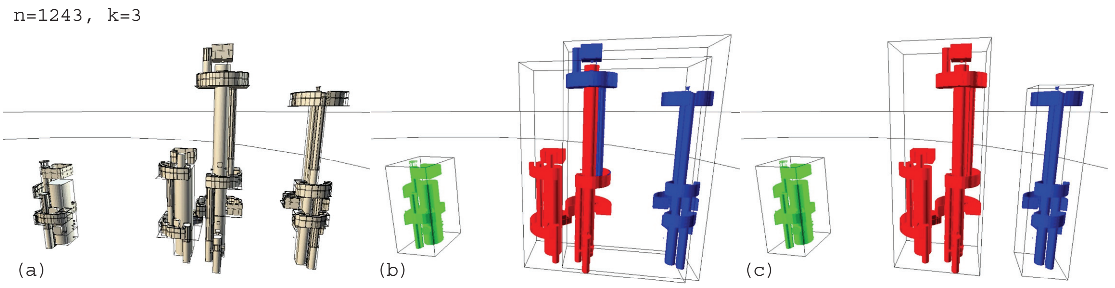

FIG. 1: Using the k-means clustering method: (a) original model; (b) clustering without weights; (c) clustering with weights such that $(w_x, w_y, w_z, w_w, w_h, w_l) = (3,1,3,1,1,1)$

4.2 Measurement of the classification quality

To measure the quality of the groups classified by the proposed method, we can utilize the volume of the groups' AABB boundary. When less volume of the box is generated, this means that it contains less collision-free space. The collision-free space is the space inside the bounding box that is not occupied by the objects, as shown in Fig.2. More collision-free space means that the collision boundaries are less accurate and the clustering are of lower quality. However, accurately determining the volume of the collision-free space is difficult, making the measurement and evaluation more difficult and requiring much computational time. Hence in this paper, a simplified and fast measuring index for determining the quality of the clustering, called the *Box Volume Ratio* (BVR), is developed. Equation 2 shows the calculation method of the BVR, where r_{bvr} stands for the value of the BVR, **b** stands for the AABB volume of the objects in the scene, and **g** represented the AABB volume of the clustered groups. This method ignores the volume of the overlapping parts between the bounding boxes such that the computational cost is in O(n) order. A larger BVR value means that the boundary is wasting more collision-free space; on the other hand, the boundary with a smaller BVR value is more accurate to fit the objects' shape.

$$r_{bvr} = \sum_{i=1}^{k} g_i / \sum_{j=1}^{n} b_j \quad (2)$$

$$r_{bvr}^{i} = g_i / \sum_{j=1}^{n_i} b_j^i \quad (3)$$

However, the scale of the size in a construction site model is usually very large. This index is used to approximately determine the space occupied by the bounding box of the clustered group, and cannot reflect the quality of the boundary of each of the clustered group. In order to ensure that all the clustered groups with different scale can have the same level of accuracy, we must examine each individual group. Therefore, the *Group Box Volume Ratio* (GBVR) is developed to calculate the BVR of each clustered group. The calculating method of GBVR is shown as Equation 3, where r_{bvr}^{i} represents the value of the *i*-th GBVR, and the b^i is the set of the object's AABB volume which is in the *i*-th group. By analyzing all the groups' GBVR, it can help us evaluate the quality of the clustering result.

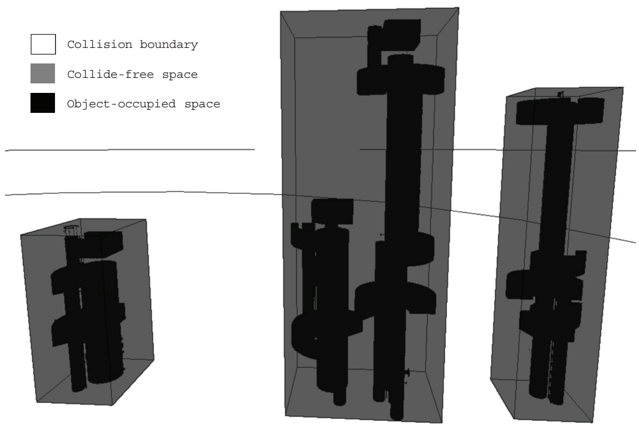

FIG. 2: Quality evaluation method using AABB boundary of the classified groups

4.3 Propagation clustering method

The use of the k-means clustering method to classify the objects and the indices for measuring the quality has already been discussed previously. However as mentioned earlier, the size of elements and objects in a construction site can be in a large scale. The k-means clustering is a fast and simple method to roughly classify input data by distance only. This method can present a good result in the BVR, but cannot achieve consistent quality of each clustered grouped even through increasing the number of clusters.

TABLE 2 Algorithm of the propagation clustering method

G: a set of n data with d dimension.

k_{prop}: propagating cluster number of k − means clustering.

S: subset of the G.

$R(S)$: the CR of the group s.

r_{pr}: propagating ratio.

$Kmeans(S,k) \rightarrow List\ of\ S$: k − means clustering method.

```
Set k_prop, and r_pr
Let S_list = Kmeans(G, k_prop)
    Repeat:
        For all the S_i in the S_list:
            If R(S_i) > r_pr
                Let S_sub = Kmeans(S_i, k_prop)
                Add S_sub into S_list
            Else, add S_i into S_result
            Remove S_i from S_list
    Until S_list is empty
Generate collision boundary using grouping result S_result
```

Instead of increasing the number of clusters for higher quality, at the expense of unnecessarily generating more groups, a method called the Propagation Clustering Method (PCM) was developed to reach a balance between effectiveness and efficiency. The idea of the PCM is to re-cluster the group for which the GBVR cannot reach a specified value, and propagate higher quality sub-groups to replace the original group. The algorithm is shown in Table 2. This method will continue breaking the groups using the k-means clustering method until each group's GBVR is under a certain value called the *propagating ratio*. The number of clusters using k-means during each propagation is called the propagating number. This method can ensure that all the groups that are clustered can have the same level of quality. The experimental results of the method will be further discussed in the 'test and discussion' section below.

4.4 Hierarchical Collision Boundary Tree

We can use the results of the PCM as the boundary for collision checking. Fig. 3 shows the boundary generated by the PCM with different numbers of propagating iterations. User can obtain a more accurate boundary by increasing the iteration number, or a boundary that is more efficient at collision detection with lower iterations. However, in many critical erection project simulations, both accuracy and efficiency are normally required to provide users with a real-time and precise simulation.

Therefore, in order to have an accurate and efficient collision strategy, we can use the PCM method to construct a hierarchical collision boundary tree, as shown in Fig. 4 (Li and Chen, 1997). As indicated in the figure, s_{i+1} were propagated by s_i, where i means the number of generations. In a collision checking cycle, the system will first check if the objects intersect with s_0; if this is true, the system will then check its children, $s_{i,0}$, $s_{i,1}$, and so on; otherwise, this cycle is finished and the system will start a new collision checking cycle during the next time duration. This collision checking policy can save much computational effort, and also achieve accurate boundary checking.

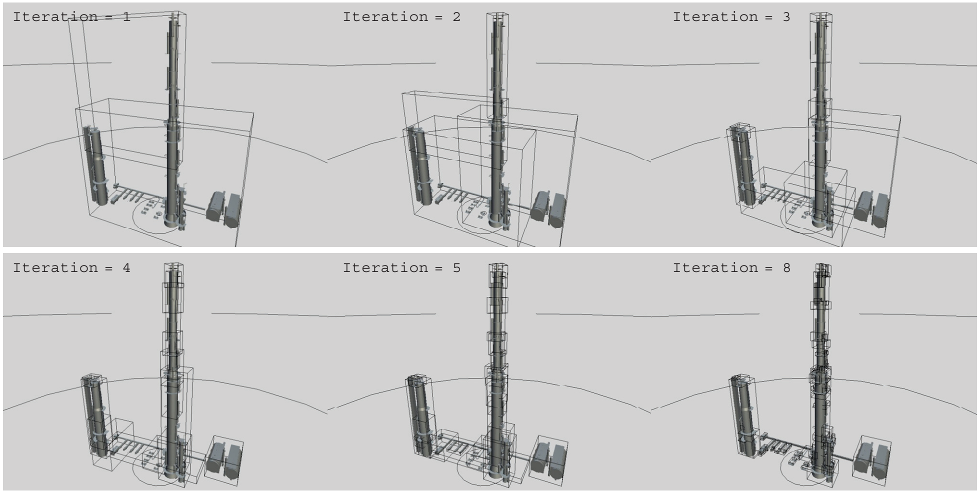

FIG. 3: Collision boundary constructed by using the PCM with different number of iterations

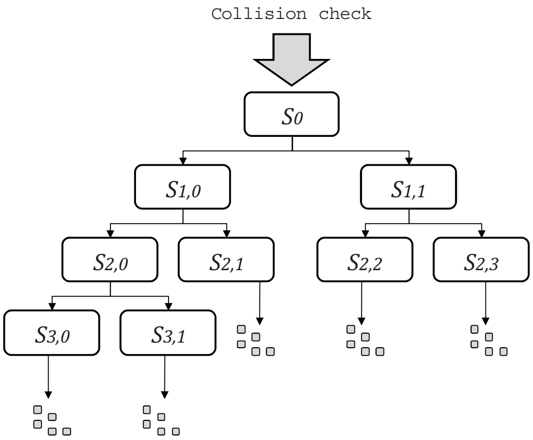

FIG. 4: Hierarchical collision boundary tree constructed by the PCM

5. IMPLEMENTATION

To implement and test the proposed method, a system called the Erection Director (ED), which is developed based on the research conducted by Chi and Kang (2010), was used. ED was built to simulate the single and cooperative crane erections in a virtual construction site. The system can perform a smooth, realistic, and physics-based construction simulation, which allows users to control cranes and real-time interaction with the environment. It is developed based on two major components: XNA and PhysX.

XNA is a framework based on DirectX, which is generally used to develop PC and Xbox360 games (Microsoft, 2008). It is implemented here as a rendering engine which can support various formats of 3D model, 2D texture, and audio. The scenes in XNA are all rendered using a graphics processing unit (GPU) shader. With the benefit of the advantages of XNA, ED can efficiently process a complicated 3D scene of a virtual construction site, and provide a realistic real-time virtual world.

The PhysX, a physics engine integrated into the ED, is used to simulate the dynamical motions of cranes, and deal with collision detection and reaction (Nvidia, 2009). Users can define their construction machineries using joints and rigid bodies. The bounding shapes can also be assigned for performing collision detection. It supports various type of bounding shapes including the sphere, box, capsule, convex, and the shape built by triangle mesh. It also enables hardware acceleration using the GPU of Nvidia graphics cards, and can potentially be used for real-time simulation due to its efficient solver and its high stability derived from position-based dynamic methods.

The auto-generating boundary method proposed in this paper was implemented as a plug-in module of the ED, called the Boundary Generator. Fig. 5 shows the architecture of ED and the Boundary Generator module. Before beginning the simulation, the developer has to define the simulation environment including the construction scene, construction machineries, and construction scenario. Subsequently, the system generates the visual model for rendering, and the physics model for computing physical behaviors. The physics model contains the rigid body, joint definitions, and bounding shapes. Before the introduction of the Boundary Generator module, the bounding shapes of the physics model were defined manually by developers. The process was tedious and not systematic. Therefore, the module plays the role of processing the built visual model to construct the bounding shapes of the physics model for collision detection. The first step of boundary generation is to convert the 3D model into a dataset of bounding boxes, and the PCM is then used to cluster the dataset into several groups. The last step is to use the group to generate the boundary for collision checking. In this study, we used AABB as the boundary for each clustered group to invest the feasibility of the proposed method. During the simulation, users can dynamically change and re-generate the boundary according to the demands, such as the 4D model applications.

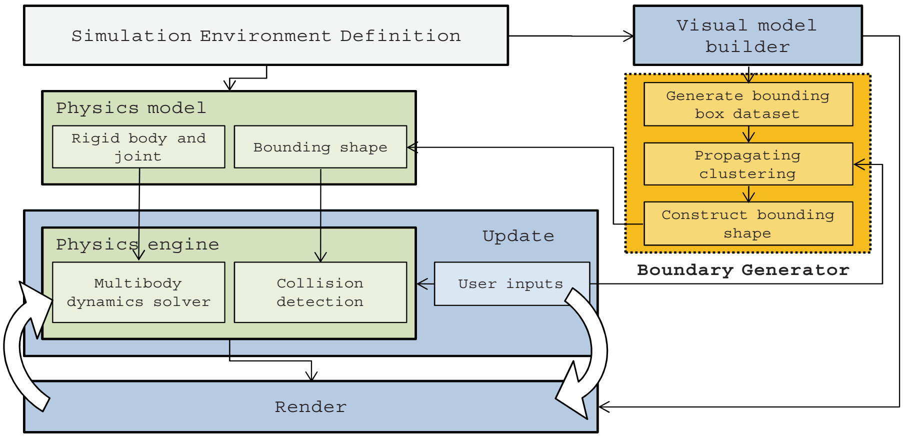

FIG. 5: Architecture of the Erection Director with the Boundary Generator module (the blue parts are supported by XNA; the green parts are supported by PhysX; and the orange part is the Boundary Generator).

6. EXPERIMENT

To investigate the feasibility of the developed method for generating collision boundaries, a real construction site model, the Dalin oil refinery, was used. Three different portions of the model was used to test the proposed method under different structures of the scene, shown in Fig. 6. The diverse scene is a scattered and large scale scene in which the size and dimension of objects are quite different. The uniform scene presents a common construction site, a steel structure scene composed primarily of columns, beams, and floors in which the dimensions are almost the same. The composite scene is a type of construction site which contains steel structure, and the scattered cylinder objects.

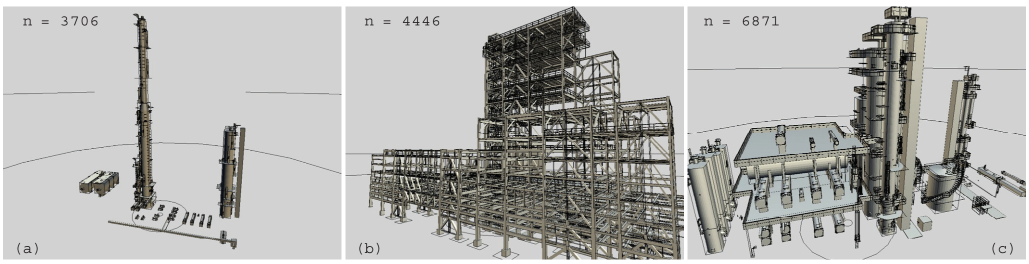

FIG. 6: Three construction scenes retrieved from different portions of the Dalin oil refinery model: (a) diverse scene; (b) uniform scene; (c) composite scene.

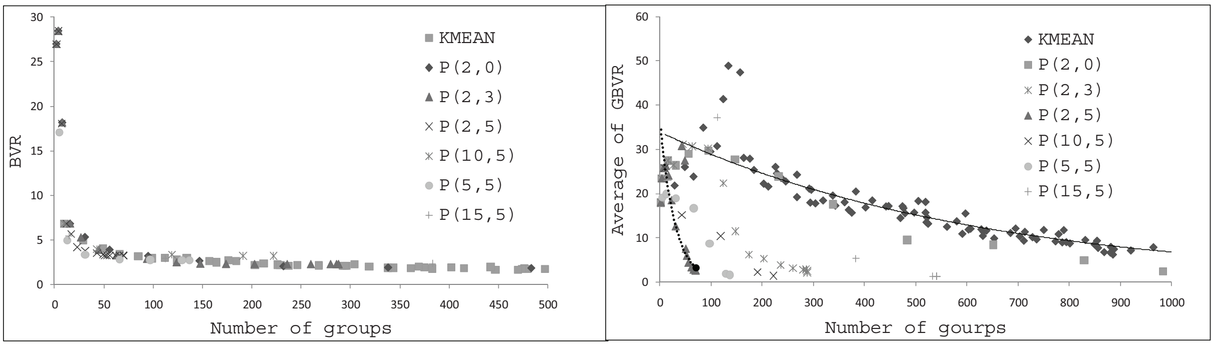

FIG. 7: The grouping result of the diverse scene using k-means directly, and the PCM, $p(k_{prop}, r_{pr})$, with different propagating cluster number, k_{prop}, and propagating ratio r_{pr}

The experiment uses a movable sphere boundary to perform the collision check to determine if the object collides with the elements in the construction scenes. The AABB boundary is used as the boundary shape of the elements, and the testing results are shown in Table 3. The computing cost was first determined before the grouping of each scene. The computing time is approximately in the range of 1 to 10 millisecond seconds, according to the number of the elements. Each scene is tested with three sets of propagation ratio and clustering numbers. The result contains the number of convergent groups, the GBVR average, and the computing cost. The *convergent group* is the number of the groups when all the groups' GBVR reach the propagating ratio.

TABLE 3: Computing cost of the collision detection using AABB boundary

Diverse scene: Total number of elements: 3706 Computing cost: 1.04 (millisecond)			
(k_{prop}, r_{pr})	Convergent Groups	Average GBVR	Computing cost (millisecond)
(2, 3)	288	2.16	8.59×10^{-2}
(2, 5)	70	2.60	2.37×10^{-2}
(10, 5)	222	1.46	7.33×10^{-2}
Uniform scene: Total number of elements: 4446 Computing cost: 6.11(millisecond)			
(k_{prop}, r_{pr})	Convergent Groups	Average GBVR	Computing cost (millisecond)
(2, 5)	1063	1.86	3.23×10^{-1}
(2, 10)	756	3.58	2.45×10^{-1}
(10, 5)	2391	1.13	1.38
Composite scene: Total number of elements: 6871 Computing cost: 9.57(millisecond)			
(k_{prop}, r_{pr})	Convergent Groups	Average GBVR	Computing cost (millisecond)
(2, 5)	70	2.60	2.57×10^{-2}
(2, 10)	150	4.31	4.22×10^{-2}
(10, 5)	2035	1.26	9.09×10^{-1}

TABLE 4: Maximum computing cost of hierarchical boundary tree using AABB boundary (in millisecond)

Iteration ($k_{prop} = 2, r_{pr} = 5$)	Diverse scene	Uniform scene	Composite scene
6	4.52×10^{-1}	8.91×10^{-1}	2.29
9	3.21×10^{-1}	7.51×10^{-1}	1.25
12	1.21×10^{-1}	7.62×10^{-1}	8.91×10^{-1}

Fig. 7 shows the detailed result of the diverse scene using the PCM, compared with the result using the k-means clustering method directly. The figure shows that the k-means method can perform grouping as well as the PCM performs in the BVR. It converts thousands of elements to approximately one hundred groups with around three values of BVR. It is suitable for purposes for the rapid generation of collision boundaries that require less accuracy. However, the average of the GBVR displayed in Fig. 7 shows that the using PCM can have better results using the GBVR. Even though the PCM has the ability to retain the quality of each group's boundary, it works better in scattered construction scenes rather than in the structural-steel scene as we used the AABB volume as the evaluating criterion. In a steel structural scene, it is easy to generate more collision-free space in a group such as when perpendicular long-elements (beam or column) are grouped together. We also experimented with the hierarchical boundary tree built by the PCM according to three cases, and the results are shown in Table 4. The hierarchical boundary tree can reduce the computation cost within a tenth of the original and retains the same accuracy.

The rendering speed can achieve approximately 30 frames per second while running on a mid-ranged personal laptop computer equipped with an Intel Core2 Duo 2.13GHz processor, 3GB of RAM, and a Nvidia Geforce 7950 graphics card. This computational efficiency is sufficient to support real-time visualization. Crane operators and planners may use the visualization tool to virtually examine their erection plans in order to avoid possible problems on the actual sites.

7. CONTRIBUTION

The major contribution of this study is the development of a efficient method for automatically generating collision boundary in virtual construction. The major contributions are summarized below:

- Automation: The method can automatically classify the objects of the models, and group the objects according to their dimensions and positions. Engineers can save effort on manually building and developing the collision boundaries.
- Fast generation: The developed method is fast and efficient which can dynamically re-generate the collision boundaries when the scenes are modified or changed. This can help the collision boundary of the 4D model application easier to construct.
- Adjustability: The method can generate the collision boundary with different accuracy for different levels of simulation details. Developers can easily adjust the balance between the efficiency and the accuracy of the collision boundary according to the purpose of the simulation.
- Extendibility: This research developed a grouping method for generating collision boundaries. This research currently uses the AABB boundary to clad the clustered group, which can be replaced by or combined with other collision boundaries or strategies to improve the collision accuracy and efficiency.

8. CONCLUSION

This paper presented a method that can help construct and simplify the collision boundary of the scenes in virtual construction. The proposed method utilizes the k-means clustering method to classify the objects using the AABB boundary as the input data of clustering. The *Propagation Clustering Method* developed in this study improves the quality of the clustering result and can generate the hierarchical boundary tree for both accuracy and efficiency of collision detection. The proposed method for three common types of the construction scenes were tested and experimented and the result shows that the proposed method can effectively group the objects automatically. The built hierarchical boundary tree can also deliver an object-based collision checking which is appropriate for construction applications.

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VI. STRUCTUAL DESIGN IN VR

VIRTUAL MODEL OF STRUCTURAL STEEL CONSTRUCTION USING COSYE FRAMEWORK

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ABSTRACT: *Structural steel construction is a permanent base in a variety of construction projects, e.g., building construction, bridge construction and industrial plant construction, and has a major contribution in the construction industry. The broad and highly interrelated processes within steel construction have made development of inclusive plans for steel construction projects quite challenging for construction managers. We have developed a simulation model for steel construction, using a distributed simulation framework based on High Level Architecture (HLA), to facilitate the planning phase of steel construction projects. This simulation model works as a virtual environment which accommodates and synchronizes a set of modeling tools from different aspects of steel construction. In this paper, our main focus is on presenting the design and implementation efforts involved in the development of this virtual model.*

KEYWORDS*: Steel Construction, Distributed Simulation, High Level Architecture, Discrete Event Simulation, System Dynamics, Concurrent Visualization.*

1. INTRODUCTION

Structural steel construction plays an important role in the construction industry. Various phases are followed for constructing structural steel components, including design and engineering, procurement, fabrication, shipping and site erection. In many cases a variety of companies from all around the globe are involved in different phases. Structural steel projects usually require large amounts and different types of steel materials, equipment, and labour disciplines. Given the complexity of steel construction projects and the number of steel pieces involved, the planning and control of structural steel construction projects is frequently challenging for construction managers.

To address this issue, we have previously proposed and briefly explained a framework for automating and integrating project monitoring and control in steel fabrication (Azimi et al., 2010) where simulation was a key, but independent, component. This simulation component forms a virtual environment in which the interactions among different phases of structural steel construction from various stakeholders' points of view can be followed and analyzed. Since then we have expanded this simulation component and added more flexibility. In this paper we are presenting the design and implementation efforts involved in developing this virtual model.

Development of such an inclusive tool requires extensive computational resources, especially when we are dealing with large projects such as those found in the construction industry. Running such a simulation-based system on a single computer is not usually successful; either the simulation model simply takes too long to run, or the computer crashes due to lack of resources. Also, the development of such a large virtual model is typically incremental. Therefore, a tool is needed which can accommodate modules developed at a later date with minimal interruption to the initially developed modules. We used the Construction Synthetic Environment (COSYE) (AbouRizk and Hague, 2009), which is a distributed simulation framework based on the High Level Architecture (HLA) (IEEE 1516), to cope with these challenges. COSYE allows the distribution of computational loads to multiple computers during simulation runs. It also follows a set of procedures which facilitate the integration of gradually developed modules into the main body of the virtual model. COSYE can handle concurrent use of various types of modeling tools, such as Discrete Event Simulation (DES), System Dynamics (SD), Agent Base Modeling, and concurrent 3D Modeling and Optimization tools, which allow the capture of different aspects of system behaviors.

In the following, we first present an overview of the processes and the conceptual design of distributed simulation of structural steel construction. We then describe our progress on the model development at this stage of the work, which is mainly related to the fabrication process of the steel construction. We have utilized DES, SD and concurrent 5D (3D plus time and cost) models for capturing different aspects of the fabrication shop behavior and to provide the fabrication shop managers with valuable planning and control information.

2. STEEL CONSTRUCTION

Steel construction consists of a range of processes which result in the structural steel installed in place and ready to support the designed loads. The steel construction processes may vary from one project to the other, but commonly there are six phases: Detailing, Procurement, Fabrication, Module Assembly, Shipping, and Site Erection. Fig. 1 presents these processes and the direction of data and material flow in steel construction. The Detailing process consists of all engineering and drafting activities which detail the final design of the structural steel and define the bill of material and the operations that should be performed for completing the structural design. In the procurement process the required material for the steel structures are supplied. Steel fabrication shops perform operations on the steel elements by using specialized stationary and non-stationary equipment in a controlled environment and minimize the amount of effort required on the construction job sites. Module Assembly yards are also meant to facilitate the job site erection; their main operation is assembling the structural steel elements together with other industrial elements, e.g., spools, valves and vessels, in a form of a sub-plant. Shipping is usually done via shipping trucks from fabrication shops or module assembly yards to the construction job sites. Structural steel erection is the final process in the steel construction, where all of the shipped structural steel elements and modules are placed in their designated locations in accordance with the design provided by the consulting companies.

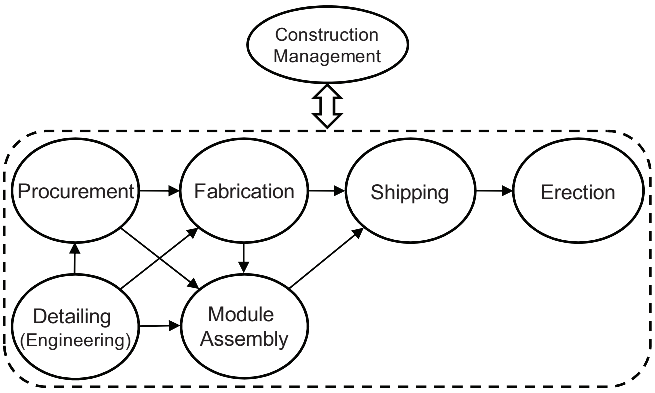

Fig. 1: The common processes in structural steel construction and the interactions among them (an enhancement of previous model by Azimi et al. 2010).

As illustrated in Fig.1, a steel piece goes through a long journey from Detailing to Procurement, Fabrication, Module Assembly, Shipping, and Erection. Furthermore, some of these processes such as Fabrication, Erection and Module Assembly comprise complex combinations of operations and managerial issues, which makes steel construction management challenging. To improve management of steel construction projects, construction companies typically use a hierarchical Product Breakdown Structure (PBS) and break down the main structure to the structural steel elements (or steel pieces) which can be fabricated independently and shipped to the module assembly or erection sites (Azimi et al. 2010). Fig. 2 shows the PBS which has been used in this research.

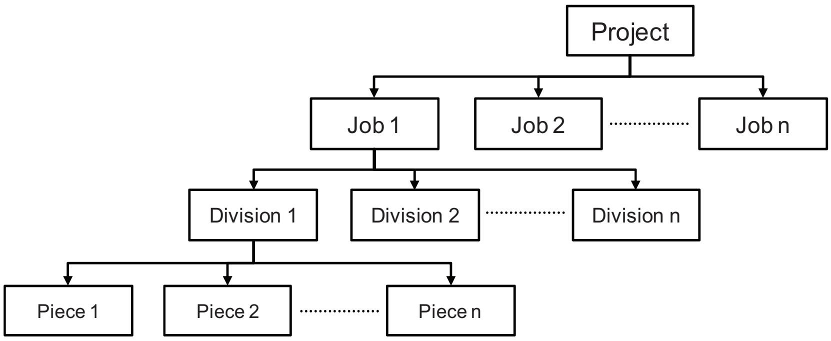

Fig. 2: Product Breakdown Structure (PBS) used in this research

A typical steel construction project or job usually consists of thousands of pieces which should go through every single process. Depending on the type of project or piece, a steel piece might spend days to months within each process. Delayed material, late reveal of detailing, or miscalculations can shift the completion of structural steel projects significantly.

3. DISTRIBUTED SIMULATION

The planning phase of the steel construction is composed of a range of dependent working processes which are applied to thousands of pieces in different manners, creating challenges for construction managers. When it comes to this level of complexity, simulation based approaches provide more accurate and flexible tools for managers than analytical approaches. Simulation allows construction managers to test various alternatives for project construction, such as outsourcing, employing additional workers or equipment, and probable delays, and ultimately to develop a balanced smooth plan for the steel construction project.

Different work processes in the steel construction are usually completed by different types of construction companies or at least different types of specialties. For example, Detailing can be done by engineering companies, Fabrication is done in fabrication shops, transportation companies do the Shipping and erection sub-contractors do the Erection. A centralized simulation model which captures interactions inside every working process – which are set according to different companies' working structures – will be extremely complex. Furthermore, any changes in one of the companies within the chain of steel construction processes will affect the entire simulation model. Our answer to these issues is Distributed Simulation.

In distributed simulation the target system is divided based on the main participating processes. Every process is simulated in an independent simulation module which can be run separately and can communicate with other simulation modules. We have used the Construction Synthetic Environment (COSYE), developed at the University of Alberta (Edmonton, Alberta, Canada), as our main distributed simulation framework. COSYE follows the standards in the High Level Architecture (HLA) and therefore all of our development fulfills this standard as well.

HLA was developed in the 1990s by the United States Department of Defense (DoD) to simulate military systems (Kuhl et al. 1999). In HLA terminology an HLA-based distributed simulation model is called a Federation. At the top level of every Federation, there are three main elements: the Federates, the Runtime Infrastructure (RTI), and the Object Model Template (OMT). A federate is an independently developed and run simulation module. A federate inside a federation can send and receive updates to and from other federates in the federation. In the case of steel construction, each process previously mentioned is a good candidate to be simulated in a form of a federate. Data communication among different federates is managed by the RTI, and the structure of communal data shared among federates is defined in the OMT (for further information, see [Kuhl et al. 1999]).

The use of the COSYE framework facilitates simulation model development for complex systems: the model development can be easily assigned to different groups of developers with minimal need for additional arrangement among working groups. Furthermore, by using the COSYE framework, any changes made to any working process will only affect the corresponding federate. As long as the input and output of the process remains unchanged, there will be no need to change either other federates or the OMT. In addition, any changes to the input and output of a federate can be handled through limited changes to the OMT and any linked federates. Model maintenance and update become much easier compared to the development of centralized models. The COSYE framework also allows the distribution of simulation runs to multiple computers, thus reducing simulation time. In addition, COSYE does not mandate the presence of all participating federates in the federation for a simulation run. These capabilities of COSYE allow the development of the entire federation in an incremental fashion and in different time frames (for further information, see [AbouRizk and Hague 2009]).

4. CONCEPTUAL DESIGN OF THE MODEL

The distributed simulation model provides a virtual environment through which different steel construction working processes can interact with each other. The model is designed to help steel construction management companies; however, companies participating in other steel construction processes, e.g., detailing, fabrication shops, and erection sub-contractors, can also use the model results.

The steel construction federation is designed to have six main simulation sub-models to capture 6 working processes of steel construction. Depending on the level of detail, each simulation sub-model can be implemented in one or more simulation federates. For example, the steel fabrication process can be modeled in just one simulation model of the fabrication operation by using a Discrete Event Simulation (DES) approach, or more details such as organizational policies and concurrent visualization can be added to the model to make the simulation model more accurate and understandable. Furthermore, there are some common functionalities which have similar functions in multiple processes, such as the calendar, weather, or database communication federates. These functionalities can be implemented in independent federates to support multiple other federates.

Fig. 3 depicts the top level architecture of the steel construction federation. As shown, none of federates are directly linked to each other and the RTI acts as the medium for them. There are three supporting federates, which serve multiple other federates: the Calendar federate synchronizes the dates in all federates; the Weather federate serves weather-sensitive federates, i.e., Erection, Module Assembly, Shipping and Procurement; and the Database Communication federate facilitates communications with the participating company's database, i.e., importing required data and exporting reports on the achieved results, as time progresses.

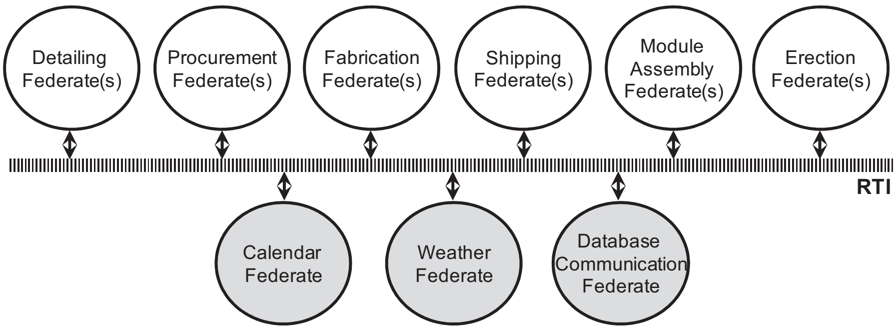

Fig. 3: Top level architecture of the steel construction federation.

The development of the steel construction federation is completed in several phases as in below:

Phase 1: development of Fabrication, Calendar, and Database federates.

Phase 2: development of Shipping, Erection, and Weather federates.

Phase 3: development of Detailing, Procurement, and Module Assembly federates.

5. MODEL DEVELOPMENT

At this stage of the research we have developed the first phase of the steel construction federation. As mentioned, the COSYE framework provides the required services for distributed simulation. The model was developed in Visual Studio 2008, and is described below.

5.1 Object Model Template

The Object Model Template (OMT) defines the object classes and attributes which are shared between multiple federates. When a federate is responsible for updates to an attribute, in HLA terminology that federate is Publishing that attribute; when a federate uses the updated values of an attribute, that federate is Subscribing to that attribute. In addition to shared object classes and their attributes, OMT should be aware of the Publishing and

Subscribing federates.

Table 1 presents the OMT that has been used in our steel construction federation, which consists of five main object classes shared among five participating federates. Every attribute should have at least one Publishing federate and one Subscribing federate to be eligible for OMT inclusion. Because the supporting federates, i.e., Data Management and Calendar, provide services to the other federates they will do more Publishing than Subscribing; for the main federates, i.e., DES, SD and Visualization, we expect more Subscribing.

Table 1: Steel Construction Federation Object Model Template

Object Class	Attribute	Type	Federates*				
			DES	SD	Visualization	Data Management	Calendar
Calendar	StartDate	Date	S			P	
	CurrentDate	Date	S	S	S	P/S	P/S
	CurrentShiftHours	Integer	S	S		P	P
	CurrentShiftType	Integer	S	S		P	P
	DayNo	Integer	S	S	S	S	P
	DesireOvertime	Double		P			S
	MaxOvertime	Double		S			P
	SetOverTime	Double		S		P	P
Entity (Piece)	PieceID	Integer	S			P	
	PieceStartDate	Date	S			P	
	Weight	Integer	S			P	
	Cutting Man Hour	Double	P/S			P/S	
	Fitting Man Hour	Double	P/S			P/S	
	Welding Man Hour	Double	P/S			P/S	
	Inspection Man Hour	Double	P/S			P/S	
	Painting Man Hour	Double	P/S			P/S	
	CuttingStart	Date	P/S			P/S	
	CuttingFinish	Date	P/S			P/S	
	FittingStart	Date	P/S			P/S	
	FittingFinish	Date	P/S			P/S	
	WeldingStart	Date	P/S			P/S	
	WeldingFinish	Date	P/S			P/S	
	InspectionStart	Date	P/S			P/S	
	InspectionFinish	Date	P/S			P/S	
	PaintingStart	Date	P/S			P/S	
	PaintingFinish	Date	P/S			P/S	
ShopProductivity	DelayRate	Double		S		P	
	TotalDelay	Double	S	S		P	
	Accuracy (MLC)	Double	S	P		S	
StationProductivity	ID	Integer	P	S			
	CurOperator	Integer	P/S	P/S			
	MaxOperator	Integer	P	S			
	MinOperator	Integer	P	S			
	Productivity	Double	S	P			
	State	Integer	P	S			
	Utilization	Double	P	S			
VisualPiece	PieceKey	Text			S	P	
	DivisionID	Text			S	P	
	CPI	Double			S	P	
	SPI	Double			S	P	
	Progress	Double			S	P	

* P stands for Publisher of an attribute and S stands for Subscriber to an attribute.

5.2 Federates

The developed model at this phase consists of five different federates, including three federates related to the fabrication shop, the Calendar federate and the Database federate.

5.2.1 Calendar Federate

This federate is responsible for advancing the date and determining the working hour arrangements (day shifts, night shifts and overtime). Users can enter upcoming holidays, and the model will take care of set holidays during the simulation. The Calendar federate publishes the date information to the federation to be used by other participant federates in the federation. The calendar interface has three main parts. The first part determines the required information for linking to the RTI, which is similar in all federates. The second customizes the working hours, and the third provides a place for setting the holiday schedule.

5.2.2 Database Federate

The Database or Data Management federate provides database communication services for different federates. At this phase of the federation development this federate retrieves information about steel pieces for the pieces which should be sent to the fabrication shop and reports the fabrication completion of the pieces to the database. The federate interface allows the user to set the simulation start time and the duration of the shop simulation as the main constraints for running related queries in the database; other inputs to this federate are the importance weights of different fabrication operations. The federate reports some managerial project information through the interface – such as delays, number of completed pieces, and finish time – and writes aggregated reports on project performance to the database.

5.2.3 Discrete Event Simulation (DES) Federate

The Discrete Event Simulation (DES) federate captures the operational part of the fabrication process. The fabrication operation starts by sending the fabrication orders and their related materials to the fabrication shop. The DES federate then simulates the flow of materials in the fabrication shop from one station to the other and sends the pieces out when the required set of operations are completed. Fig. 4a presents the main interface of this federate. Three buttons on the left side of the form open the detailed forms for entering the specifications of stations, mid buffers or storages and movers (cranes and rail cars) within the fabrication shop. The pink and green buttons on the middle of the form represent different stations, including cutting, fitting, welding, inspection and painting. The user can set the number of dedicated stations for each operation type, e.g., welding, by selecting the proper number of stations from the drop down combo box on the top of each series of stations. The buttons are green when stations have no job to do and are pink with the number of the piece written on them when they are busy serving the pieces. The initial number of on progress pieces at each station is also listed in the list boxes at the bottom of the form.

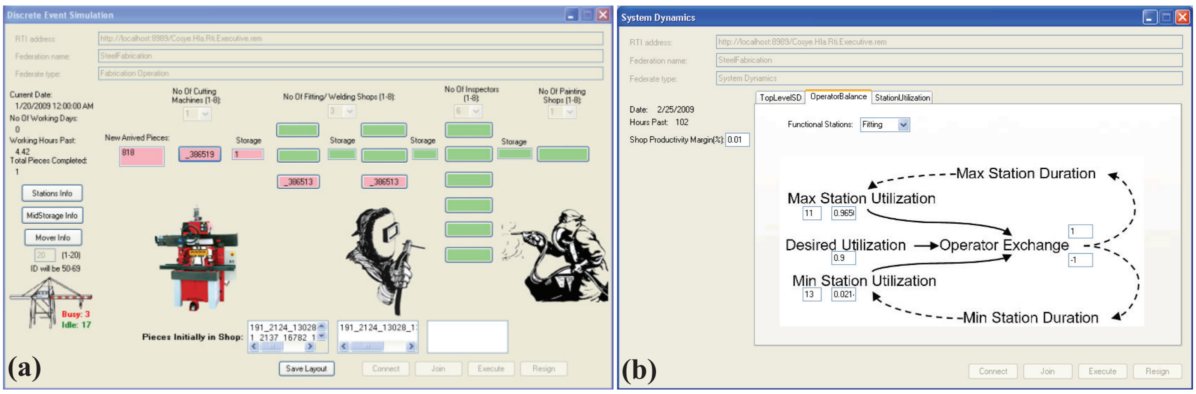

Fig.4: Interface for the Discrete Event Simulation federate (a) and the System Dynamics federate (b)

5.2.4 System Dynamics (SD) Federate

The System Dynamics (SD) federate captures the effects of non-operational mechanisms on the fabrication shop's productivity. The non-operational mechanisms which we included in the SD model are: fatigue, skill level, hiring and firing, and the work balance. Fig. 4b presents the main interface of this federate. The user can enter the marginal inaccuracy that is acceptable for calculating and reporting the productivity rate through different feedback loops in the model. Different types of feedback loops have been put in the tabular forms on the main form and the user can browse through them during the simulation run and see the changes in the non-operational mechanisms of the fabrication shop.

5.2.5 Visualization Federate

The Visualization federate visualizes the progress of the fabrication shop using 3D models of structural steel projects. This federate lists the current steel divisions that are under way in the fabrication shop. The user can select any division to load the related 3D model. The completed pieces in the fabrication shop are found and highlighted inside the 3D model. Different colors have been used to visually illustrate the cost and time performance of the completed pieces (resulting in a 5D model). Fig. 5 presents the main interface of this federate. In-progress steel divisions are listed in the list box on the left side of the form. The user can select every in-progress or completed division from this list box and push the Change the Division button; the federate will then show the progress and performance indices of related pieces in the list box on the right. Because the visualization process slows down the simulation, the default option in the visualization federate is set to just update the progress in the text. The user can select the Show in Tekla radio button on the form and ask the federate to run Tekla, a structural steel 3D detailing package (Tekla Corporation, Finland, http://www.tekla.com), and reflect the progress concurrently in the 3D model. The color coded structural steel 3D model in Fig. 5 shows a snap shot from Tekla during the model run.

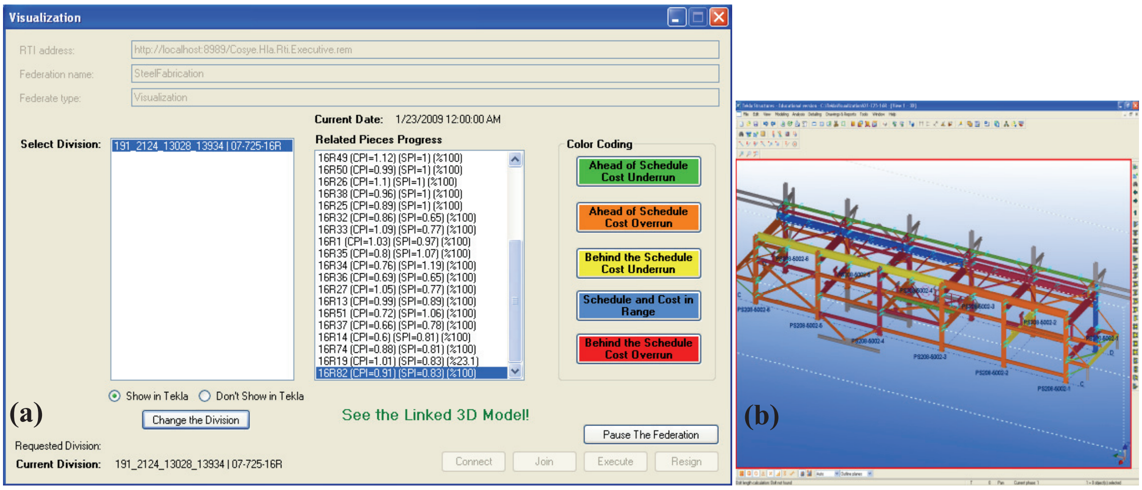

Fig.5: Interface for the Visualization federate (a) and the 5D Model (b) (for further information, see [Azimi et al. 2010])

6. APPLICATION

This model has been used for planning purposes in the fabrication shop of a collaborative steel construction company in Alberta, Canada. The expected performance of the assigned projects, effects of set overtime, effects of working hour arrangements, and an estimation of free capacity of the fabrication shop are some of the consulting capabilities that the developed model is able to provide to the fabrication shop managers. The client considered the Visualization federate to be one of the most attractive features, as it provided visual and easily understandable estimations for the project. In addition, the 3D models were previously developed for the detailing process and can now be used for planning and control purposes as well. Linking the Visualization federate to Telka Structures 14 for visualization does occupy most of the resources of a single computer, but the federation can be easily run in two computers, i.e., one which runs the visualization federate and one for the rest of federates, which keeps the simulation time at a reasonable level.

Another advantage is that because of the independent nature of federates, both in development and at run-time, we could easily inactivate one or more federates during specific experiments. For example, for our hybrid simulation experiments (Alvanchi et al. 2010) we did not use the visualization federate. We also successfully tested linking the steel federation to a process control system based on RFID technology, which was used for setting up the initial condition of the fabrication shop and using the most current data for the simulation (Azimi et al. 2010).

7. CONCLUSION

A new modeling approach has been utilized for steel construction in this research. This modeling approach opens a new horizon for developing inclusive and extensible construction projects, such as steel construction projects, which were not possible using traditional modeling approaches. This approach creates a virtual environment in which a variety of modeling tools, such as discrete event simulation, system dynamics, concurrent animation, and process control and monitoring tools, can plug in and work together.

A truly comprehensive model of steel construction is still in progress; however, because of our approach, the current model is still usable and beneficial to steel construction, especially for the fabrication process. In the future, we will gradually integrate other structural steel construction processes into the current model. This will allow construction managers to base their planning on a comprehensive view of the long chain of steel construction processes.

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Study on the use of 3-dimensional data in the design, construction and maintenance of bridges in Japan

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ABSTRACT: *In the "CALS / EC Action Program 2008", the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) sets out to study specific methods of circulating and using 3-dimensional data through the processes of research, design, construction and maintenance of bridges, and to verify them in experimental projects with regards to improving the productivity of works. There is a 3-dimensional technique, based on 3-dimensional data and 3-dimensional view (presentation of design, display of simulation results, etc.). It is expected that such 3-dimensional expressions of infrastructures could improve productivity, regardless of the engineer's skill; for example, they will make it easier to confirm problems in the implementation of works. In this study, the present status and problems of 3-dimensional techniques are firstly enumerated. Secondly, the findings by the Working Group (1st-3rd Meetings) of the MLIT CALS/EC committee on the use of 3-dimensional data will be discussed. Finally, how to apply 3-dimensional data and 3-dimensional view to real public works will be summarized.*

KEYWORDS*: CALS, CAD, 3-D data, Bridge*

1. FOREWORD

In the "CALS / EC (Continuous Acquisition and Life Cycle Support / Electronic Commerce) Action Program 2008[MLIT,2006]", the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) sets out to study specific methods of circulating and utilizing 3-dimensional data through the processes of research, design, construction and maintenance of bridges, and to verify them in experimental projects, with regards to improving the productivity of works.

There is a 3-dimensional technique, based on 3-dimensional data and 3-dimensional view (presentation of design, computer graphics, display of simulation results, etc.). Such 3-dimensional expressions of infrastructures make it easier to confirm works related to design, construction and maintenance and to discover problems, regardless of the level of engineer's skill. Methods of 3-dimensional design and simulation have already been introduced in the manufacturing and construction industries.

In this study, the present status and problems of 3-dimensional techniques in the design, construction and maintenance of bridges are firstly enumerated. Secondly, findings by the Working Group (1st-3rd Meetings) of the MLIT CALS/EC committee on the use of 3-dimensional data [MLIT,2009a;MLIT,2009b;MLIT,2010] will be discussed. Finally, how to apply 3-dimensional data and 3-dimensional view to real public works will be summarized.

2. RESEARCH METHOD

The procedure for construction projects in Japan is that national governments or local authorities, as the purchaser side, contracts with individual companies (consultants, construction companies and maintenance companies) in the processes of design, construction and maintenance. In this process, project data, information and outcomes are exchanged between the respective company and the governments.

For bridges, design is carried out 2-dimensionally, but 3-dimensional techniques are adopted at the stage of factory fabrication or manufacture of bridge superstructures. At the maintenance stage, however, management works returns again to 2-dimensional drawings. As such, there is no consistency in data related to drawings. If 3-dimensional data could be standardized for bridges, design checks and works involved in construction and maintenance could be carried out more efficiently; it is expected that 3-dimensional data will become easily popular with the development of CAD software.

The current circumstances of the use of 3-dimensional data for each phase will be shown in Fig.1.

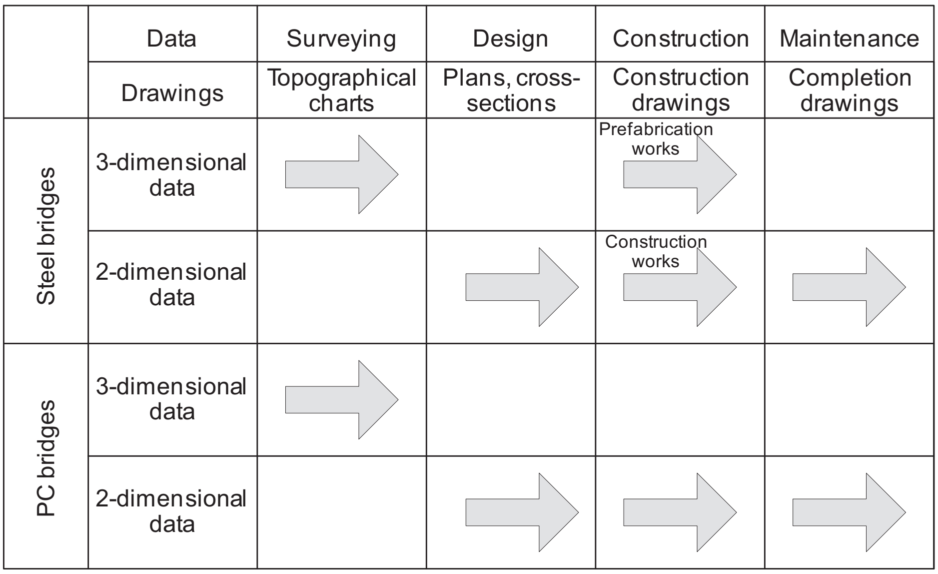

Fig. 1: Deployment of information over the life cycle of bridge works (present status)

2.1 Design

While the FEM analysis is used by 3-dimensional data in some cases, 3-dimensional techniques are not used in the design of structural members.

(Reasons why not used)

・ Currently, 3-dimensional design is not necessarily considered to enhance the efficiency of design;

・ Engineers who understand design are not capable of handling 3-dimensional CAD;

・ A specification for 3-dimensional delivery (drawing, file formats, etc.) could provide a trigger for the introduction of 3-D; and

・ 3-dimensional design could be promoted if there were a software that could deal with detailed structure model (e.g. no software for reinforcing bar arrangements).

2.2 Construction (PC bridges, substructure works)

3-dimensional data is not used when fabricating post-tension and pre-tension concrete superstructures or constructing substructure works.

(Reasons why not used)

・ A construction system using 2-dimensional drawings has been practiced efficiently;

・ It will take a lot of time to make a model for a reinforced concrete; and

・ There is no 3-dimensional component data for reinforcing bar, and it has to be made from individual and original designs.

2.3 Construction (steel bridges)

3-dimensional data is prepared from 2-dimensional design drawings, and NC (Numerical Control: an automatic machine control), design checks, and element processing are carried out using CAD/CAM systems (Computer Aided Design / Computer Aided Manufacture) with 3-D data shown in Fig.2. In addition, 3-dimensional data is used in the process of tentative superstructure assembly simulation and testing.

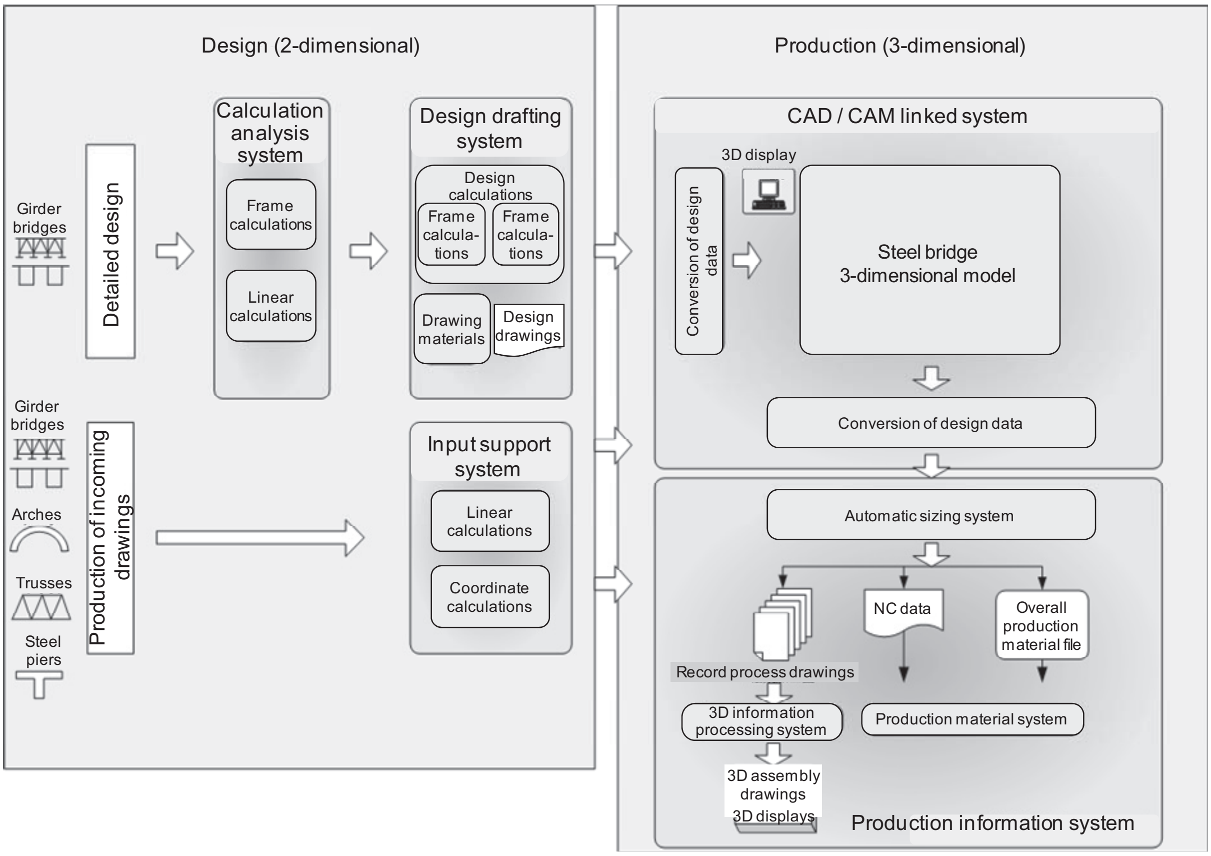

Fig. 2: CAD/CAM System Composition Chart

2.4 Maintenance

Although no system for maintenance exists on a 3-dimensional level, research papers on 3=dimensional maintenance systems have been published in the Japan Society of Civil Engineers (JSCE) and other academic studies.

(Reason why not utilized)

・ No need for 3-dimensional maintenance has become apparent from the viewpoints of engineering experts; and

・ 3-dimensional data and view should be studied to improve and increase the efficiency of daily, periodical and emergency checks and maintenance.

3. DISCUSSIONS FOR THE USE OF 3-DIMENSIONAL DATA

3.1 Circumstances on the use of 3-dimensional data

In public works in the MLIT, electronic delivery of 2-dimensional data is already applied to all the projects. Moreover, electronic data can be exchanged and shared in standardized formats (SXF or DWG), and electric delivery of 3-dimensional data is highly possible in the near future.

It is anticipated that 3-dimensional data will come into use as a result of automated construction machinery compatible with TS (total station: an electronic distance and angle measurement instrument) or GPS(Global Positioning System), and that the use of 3-dimensional data will be easily employed by CAD software in the future.

Meanwhile, related organizations and institutions are conducting research and development to standardize bridge product models, which could promote the use of 3-dimensional data on bridges and enhance the efficiency of the works.

On the other hand, the national government need to formulate rules and motivate contractors to promote the utilization of 3-dimensional data. Nevertheless, because it is impossible to quantify the work efficiency and cost reduction resulting from the use of 3-dimensional data, it is difficult for the government to apply it at present.

3.2 Need for the use of 3-dimensional data

Need for the use of 3-dimensional data has brought about the following possible options. Simple and understandable 3-dimensional data should be transferred from the design to the construction of steel bridges, and used in the CAD/CAM system. This method could make existing work (calculating 3-dimensional data from 2-dimensional data) more efficient.

In the design and construction of PC bridges, interference checks of congested reinforcing bar and construction site plans would be more visible. In terms of maintenance, 3-dimensional data for substructures, superstructure and 3-D structural configuration could be efficiently used in daily and periodic checks and urgent checks for earthquake and other accidents.

3.3 Policies for the use of 3-dimensional data

Due to the insufficient circumstances for using 3-dimensional CAD in public organizations and contractors, as well as high costs of preparing 3-dimensional data, it will not be possible to make entire structural data in 3-dimensional form. It would be more realistic to keep 3-dimensional data to a minimum: for example, structural linear data necessary for factory prefabrication of steel bridges, control points necessary for constructing substructure works, and control points for confirming structural configuration of bridges. Several methods for the use of 3-dimensional data will be discussed in the next section.

4. PROPOSED METHODS OF USING 3-DIMENSIONAL DATA

In bridge construction works, 3-dimensional data in the form of locational coordinates transferred from design to construction, and locational coordinates for measuring structural displacement during maintenance, would provide the following merits. If 3-dimensional coordinates on control points such as center points and intersecting corners of structures could be transferred from design, they would be of more benefit to construction.

At present, construction engineers obtain and confirm the coordinates of structural points by calculating from road alignments. However, if coordinates could be delivered in the form of 3-dimensional data, they would eliminate measurement errors in surveying length, height, and locations at construction sites.

The need to circulate the necessary and practical 3-dimensional data are proposed as follows.

4.1 Reference points for determining the installation positions of structures

- (Tentative name) Structural installation points
- Cases where the points are effectively used

Engineers can easily notice errors of design outputs by checking the structural installation points, thus helping to “prevent errors”. 3-dimensional visualization will enable those responsible for works to point out hazardous situations to site workers clearly, helping to “prevent construction site accidents”.

4.2 Reference points for monitoring the displacement of structures

- (Tentative name) Structural monitoring points
- Case where the points are effectively used

Engineers can easily obtain 3-dimensional positional data in order to monitor the displacement of structures after the completion of works, leading to “efficient maintenance”.

4.3 Examples of structural installation points

4.3.1 Proposal by the Japan Civil Engineering Contractors’ Association (Fig.3)

・In design, control points calculated from road alignments and transferred to construction will be center points of pier deck slabs, center points on the lateral surfaces of deck slabs, center points of girders, and center points of bearing supports.

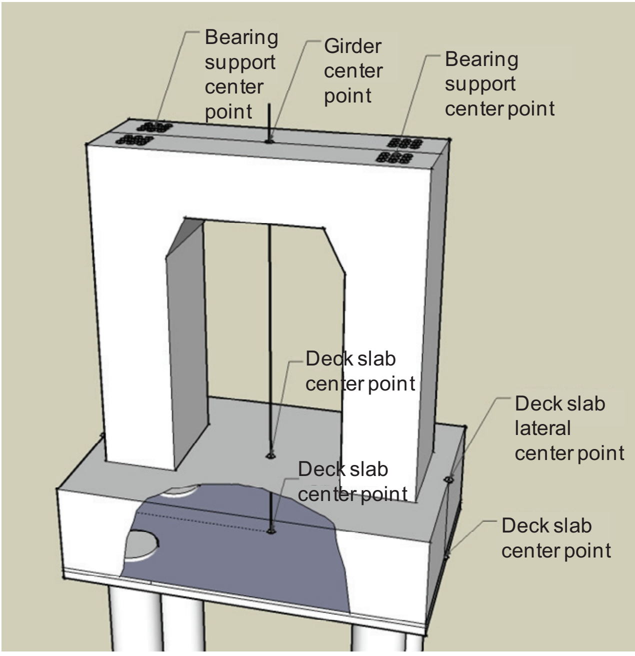

Fig. 3: Proposal by the Japan Civil Engineering Contractors' Association

4.3.2 Proposal by the Japan Bridge Association (Fig.4)

- Control points transferred from substructure works to superstructure works are bearing support center points, bearing support heights, angles, gradients and etc.

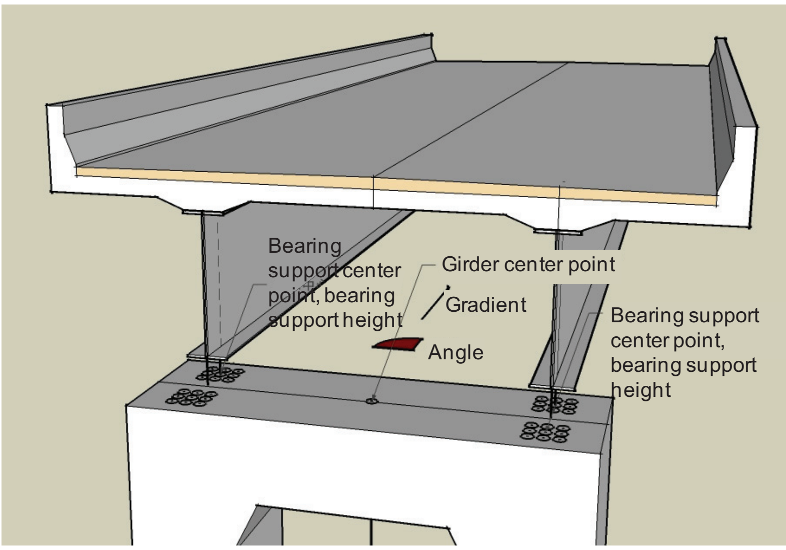

Fig. 4: Proposal by the Japan Bridge Association

4.3.3 Proposal by the Japan Bridge Association and the PC Contractors' Association (Fig.5)

・Control points transferred from design to prefabrication works (steel bridges, PC bridges) are data on structural framework, height of main girder, bearing support points, bridge surface width and etc.

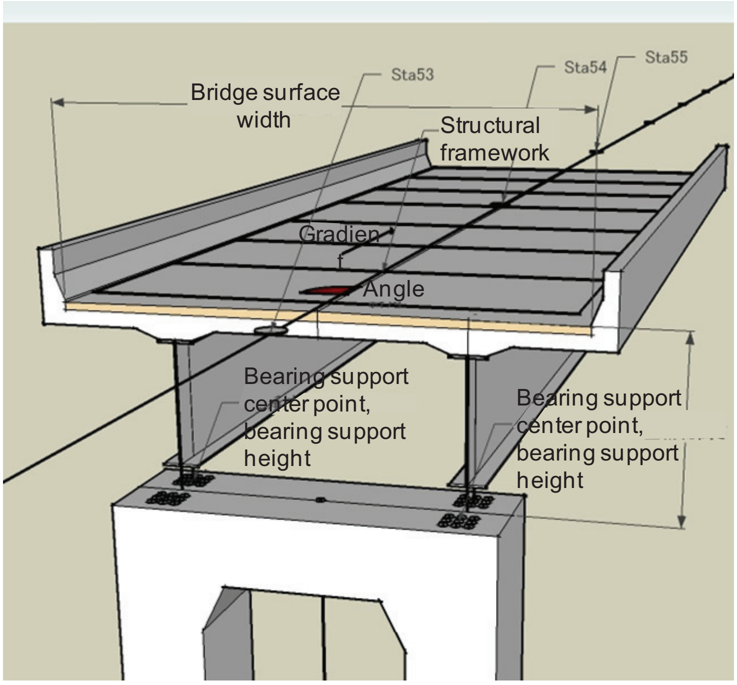

Fig. 5: Proposal by the Japan Bridge Association and the PC Contractors' Association

4.4 Examples of structural monitoring points (Fig.6)

New control points will be established from construction to maintenance, since the control points previously used cannot be confirmed by sight. These will include the lateral surfaces of bearing supports, lateral surfaces of abutments, and other points designed to determine the direction of displacement, totaling at least 3 points.

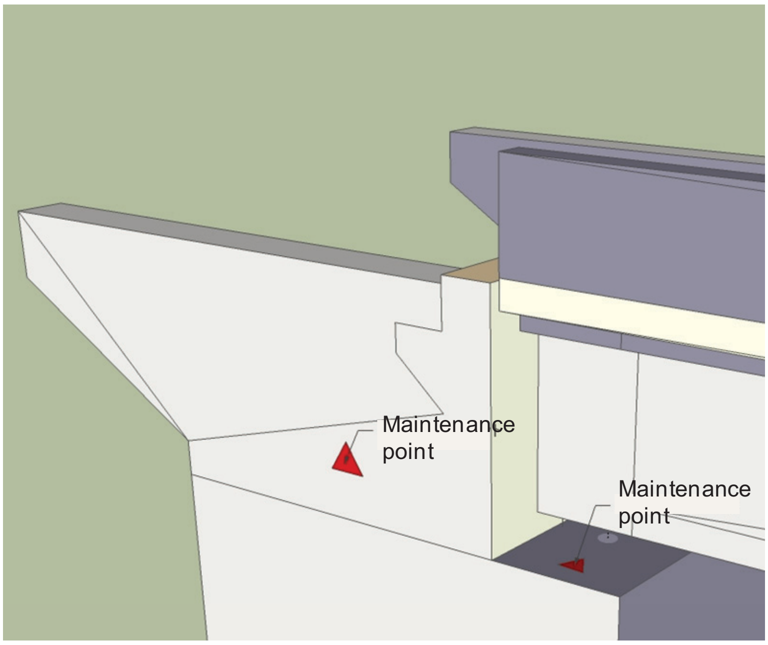

Fig. 6: Examples of structural monitoring points

4.5 Effectiveness on the use of 3-dimensional data

Work efficiencies are improved by preventing errors and construction site accidents, and providing maintenance support. Structural installation points and Structural monitoring points, as positional information on structures, will be useful in the processes of public works.

4.5.1 Preventing errors

・ Calculation errors will be discovered quickly by plotting the results of design coordinate calculations on 3-dimensional graphs.

・Coordinates resulted from the construction will be compared with design drawings to prevent errors.

・ The external shape of bridge structure works after the construction will be expressed 3-dimensionally and compared with the design results.

4.5.2 Preventing construction site accidents

・By creating 3-dimensional expressions of safety equipment, site workers will understand hazard points easily.

・Temporary construction facilities are optimized by simulation using 3-dimensional drawings.

・ Contact accidents will be prevented by confirming the distance between bridge structures and surrounding obstacles.

4.5.3 Maintenance support

・Recovery works after disasters and earthquakes will be assisted by speedy assessment of deformation.

・ Aged deformation will be checked by comparing with the results of periodic measurement.

・ The results of periodic checks will be made 3-dimensional and expressed so that they can also be understood by non-experts.

5. CONCLUSION

The study has discussed the reasons why the use of 3-dimensional data in a bridge domain could not be promoted throughout the implementation process. Recently, advanced 3-dimensional CAD systems have enabled engineers to design a type of bridge such as simple beam bridges and box girder bridges. It is theoretically proper and correct that bridges are firstly designed with 3-dimension and that its data is transferred and utilized in the construction and maintenance phases.

As mentioned in the section 2, bridge manufacturing companies have their original and special computing systems for the factory fabrication of bridges; those systems are not to be applied to bridge designs by design consultant companies and could not become widespread due to their patents. It is recommended for governments to formulate a bridge design standards to promote the development of 3-dimensional CAD software.

Under the conditions of insufficient circumstances for 3-dimensional CAD in public organizations and public companies, simple and understandable 3-dimensional works should be the first step rather than the introduction of the advanced systems. As such, the study proposes 3-dimensional data in the form of location coordinates of structural installation points and structural monitoring points as realistic and effective measurement.

This year, we will formulate a method of utilizing such 3-dimensional data as structural installation points, structural monitoring points, and external shape, taking account of on-site IT environments. We also plan to carry out experimental works in a couple of real public work projects to verify the effectiveness and problems of using 3-dimensional data. Work items will be calculating 3-dimensional data, producing bridge configuration or shapes, inspecting design contents, modifying 3-dimensional data and shapes based on site execution, and establishing installation monitoring points. Based on the outcome of the experimental works, we will identify effectiveness and possibilities of 3-dimensional data in the form location coordinates for bridge domain for the viewpoints of the improvements of work productivities.

In future, we will study a method of utilizing such 3-dimensional data as structural installation points, structural monitoring points, external shape, taking account of on-site IT environments, the effectiveness and problems when doing so. We also plan to carry out experimental works to verify the effects of using 3-dimensional data.

Acknowledgement: We extend our sincerest thanks to all of the concerned organization for their tremendous assistance.

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A REINFORCING BAR DESIGN AND CONSTRUCTION SUPPORT USING VR AND 3D CAD

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ABSTRACT: *Traditionally, reinforcing bar design of reinforced concrete (RC) structures has been represented on 2D drawings. In 2D drawings, main reinforcing bars and sub reinforcing bars may not be easily distinguished. Thus, at construction site, construction workers may misunderstand the important reinforcing bars. In the lifecycle (design, construction, maintenance) of RC structures, currently, many problems can be identified. These problems are attributed to the usage of 2D drawing in design. Thus, we developed a 3D reinforcing bar design support approach with Revit Structure (a 3D CAD system) and NavisWorks (a VR software) of Autodesk. We proposed a new direct 3D design approach and described an application case to consider the feasibility.*

KEYWORDS: *VR, 3D CAD, Reinforcing Bar, Reinforced Concrete, Clash Check.*

1. INTRODUCTION

In the construction industry, cost reduction and quality assurance are crucial issues, and thus, information technology is expected to play a significant role and has been investigated in multiple disciplines. Especially, 3D model-based design and construction, as known as Building Information Modeling (BIM), has attracted much attention recently (Barak et al., 2007; Gu et al., 2008).

Traditionally, reinforcing bar design of reinforced concrete (RC) structures has been represented on 2D drawings, which are useful for illustrating detailed reinforcing bar situations in a simple and quick way. However, since reinforcing bars are often highly densely arranged partially due to the revisions of seismic design codes in Japan, there are reported troubles such as reinforcing bars cannot be properly arranged as indicated by the designer or concrete cannot be cast appropriately under the dense reinforcing bars. The most influential cause of these problems is the design method relying n 2D drawings. Therefore, in this research, to solve such problems, 3D reinforcing bar design and construction support approach (Yabuki and Shitani, 2004) was developed based on Building Information Modeling (BIM) using Virtual Reality (VR) and 3D CAD (Fujisawa et al., 2009; Kobayashi and Igarashi, 2009).

2. CURRENT PROBLEMS RELATED TO REINFORCING BARS

In the lifecycle (design, construction, maintenance) of RC structures, currently, the following problems can be identified.

2.1 Problems due to the Design

The following problems are often seen because of the usage of 2D drawing system in design of RC structures.

- As each member is drawn in each drawing, when the members are superimposed or connected, clash of members often occur.
- In 2D drawings of reinforcing bars, the diameter of each reinforcing bar is usually not illustrated, and each bar is represented by a single line. Therefore, many clash cases of reinforcing bars occur.
- In 2D drawings, main reinforcing bars and sub reinforcing bars may not be easily distinguished. Thus, at

construction site, construction workers may misunderstand the important reinforcing bars.

2.2 Problems in Construction

The following problems are seen in construction.

- At the connection of head of piles and underground beams or box culverts, reinforcing bars may not be placed as indicated in the 2D drawings.
- Additional supplementary reinforcing bars may be placed at a pitch designated in the drawing at hunches and opening of a box culvert and other special sections.
- Since the procedure of placing reinforcing bars may not be considered, reinforcing bars, especially stirrups, may not be placed properly.
- The number of good reinforcing bar placing workers is decreasing (Yabuki and Li, 2007).

2.3 Problems in Construction Management

The following problems are often heard at construction sites.

- Contractors inspect whether the placement of reinforcing bars are done properly with the owner engineer's presence before casting concrete, checking drawings and taking pictures, which takes time and effort.
- If they find reinforcing bars which cannot be placed actually, they have to change design, which takes time and effort.
- As densely placed reinforcing bars are increasing, it is difficult to confirm that concrete is properly cast under the dense reinforcing bars.

2.4 Problems in Maintenance

- Although design drawings exist, as built drawings are not provided. Thus, if cracks in the concrete member are identified, it is difficult to precisely locate the reinforcing bars in the concrete.
- As precise reinforcing bars locations cannot be identified, main reinforcing bars are sometimes cut in the borehole inspection.

3. 3D REINFORCING BAR DESIGN SUPPORT APPROACH

3.1 Overview of the Approach

Most problems described in section 2 are due to the usage of 2D drawing in design. Thus, we developed a 3D reinforcing bar design support approach with Revit Structure (a 3D CAD system) and NavisWorks (a VR software) of Autodesk. In this approach, the user, first, makes a 3D reinforcing bar model from 2D drawings, using Revit Structure, as shown in Figure 1. Then, the DWF data of the 3D model is exported to NavisWorks, by which the user checks clash of reinforcing bars. If a clash is detected, the design is modified in the 3D model of DWF, using Revit Structure. Then, the same check is done until no clash is detected. In NavisWorks, the procedure of how to place reinforcing bars can be checked as well.

3.2 Strengths and Limitations of the Approach

3.2.1 Strengths of the Approach

- Since places of reinforcing bars can be confirmed and clash detection can be performed, mistakes in arranging complex reinforcing bars decrease.
- From the 3D model, the user can make a precise bill of quantity of reinforcing bars easily, which leads to more precise cost estimation.
- Placing procedure of reinforcing bars can be investigated easily, which can decrease mistakes and thus, quality of RC structures can be improved.

- Since the cover, pitch, diameter of reinforcing bars are often modified according to the actual construction conditions, the changes can be checked and verified by using this system.

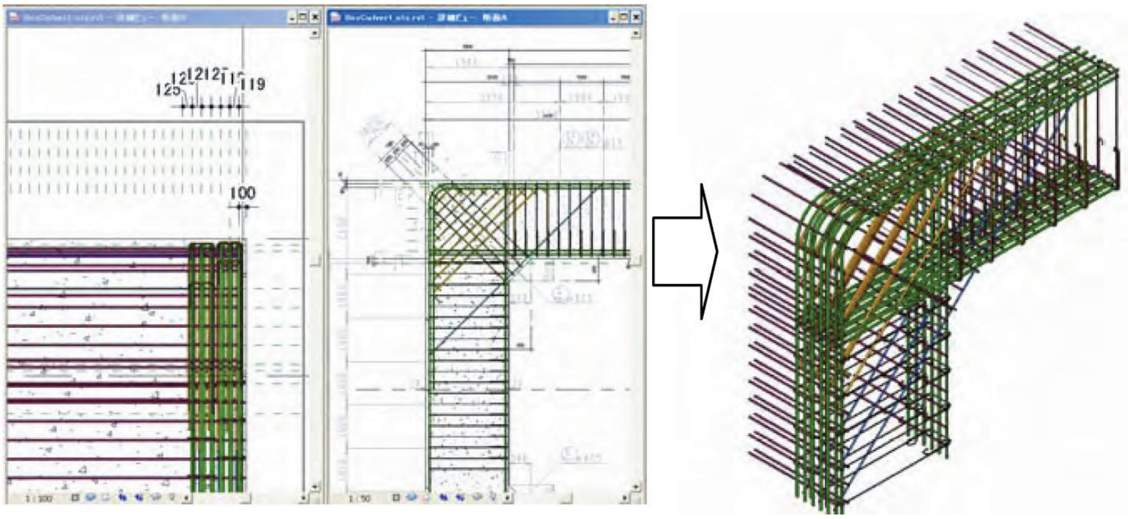

FIG. 1: Making a 3D reinforcing bar model from 2D drawings using the proposed approach

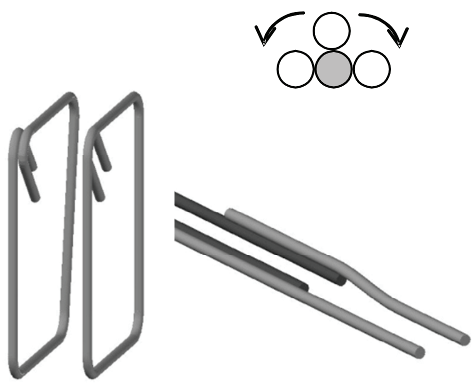

FIG. 2: Different kinds of placement of reinforcing bars with 3D consideration

3.2.2 Limitations of the Approach

- As some particular 3 dimensional considerations are not given, multiple different design cases can be generated, depending on the engineer, as shown in Figure 2.
- Precision at the construction site is different from that of 3D CAD.
- It is difficult to check whether concrete can be filled properly under densely placed reinforcing bars.

4. NEW DIRECT 3D DESIGN APPROACH

The limitations of the 3D system described in the previous section are due to the adopted method, in which 2D drawings are drawn first and then, 3D model is generated from the 2D drawings. If members are designed directly using the 3D system without drawing 2D plans anymore, various limitations can be eliminated. We are trying to adopt a new direct 3D design approach instead of the traditional 2D drawing method, using the 3D reinforcing bar design support system.

4.1 Overview of the New Direct 3D Design Approach

The flow of the new direct 3D design approach is as follows.

1) Preparation: Determining input data such as soil properties, loads, etc., for analysis.

2) Assumption of structural type: Making an assumption of the structural type and size of each member, based on the experience and previous design examples.

3) Creation of an analysis model: Making a 3D analysis model for simulation, including soil properties, loads, etc., using Revit Structure.

4) Analysis: Exporting the 3D analysis model data to the structural analysis software packages such as SAP 2000 and running the program. The output of the analysis is represented in the 3D model.

5) Determination of the number of reinforcing bars and their sizes.

6) Arrangement of reinforcing bars in the 3D model.

7) Clash detection: Exporting the 3D model data to VR software such as NavisWorks. In NavisWorks, clash can be detected.

If a clash is detected, the designer has to move one or more reinforcing bar(s). In that case, the following two conditions must be satisfied.

- The cover must be equal to or greater than the required value.
- The pitch must be equal to or less than the required value.

Since the location of main reinforcing bars is determined from the shape of the member, main bars do not usually clash with other members. However, stirrups tend to do if they are densely arranged. In that case, stirrups can be moved somewhat. Stirrups of columns can be moved vertically, while those of beams horizontally.

4.2 Application of the New Approach

In order to investigate the applicability of this approach, a rigid RC frame railway elevated bridge was selected (Figure 3). In the design of such viaducts, a clash of reinforcing bars occurs if the height of both longitudinal and lateral beams is the same (Figure 4). This problem can be solved by modifying the beams, based on their mutual relationship.

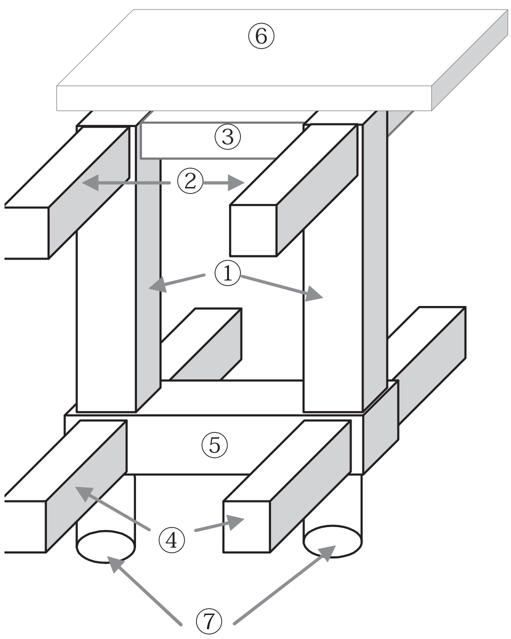

FIG. 3: A rigid RC frame railway elevated bridge

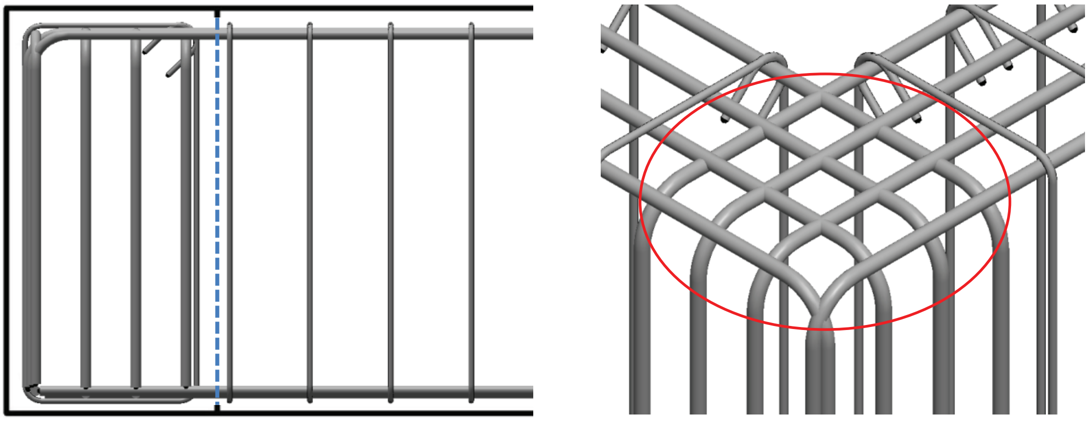

FIG. 4: Clash of reinforcing bars in the connection of longitudinal and lateral RC beams

In the present Japanese railway field, design of elevated bridges is based on the following concept. In Japan, where large earthquakes occur frequently, seismic performance has high priority. It would be extremely expensive if a structure is designed so that it would never collapse even if a very strong earthquake occurs near the site. Thus, more reasonable approach is adopted such as some type of member should be collapsed if a large earthquake occurs so that other parts should be maintained. To have a weak part in the structural system is similar to have a fuse in the electric system. In the elevated bridge system, since columns do not directly support the railway and are above ground, it would be easier to repair compared to beams or footings. Thus, columns are designed so that they collapse first before beams and other members do. So, after executing analysis, the sequence of section design is 1) determine the column section, 2) determine the longitudinal beam section, 3) determine the lateral beam section. Based on the design concept described above, the new 3D design approach can be applied as the following.

1) Assume section size of each member and properties of each member and soils. Generally, the width of longitudinal beams is designed smaller than that of columns, and the width of lateral beams is larger than that of columns. The height of longitudinal beams is greater than that of lateral beams.

2) Execute structural analysis.

3) Design the section of columns, based on the result of the analysis (Figure 5).

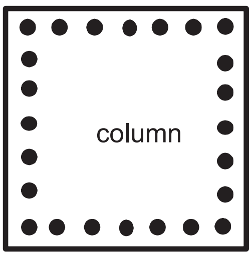

FIG. 5: Arrangement of reinforcing bars for a column

4) Design the section of longitudinal beams, based on the number of reinforcing bars in the column and the analysis result (Figure 6).

5) Design the section of lateral beams. The height of the lateral beam is smaller than that of longitudinal beam. Place the main reinforcing bars of the lateral beam inside of those of longitudinal beam (Figure 7).

6) Make a 3D model of the reinforcing bars (Figure 8).

7) Export the 3D model data to VR software and check clash.

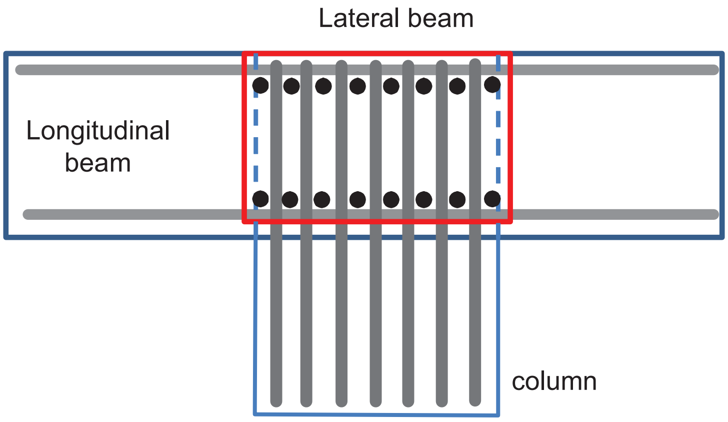

FIG. 6: Design of a longitudinal beam

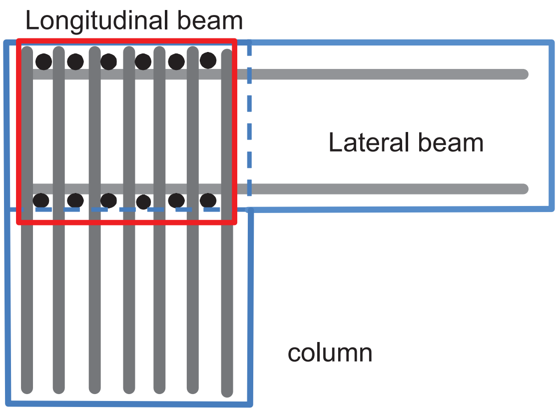

FIG. 7: Design of a lateral beam

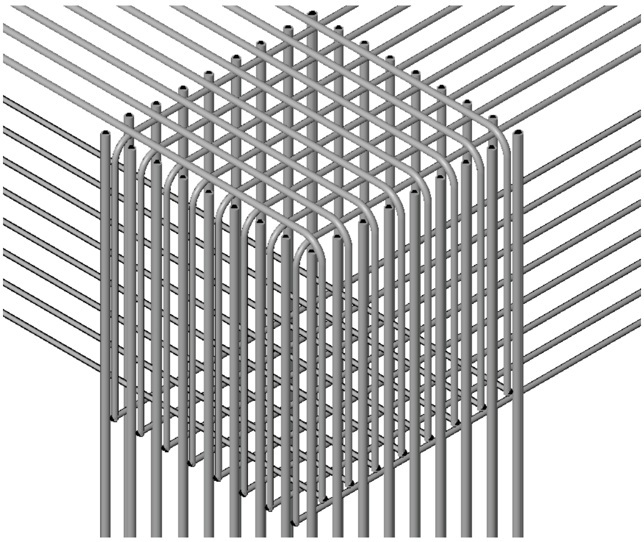

FIG. 8: 3D model of reinforcing bars

5. CONCLUSION

In the design of reinforced concrete structures, engineers still draw 2D plans. Many problems occur due to the use of 2D drawings. Thus, we had proposed a 3D reinforcing bar design support approach, using a 3D CAD and VR systems. We evaluated this approach and pointed out strengths and limitations. In this paper, we proposed a new direct 3D design approach and described an application case to consider the feasibility. As a future work, we are investigating more detailed figures and properties of reinforcing bars, such as fixing length, shape and location of fixing,

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VII. 3D SCANNING AND MODELING

SEMI-AUTOMATIC 3D RECONSTRUCTION OF PIECEWISE PLANAR BUILDING MODELS FROM SINGLE IMAGE

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ABSTRACT: *This paper presents a novel algorithm that enables the semi-automatic reconstruction of man-made structures (e.g. buildings) into piecewise planar 3D models from a single image, allowing the models to be readily used for data acquisition in 3D GIS or in other virtual or augmented reality applications. Contrary to traditional labor intensive but accurate Single View Reconstruction (SVR) solutions that are based purely on geometric constraints, and recent fully automatic albeit low-accuracy SVR algorithms that are based on statistical inference, the presented method achieves a compromise between speed and accuracy, leading to less user input and acceptable visual effects compared to prior approaches. Most of the user input required in the presented approach is a line drawing that represents an outline of the building to be reconstructed. Using this input, the developed method takes advantage of a newly proposed Vanishing Point (VP) detection algorithm that can simultaneously estimate multiple VPs in an image. With those VPs, the normal direction of planes which are projected onto the image plane as polygons in the line drawing can be automatically calculated. Following this step, a linear system similar to traditional SVR solutions can be used to achieve 3D reconstruction. Experiments that demonstrate the efficacy and visual effects of the developed method are also described.*

KEYWORDS*: Computer Vision, J-linkage, Vanishing Point, Single View Reconstruction, Image Based Modeling, Virtual Reality, Augmented Reality*

1. INTRODUCTION

Single view reconstruction (SVR), as one of the image based modeling (IBM) techniques, has been extensively studied from both the side of computer graphics and computer vision. It could help us in the situation when we want to recover a 3D scene while having only one image at hand, which means the traditional multiple view reconstruction approaches in either close-range photogrammetry or computer vision cannot be applied.

In the past, the main stream of SVR algorithms focused purely on the geometric structural information that one can infer from a single view of the scene as apriori knowledge. The key idea of these approaches is that through this knowledge provided by users, a scene's 3D structure can be calculated by geometry theorems. "Tour into the picture (TIP)", proposed by computer graphic researchers (Youichi et al., 1997), is probably the earliest solution taking advantage of vanishing point (VP) to recover 3D structures, though the assumption that the picture has only one VP limits its application. Almost at the same time, computer vision researchers from University of Oxford conducted a series of research works on single view metrology (Criminisi et al., 2000, Liebowitz and Zisserman, 1999), introducing the theory of projective geometry which laid a solid mathematical foundation for SVR. Later, researchers from INRIA proposed a SVR algorithm based on user-provided constraints such as coplanarity and perpendicularity to form a linear system (Sturm and Maybank, 1999). Compared with other similar methods (Grossmann and Santos-Victor, 2005, van den Heuvel, 1998), Sturm's algorithm is regarded as one of the most flexible ones and will be the basis of SVR method in this paper.

Recently, a group of computer vision researchers have shifted their attention from geometry to machine learning to develop new SVR algorithms. Arguing the traditional SVR to be labor-intensive, Hoiem et al. from Carnegie

Mellon University proposed a fully automatic algorithm that folds the image segments into a pop-up model (Hoiem et al., 2005). Similar algorithms include dynamic Bayesian network SVR of indoor image (Delage et al., 2006) and Markov Random Field (MRF) SVR (Delage et al., 2007, Saxena et al., 2006). Although these algorithms can achieve full automation, their reconstructed 3D model's visual effects still need to be improved for virtual reality or augmented reality applications.

In this research, inspired by the idea of utilizing machine learning algorithms to deduce some of this geometric structural information so as to reduce a part of labor burden on users, we integrate a newly proposed line segment detector(LSD) (Grompone et al., 2010) and a robust multiple structures estimator (Toldo and Fusiello, 2008) into Sturm's SVR algorithm. It will first be compared with traditional methods in section 2 and then be explained in detail in section 3. Some of the experimental results are given in section 4, followed by summarization of this paper's contributions and a conclusion.

2. OVERVIEW

2.1 Traditional SVR

Figure 1 presents the general schema of traditional SVR algorithms (*FIG. 1*).

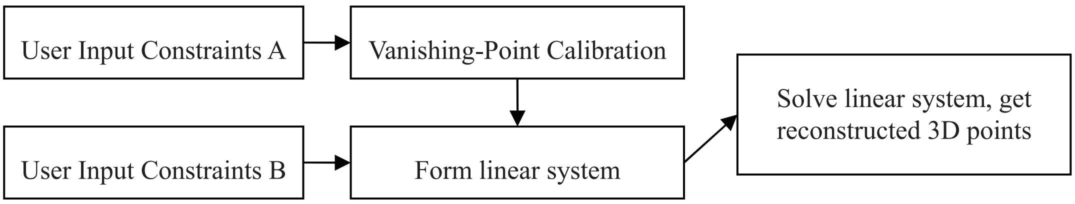

FIG. 1: General schema of traditional SVR algorithms

Constraints A provided by users are usually parallel constraints, i.e. which image line segments' 3d object space correspondences are with the same direction. In fact, this process equals to a manual classification on line segments - line segments whose 3D correspondences with the same direction are grouped into a same class. Each group of line segments' extended lines should intersect (ideally if without measurement errors) at the same point in the image plane, i.e. the vanishing point. If three vanishing points are found whose corresponding 3D directions are perpendicular to each other, the camera's principle point and focal length can then be calculated (Caprile and Torre, 1990).

Constraints B are mainly coplanar constraints in Sturm's methods. By specifying which image points' 3D correspondences lie on the same 3D plane, whose normal direction is also specified through combination of any two vanishing points, a linear system could then be formed and solved. The solution of that linear system contains each image point's depth, which also means the 3D structure of the scene.

2.2 Semi-auto SVR

Compared with traditional SVR approaches, our method tries to minimize the user input by taking advantage of a multiple structures estimator called j-linkage (*FIG. 2*).

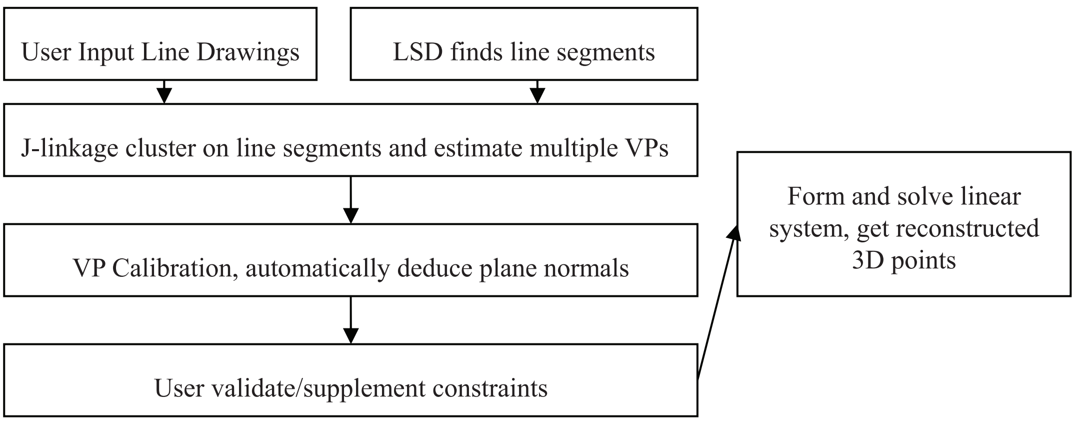

FIG. 2 Schema of our semi-automatic SVR algorithms

As we can see from *FIG. 2*, the user input constraints A and B in *FIG. 1* are replaced with "user input line drawings" and "user validate/supplement constraints". This means the parallel constraints and 3D plane's normal directions will be automatically deduced instead of being specified by users. Thus users will only need to sketch out the building to be reconstructed from a single image, leave all the computation to the algorithms, then check and validate the constraints reasoned by the algorithms, and supplement other constraints if necessary. This will then allow the reconstructed 3D model to be manipulated on the computer.

2.3 Global Assumptions

Before we explain our semi-automatic SVR algorithm in detail, there are several global assumptions that must be addressed:

- *No radial distortion.* The image used in our algorithm should already be corrected for radial distortion, or the radial distortion parameter must be small enough to be ignored. Generally, this assumption can be easily met, as long as we do not use special lens (such as wide-angle lens or fish-eye lens) and the building to be reconstructed lies in the middle of the image.

- *Camera's principle point is located at the image center, its aspect ratio is 1 and skew factor is 0.* This assumption means the calibration matrix of the camera has the form (with known image width W and height H, while focal length f as the only unknown parameter to be calibrated)

$$\mathbf{K} = \begin{bmatrix} f & 0 & W/2 \\ 0 & f & H/2 \\ 0 & 0 & 1 \end{bmatrix}, \tag{1}$$

  Although the assumption that principle point locates at the center of the image seems to be too strong, considering the manufacturing quality of digital consumer cameras, experiments have shown that this error will not induce much effect on the reconstructed model's visual effects.

- *Camera coordinate system is our world coordinate system.* This means we ignore all the six exterior parameters, i.e. the translation and rotation of the camera, so the projection matrix of the camera will be of the following form:

$$\mathbf{P} = \mathbf{K}[\mathbf{I} \mid \mathbf{0}].$$

  Also our reconstructed 3D point is up to a scale factor, meaning we are only concerned about its shape but ignore its size. In many virtual reality applications, this is sufficient.

- *Manhattan World Assumption (Coughlan and Yuille, 1999).* This assumption is saying that a natural reference frame is given in most indoor and outdoor city scenes, for they are based on a Cartesian coordinate system. Under this assumption, we could use vanishing-point calibration algorithm to recover the focal length of the camera.

3. ALGORITHM MODULES

Our proposed SVR algorithm consists of six sub-procedures, as can be seen from *FIG. 2*. Each module will be described in detail in the following sections.

3.1 User Input

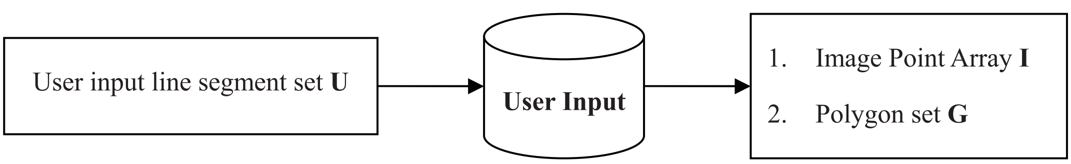

FIG. 3 Input and output(I/O) of user Input module

Most of the user interactions in our method are handled in this module. It enables users to sketch out the skeleton of the building with a set of line segments $\mathbf{U} = \{l_i = (x_i^s, y_i^s; x_i^e, y_i^e), i = 1, 2, \cdots, N_u\}$, in which a line segment l is represented by its two end points $(x^s, y^s), (x^e, y^e)$.

The data structure in this module enables applying computational geometry algorithms, in order to output an image point array $\mathbf{I} = \{p_i = (x_i, y_i) \mid \forall i \neq j, p_i \neq p_j\}$, whose elements all come from end points of line segments in $\mathbf{U}$, and a set of polygons $\mathbf{G}$, in which each polygon is represented by an ordered index array of image point array $\mathbf{I}$.

To reconstruct the output image point array's 3D correspondence will be our SVR method's final objective. Along with the topological information stored in polygon set $\mathbf{G}$, one can easily get the building's 3D model.

3.2 Line Segment Detector

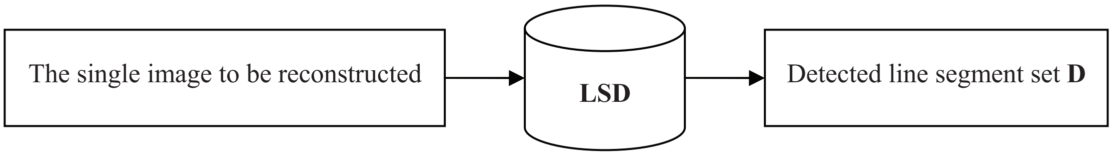

FIG. 4 I/O of LSD module

Similar to line segment set $\mathbf{U}$ in *FIG. 3*, LSD module's output $\mathbf{D}$ are also line segments represented by end points.

However, different from the traditional edge detection method which first uses Canny edge detector followed by a series of complicated post-processing (Tardif, 2009), the newly proposed Line Segment Detector (LSD) (Grompone et al., 2010) provides us a fast, simple and easy-to-use interface which also gives accurate results yet requires no parameter tuning.

3.3 J-linkage

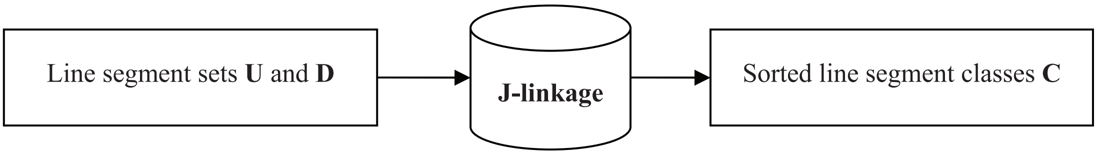

FIG. 5 I/O of J-linkage module

J-linkage module wraps a recently proposed robust multiple structures estimator (Toldo and Fusiello, 2008), taking as input line segment sets $\mathbf{U}$ and $\mathbf{D}$ in the first two modules, outputting sorted line segment classes $\mathbf{C} = (C_1, C_2, \cdots, C_{Nc}), \forall i < j, |C_i| > |C_j|$, a ordered array of line segment sets sorted by their sizes, in which each element C_i is a set of line segments coming from $\mathbf{U}$ and $\mathbf{D}$ where the operator $|C_i|$ represents the number of elements of the set. Ideally, each class of line segments should correspond to a vanishing point and hence a 3D direction in object space.

The j-linkage estimator was carefully designed to robustly estimate models with multiple instances in a set of data points. This leads us to the Hough Transform. However, quantization of the parameter space, the basis of Hough Transform, will inevitably cause many of its shortcomings such as inaccuracy and the choice of parameterization of models. Enlightened by a popular parameter estimation approach in computer vision, RANSAC (Fischler and Bolles, 1981), and the conceptual representation from pattern recognition, the j-linkage estimator also needs no parameter tuning. Besides estimation of multiple model instances, it could classify all data points according to the best model instance they fit, which will be of great use in our normal deduction module.

In our algorithm, the "data points" for J-linkage are line segments, from both user drawn and LSD detection, and the "model instances" are vanishing points. Line segments through different vanishing points are classified into different line segment groups. In order to apply j-linkage estimator, three functions have to be defined:

1. function W that solves model parameters from minimal number of data points
2. function F that estimates the distance (or fitness) of a given model and a data point
3. distance function D of a pair of data points

For function W, one can easily figure out that the minimal number of data points (i.e. line segments) needed to solve the model parameters (vanishing point's coordinate in image plane) is two. By using homogeneous coordinates, it can be written as (operator $\times$ means cross product of two 3D vectors)

$$W(l_i, l_j) = \frac{l_i \times l_j}{\|l_i \times l_j\|}, l_k = (x_k^s, y_k^s, 1) \times (x_k^e, y_k^e, 1), k = i, j. \tag{2}$$

Function F, as the discussion in literature (Tardif, 2009), could be well approximated by the distance of the line segment's end point and the line through the vanishing point and the mid-point of the line segment (*FIG. 6*), as below (v is homogeneous coordinate of a vanishing point, l is a line segment represented by two end points and $dist$ is the distance function of 2d point to line):

$$F(v, l) = dist(m, (x^s, y^s)), m = v \times (\frac{x^s + x^e}{2}, \frac{y^s + y^e}{2}, 1). \tag{3}$$

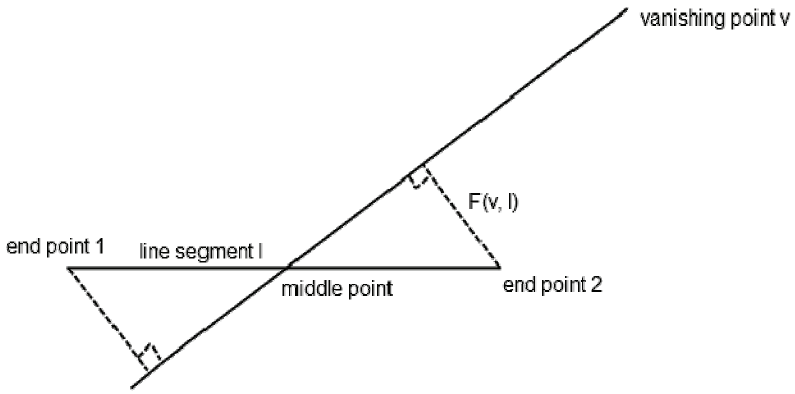

FIG. 6 Approximation of fitness function F

Function D, to be used at the random sampling step in j-linkage estimator, was not described in the literature (Tardif, 2009). According to the key idea of j-linkage and our experiments, it could also be well approximated as the distance of two line segments' middle points:

$$D(l_i, l_j) = \|m_i - m_j\|, m_k = (\frac{x_k^s + x_k^e}{2}, \frac{y_k^s + y_k^e}{2}), k = i, j \tag{4}$$

3.4 Vanishing-point Calibration

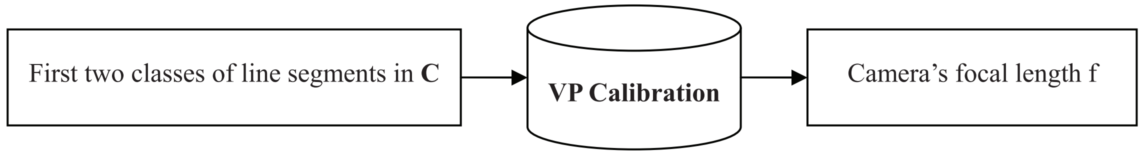

FIG. 7 I/O of vanishing-point calibration module

In this module, based on the above mentioned Manhattan world assumption, we further assume that the first three largest line segment classes in size should correspond to the three coordinate basis directions in the Manhattan reference frame, which is to say their corresponding 3D directions are perpendicular with each other. With this assumption which is often valid in most of the urban outdoor and indoor scenes, there is no need for users to specify which three classes of line segments form a orthogonal coordinate system.

Hence the vanishing point calibration could be automatically completed. Firstly, for each class of line segments, estimate the best fit vanishing point through:

$$\begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ \vdots & \vdots & \vdots \\ a_n & b_n & c_n \end{bmatrix} \cdot \begin{bmatrix} v^x \\ v^y \\ v^w \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, (a_i, b_i, c_i) = \frac{(x_i^s, y_i^s, 1) \times (x_i^e, y_i^e, 1)}{\|(x_i^s, y_i^s, 1) \times (x_i^e, y_i^e, 1)\|}, i = 1, 2, \cdots, n, \tag{5}$$

In equation (5), (v^x, v^y, v^w) is the homogeneous coordinate of the vanishing point v, and could be solved using the singular value decomposition (SVD) algorithm. After the first two vanishing points v_1, v_2 are estimated from the two classes, the camera focal length f could be calculated by the equation (Caprile and Torre, 1990):

$$f = \sqrt{-(x_1 - \frac{W}{2})(x_2 - \frac{W}{2}) - (y_1 - \frac{H}{2})(y_2 - \frac{H}{2})}, \tag{6}$$

In (6) $x_i = v_i^x / v_i^w, y_i = v_i^y / v_i^w, i = 1, 2.$

3.5 Normal Deduction

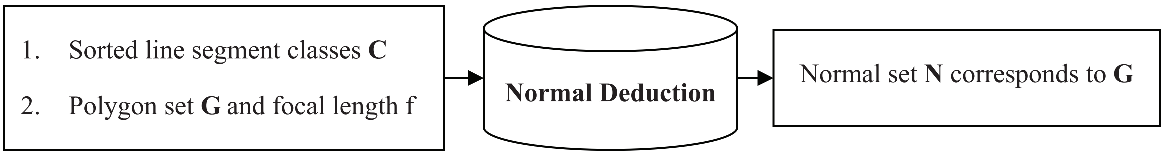

FIG. 8 I/O of normal deduction module

Normal deduction is essential in many SVR algorithms (Grossmann and Santos-Victor, 2005, Sturm and Maybank, 1999). One of our semi-automatic SVR algorithm's features is that, in this module it could automatically calculate and assign normal directions for each of the 3D planes which are projected onto the image plane as polygons, while in traditional SVR algorithms they has to be specified all by users manually.

The basic idea of this module is the fact that with two known 3D directions parallel to a 3D plane, the normal direction of the plane could be calculated, i.e. their cross product. While in camera geometry, 3D directions correspond to vanishing points in image plane, thus one can get the following equation (Sturm and Maybank, 1999):

$$\mathbf{n} = \frac{\mathbf{K^T l}}{||\mathbf{K^T l}||}, \mathbf{l} = \mathbf{v_1} \times \mathbf{v_2}, \tag{7}$$

In (7), $\mathbf{n}$ is the unit normal direction, $\mathbf{K}$ is camera calibration matrix from equations (1) and (6) and $\mathbf{v_1}, \mathbf{v_2}$ are homogeneous coordinates of two different vanishing points whose corresponding 3D directions are parallel to the plane with normal $\mathbf{n}$.

Once we know how to calculate the normal direction from the 3D plane's two different vanishing points, the only computation remaining is how to automatically find two vanishing points of a 3D plane (projected onto the image plane as polygon). With the help of some simple computational geometry algorithms, and the assumption that each 3D plane has plenty of parallel lines with at least two different directions, our normal deduction algorithm could be described in the following pseudo-code:

For each polygon **g** in polygon set **G**

    From within line segment set **U** and **D**, put all line segments that lie within **g** into a new line segment set **T**

    Find two line segment classes C_i, C_j, such that among all classes, $|C_k \cap T|, k = i, j$ are the two largest

    Estimate two vanishing points v_i, v_j from C_i, C_j by equation (5)

    Calculate the unit normal direction $\mathbf{n}$ by equation (7), which is the deduced normal for polygon **g**

Certainly, under some special cases, those assumptions do not hold, so errors may happen and some of the calculated normal directions may go wrong. That is why there needs to be a validation step for users to check those errors (*FIG. 2*), and this is still much easier than the traditional method.

3.6 Sturm's SVR

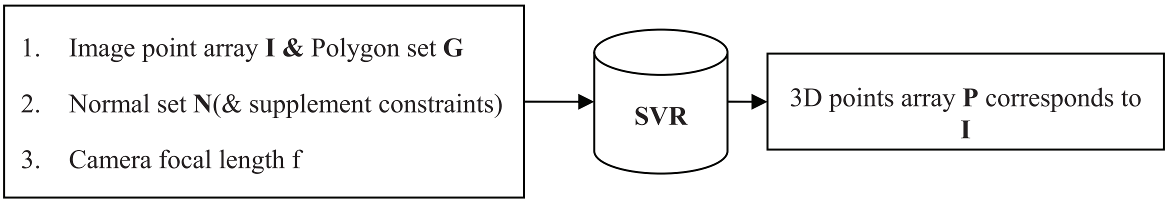

FIG. 9 I/O of SVR module

This module is basically the same as Sturm's SVR algorithm (Sturm and Maybank, 1999). However, we add another kind of constraint into their original linear system---parallelogram constraint. The purpose of this is to make our algorithm more flexible, for parallelograms are easy to find on buildings and there is no need to use normal information when adding this constraint into the system.

The parallelogram constraint is based on the geometry fact that if four 3D points $\mathbf{P_1}, \mathbf{P_2}, \mathbf{P_3}, \mathbf{P_4}$ could successively form a parallelogram, they must satisfy the equation

$$\mathbf{P_1} + \mathbf{P_3} = \mathbf{P_2} + \mathbf{P_4}. \tag{8}$$

Using the same parameterization as Sturm's method, if there are N image points to be reconstructed, M polygons, and K parallelograms, the linear system should be

$$\begin{pmatrix} \underset{M\times M}{\mathbf{D}} & \underset{M\times N}{\mathbf{C}} \\ \underset{N\times M}{\mathbf{C}^T} & \underset{N\times N}{\mathbf{L}} \\ \underset{3K\times M}{\mathbf{0}} & \underset{3K\times N}{\mathbf{E}} \end{pmatrix} \begin{pmatrix} \underset{M\times 1}{\mathbf{d}} \\ \underset{N\times 1}{\lambda} \end{pmatrix} = \begin{pmatrix} \underset{M\times 1}{\mathbf{0}} \\ \underset{N\times 1}{\mathbf{0}} \\ \underset{3K\times 1}{\mathbf{0}} \end{pmatrix}, \tag{9}$$

in which $\mathbf{E}\lambda = \mathbf{0}$ expresses the parallelogram constraint and matrices $\mathbf{D}, \mathbf{C}, \mathbf{L}$ have the same meaning as Sturm's method.

4. EXPERIMENTS

We implement the above semi-automatic SVR algorithm in Windows XP platform using C++. The LSD module is available provided by its author at http://www.ipol.im/pub/algo/gjmr_line_segment_detector/. The original j-linkage module is also provided by its author at http://www.toldo.info/roberto/?page_id=46. Some of the experiment results are shown below.

FIG. 10 User inputs a set of line segments (drawn in green)[1] (Denis et al., 2008)

FIG. 11 LSD and J-linkage output, the first three classes are drawn in red, green and purple respectively

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[1] This picture comes from York Urban Database provided by Denis et al. 2008

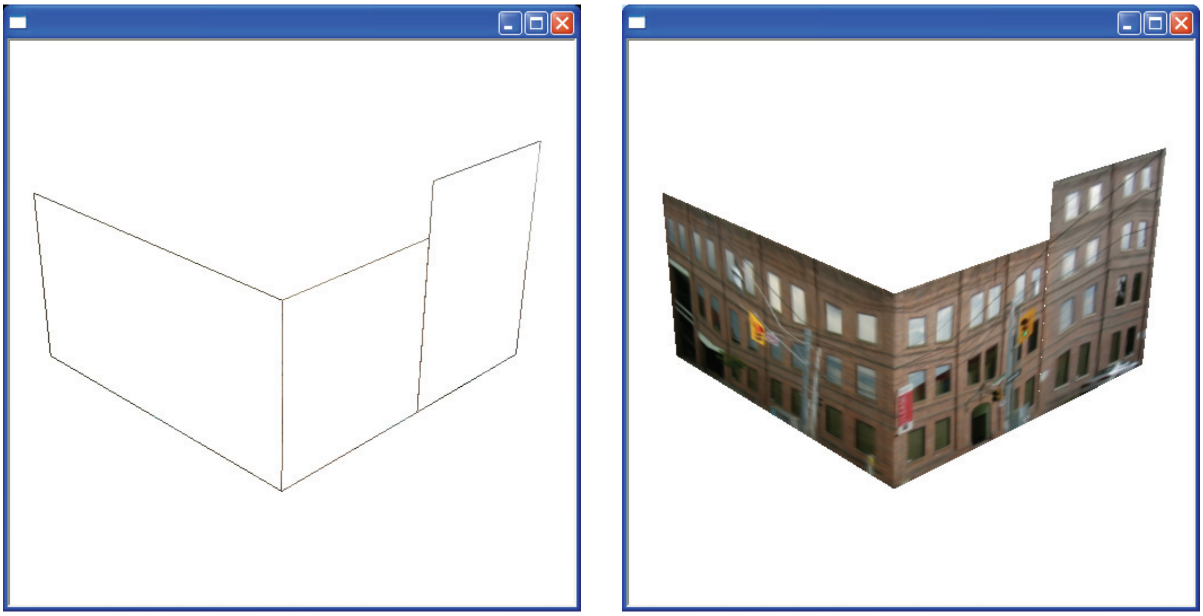

FIG. 12 Reconstructed 3D model in wire-frame and surface mode

FIG. 13 Another reconstructed 3D model

5. CONTRIBUTIONS

The main contributions of this paper are summarized as follows:

- Introducing LSD and J-linkage algorithms into SVR, under certain assumptions, the automation of vanishing point calibration and 3D plane normal deduction are made possible.
- Taking advantage of a new kind of constraint—parallelogram, integrating it into the Sturm's SVR linear system, our SVR algorithm becomes more flexible.

6. CONCLUSIONS

This paper presented a novel SVR algorithm. By utilizing a newly proposed line segment detector and a robust multiple structures estimator, we introduced automatic vanishing point calibration and 3D plane normal deduction into the algorithm, thereby reducing much of the user interaction burden. Also, we extended the traditional SVR algorithm by adding parallelogram as a new kind of constraint, which does not need normal direction to form the SVR linear system. In the future we plan to consider additional approaches to make this automation more robust.

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Shape Measurement Planning of Outdoor Constructions with Mathematical Programming and Its Practical Applications

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ABSTRACT: *A 3D scanner is a surface imaging system which is based on accurate distance measurement by electro-optical distance measurement. Lately, this type of device has been extending its measurement range to facilitate digitizing "existing" constructions, and used for examining and designing landscapes of towns and preserving cultural sites as well. One of the most difficult problems to collect complete surface data of outdoor constructions is to avoid self and mutual occlusions. If we want to collect complete data for covering whole surfaces of the constructions, then we have to measure from multiple points usually. However, examining multiple surface visibilities relative to variable multiple viewpoints is a complicated problem. Moreover, multiple measurements require plenty of time and labor, and each measurement gives a data set consisting of hundreds of millions of 3D points to be processed for further computations. So it is very important to make an effective measurement plan a priori for avoiding redundancy for both labor and computational costs. For such a problem, we have been developing a method to determine optimal measurement points with mathematical programming lately. This approach is based on a 2D diagram that would be available as a ground plan or a geological plan of the target area beforehand. To make a view plan, two mathematical programming models are proposed: one is to find the least number of measurements for recording all the walls of constructions, and the other is to determine measurement points to maximize scanning density. Both problems are formulated as integer programming problems, and thus global optimal solutions can be conveniently computed by a general-purpose solver. The numerical experiments for practical applications show that our method is flexibly adaptive for the physical conditions and effective for solving large-scale problems for finding global optima in practical computing time.*

KEYWORDS*: 3D scanner, Shape Measurement, Mathematical Programming, View Planning.*

1. Introduction

A 3D scanner is a surface imaging system which is based on accurate distance measurement by electro-optical distance measurement. We can obtain surface data of objects by performing a number of independent measurements, and a 3D image emerges by merging these data. Lately, this type of device has been extending its measurement range to facilitate digitizing "existing" constructions, and used for examining and designing landscapes of towns and preserving cultural sites as well (Ikeuchi and Miyazaki 2007, Shibuhisa et al. 2007).

One of the most difficult problems to collect complete surface data of outdoor constructions is to avoid self and mutual occlusions. If we want to collect complete data for covering whole surfaces of the constructions, then we have to measure from multiple viewpoints usually. However, examining multiple surface visibilities relative to variable multiple viewpoints is a complicated problem. Moreover, multiple measurements require plenty of time and labor, and each measurement gives a data set consisting of hundreds of millions of 3D points to be processed for further computations. So it is very important to make an effective measurement plan a priori for avoiding redundancy for both labor and computational costs. View planning with laser scanning has been developed as trial-based schemes, which segment scanned and unscanned regions in the target scene to find the next best scanning viewpoint for minimizing the unscanned regions. This approach includes the methods for promoting an efficiency of sequential scanning (Asai et al. 2007, Pitto 1999, Pulli 1999) and 3-dimensional environmental map generation by autonomous mobile robots (Blaer and Allen 2009, Grabowski et al. 2003, Surmann et al. 2003).

These foregoing studies require an additional planning for either the first scan or overall rough scanning to start their view planning procedure. This paper proposes an approach for providing optimized overall initial view plan using mathematical programming based on a 2D diagram, that would be available as a ground plan or a geological plan of the target area beforehand. Before starting the scanning process, estimating the minimum scale and the complexity of the whole scanning task is important and useful, especially for large scale outdoor measurement.

This paper is organized as follows: In Section 2, we define problems which are discussed in this paper. In Section 3, we formulate mathematical programming models as solutions to problems defined in Section 2. In Section 4, we discuss a method to calculate the value of parameters in mathematical programming models proposed in Section 3. In Section 5, we state some solutions to various requests which emerge from the real-world problem. In Section 6, we report results of numerical experiments, and we make some concluding remarks in Section 7.

2. Definition of Our Problems

In this paper, we use a 3D scanner to measure the shape of outdoor constructions in the target area. A 3D scanner performs line search vertically, and turns itself 360 degrees horizontally. Then it can measure objects omni-directionally.

The goal of this research is to determine viewpoints from which we are able to measure all the walls of structures in the target area. We measure walls from multiple points if necessary.

As we wrote in Section 1, a view plan deeply depends on shapes of structures, self and mutual occlusions, and existence of obstacles. The visibility and occluding property of walls vary with the change of viewpoints nonlinearly and discontinuously, so it is very difficult to determine the least number of viewpoints to measure all the walls.

Accordingly, we define one of the problems which are dealt with in this paper as follows:

[Problem 1] How many viewpoints do we need to measure all the walls of constructions in the target area?

On the other hand, too few viewpoints may cause deterioration of quality of measurement. The amount of data for a wall is proportionate to the scanning density, and the scanning density is proportionate to an angular distance from a viewpoint to a wall.

From this fact, we have to consider the following problem:

[Problem 2] How we can determine an optimal layout of viewpoints under the limitation of the number of measurements?

In this paper, we propose a method to solve Problems 1 and 2 with mathematical programming. Also, a ``viewplan" in this paper is defined by a set of solutions of Problems 1 and 2.

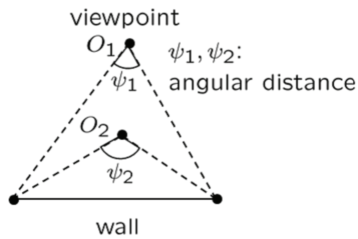

Figure 1: Angular distance

We assume that a 2D diagram will be available for making a viewplan, as a ground plan, a geological plan or an aerial photograph of the target area. Moreover, we suppose that candidate points of measurement would be placed in the target area beforehand. One of layout examples is to place candidate points on a grid in the target area. We can expect that the smaller interval of grid reduces the probability of existence of unmeasurable walls. In addition to this, we assume that candidate points are not on outlines or inside of constructions.

3. Proposed Mathematical Programming Models

In this section, we formulate Problems 1 and 2 as 0-1 integer programming problems.

We will use the following symbols in mathematical programming models which are going to be proposed.

[Sets and Indexes]

- $i \in I$: candidate points for measurement,
- $j \in J$: walls of constructions in the target area.

[Variables]

$$x_i := \begin{cases} 0, & \text{a candidate point i is unadopted as a viewpoint.} \\ 1, & \text{a candidate point i is adopted as a viewpoint.} \end{cases}$$

[Parameters]

$$d_{ij} := \begin{cases} 0, & \text{a wall j is unmeasurable from a candidate point i,} \\ 1, & \text{a wall j is measurable from a candidate point i,} \end{cases}$$

$$a_{ij} := \begin{cases} 0, & d_{ij} = 0, \\ \text{an angular distance of a wall j from a candidate point i,} & d_{ij} = 1, \end{cases}$$

$$r := \text{ upper bound of the number of measurement.}$$

We calculate the value of parameters from a 2D diagram of the target area. The calculation method will be introduced in Section 4.

In this paper, we propose these two mathematical programming models:

$$\begin{array}{ll} \text{minimize} & \sum_{i \in I} x_i \\ \text{subject to} & \sum_{i \in I} d_{ij} x_i \geq 1 \ (\forall j \in J) \\ & x_i \in \{0, 1\} \ (\forall i \in I) \end{array} \tag{1}$$

$$\begin{array}{ll} \text{minimize} & \sum_{i \in I} x_i \\ \text{subject to} & \sum_{i \in I} d_{ij} x_i \geq 1 \ (\forall j \in J) \\ & \sum_{i \in I} x_i \leq r \\ & x_i \in \{0, 1\} \ (\forall i \in I) \end{array} \tag{2}$$

The objective function of (1) is to minimize the number of viewpoints. Also, the term $d_{ij}x_i$ in the first constraint of (1) means as follows:

$$d_{ij}x_i := \begin{cases} 0, & \text{a candidate point i is unadopted as a viewpoint } (x_i = 0) \\ & \text{or a wall j is unmeasurable from i } (d_{ij} = 0), \\ 1, & \text{a candidate point i is adopted as a viewpoint } (x_i = 1) \\ & \text{and a wall j is measurable from i } (d_{ij} = 1). \end{cases}$$

Therefore, the first constraint of (1) means that all the walls are measured from one viewpoint at least.

The term $a_{ij}x_i$ of the objective function of (2) means as follows:

$$a_{ij}x_i := \begin{cases} 0, & \text{a candidate point i is unadopted as a viewpoint } (x_i = 0) \\ & \text{or a wall j is unmeasurable from i } (a_{ij} = 0), \\ a_{ij}, & \text{a candidate point i is adopted as a viewpoint } (x_i = 1) \\ & \text{and a wall j is measurable from i } (a_{ij} > 0). \end{cases}$$

Therefore, the objective function of (2) is to maximize the sum of angular distances, that is, the density of scanning. In addition, the first and third constraints of (2) are the same as that of (1). Moreover, the second constraint of (2) is to restrict the number of measurements less than or equal to r.

As we see above, mathematical programming problems (1) and (2) are the counterparts of Problems 1 and 2, respectively.

4. Calculation of Parameters' Value

To solve mathematical programming problems (1) and (2), we have to prepare the following parameters:

- positional information of walls
- visibility of walls from candidate points (d_{ij})
- angular distances from candidate points to walls (a_{ij})

In this section, we describe a method to calculate the value of these parameters.

4.1 Positional Information of Walls

We will obtain positional information of walls from a 2D diagram of the target area. In this paper, we will approximate a wall by a line segment, and the position of a wall is determined by two endpoints of a line segment. The algorithm which we propose to calculate positional information of walls is as follows:

Algorithm 1: Calculation of Positional Information of Walls
Step 1: Extract constructions from a 2D diagram of the target area by an image manipulation software, and make a binary image.
Step 2: Find outlines of constructions by the binary image.
Step 3: Approximate the outlines by line segments. ▮

In this paper, OpenCV is employed in Algorithm 1. Concretely, we use functions cvFindContours (Suzuki and Abe 1985) and cvApproxPoly (Douglas and Peucker 1973) of OpenCV in Step 2 and 3, respectively. In the rest of this paper, we assume that walls which are extracted by Algorithm 1 are not overlapped or intersected.

4.2 Visibility and Angular Distance

From the positional information of the walls obtained by Algorithm 1, we check the visibility of the walls, that is, $d_{ij} \in \{0, 1\}$, and calculate the angular distance a_{ij} if a wall j is measurable from a candidate point i ($d_{ij} = 1$).

First, we define the state of ``measurable". In this paper, a wall is measurable from a candidate point if there is no occlusion by the other walls. Namely, we call it measurable that an entire wall is visible from the candidate point, and unmeasurable that any part of the wall is invisible.

Now we set that $O(\bar{x}, \bar{y})$ is a candidate point i in a 2D diagram. Moreover, $W_{j,0}(x_{j,0}, y_{j,0})$ and $W_{j,1}(x_{j,1}, y_{j,1})$ are endpoints of a line segment which stands for a wall j, where

$$\varphi_{j,k} = \arctan\left(\frac{y_{j,k} - \bar{y}}{x_{j,k} - \bar{x}}\right) \in [-\pi, \pi) \ (k = 0, 1)$$

and $\varphi_{j,0} < \varphi_{j,1}$ holds (Figure 2). Note that we can exclude a wall j when $\varphi_{j,0} = \varphi_{j,1}$ holds, because this means that an angular distance is 0 when a wall j is measured from a candidate point i, so a wall $\bar{j}$ is unmeasurable in a case $j = \bar{j}$, or a wall j does not occlude $\bar{j}$ from i in a case $j \neq \bar{j}$.

We assume that there is no wall in a direction of $-\pi$ from O. We will discuss such walls in the last part of this section.

θ denotes two angles which are made by a candidate point and two endpoints of a wall, such that

$$\theta_{j,k} = \angle O W_{j,k} W_{j,\bar{k}} \ (k = 0, 1; \bar{k} = 1 - k).$$

Note that $\theta_{j,k}$ does not have a direction, then $\theta_{j,k} \geq 0$ holds.

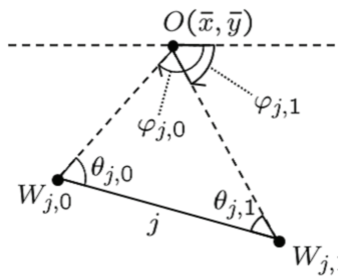

Figure 2: An example of a candidate point and endpoints of a wall

We can classify the relationship between a wall $\bar{j}$ and the other wall j as follows:
(a) Case that $\bar{j}$ and j share an endpoint
(a-1) $W_{\bar{j},0} = W_{j,0}$ (Figure 3, left), (a-2) $W_{\bar{j},0} = W_{j,1}$ (Figure 3, right), (a-3) $W_{\bar{j},1} = W_{j,0}$, (a-4) $W_{\bar{j},1} = W_{j,1}$.
(b) Case that $\bar{j}$ and j does not share an endpoint
(b-1) $\varphi_{j,1} \leq \varphi_{\bar{j},0}$ (Figure 4, left), (b-2) $\varphi_{j,0} \leq \varphi_{\bar{j},0} \leq \varphi_{j,1}$ (Figure 4, right), (b-3) $\varphi_{\bar{j},0} \leq \varphi_{j,0} \leq \varphi_{\bar{j},1}$, (b-4) $\varphi_{\bar{j},1} \leq \varphi_{j,0}$.

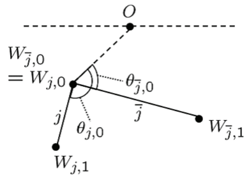

Figure 3: Examples of (a-1) and (a-2)

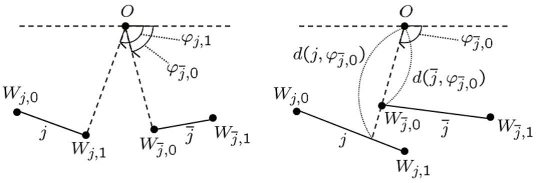

Figure 4: Examples of (b-1) and (b-2)

In addition, $d(j, \varphi)$ denotes the distance from O to a wall j in a direction φ (Figure 5).

Now we describe an algorithm to judge whether a wall j disturbs a measurement of a wall $\bar{j}(\neq j)$ from a candidate point O or not.

Algorithm 2: Judgment of Visibilities of Walls
(a-1) If $\theta_{\bar{j},0} < \theta_{j,0}$ holds, then $\bar{j}$ is not occluded by j (from O, $\bar{j}$ is nearer than j). Otherwise, $\bar{j}$ is unmeasurable (j is nearer than $\bar{j}$, so j disturbs measurement of $\bar{j}$). Note that $\theta_{\bar{j},0} = \theta_{j,0}$ does not occur because we assume that walls are not overlapped.
(a-2) $\bar{j}$ is not occluded by j ($\bar{j}$ does not exist in a direction which j exists).
(a-3) The same as (a-2).
(a-4) If $\theta_{\bar{j},1} < \theta_{j,1}$ holds, then $\bar{j}$ is not occluded by j. Otherwise, $\bar{j}$ is unmeasurable.
(b-1) $\bar{j}$ is not occluded by j ($\bar{j}$ does not exist in a direction which j exists).
(b-2) If $d(\bar{j}, \varphi_{\bar{j},0}) < d(j, \varphi_{\bar{j},0})$ holds, then $\bar{j}$ is not occluded by j ($\bar{j}$ is nearer than j). Otherwise, $\bar{j}$ is unmeasurable (j is nearer than $\bar{j}$, so j disturbs measurement of $\bar{j}$). Note that $d(\bar{j}, \varphi_{\bar{j},0}) = d(j, \varphi_{\bar{j},0})$ does not occur because we assume that walls are not intersected.
(b-3) If $d(\bar{j}, \varphi_{j,0}) < d(j, \varphi_{j,0})$ holds, then $\bar{j}$ is not occluded by j. Otherwise, $\bar{j}$ is unmeasurable.
(b-4) The same as (b-1). ▮

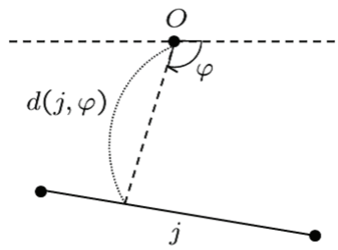

Figure 5: Distance from a candidate point to a wall in a direction φ

Applying this algorithm for all the walls $j \in J \setminus \{\bar{j}\}$, we can check the visibility of a wall $\bar{j}$ from a candidate point i. Moreover, we can set d_{ij} by applying this algorithm for all the combinations of candidate points and walls.

Also, we can easily calculate an angular distance $a_{ij} = \angle W_{j,0} O W_{j,1} = \varphi_{j,1} - \varphi_{j,0}$. It is enough to calculate a_{ij} for all combinations (i, j) which $d_{ij} = 1$ holds.

At the end of this section, we explain methods to deal with a wall which exists in a direction $-\pi$ from O. For this case, following ideas are effective:

(i) Divide a wall at a direction $-\pi$ (Figure 6, left)
(ii) Make a dummy wall (Figure 6, right)

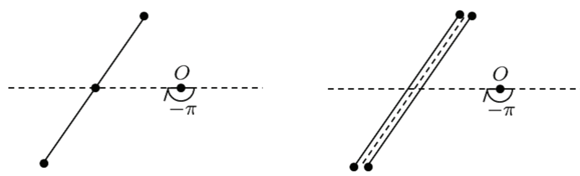

Figure 6: Concept for dealing with a wall in a direction $-\pi$

In a case (i), we divide a wall at a direction $-\pi$, and check visibility for two parts separately. If both are measurable, then an original wall is so. In a case (ii), we set an endpoint of a wall j in quadrant 1 or 2 as $W_{j,0}$, and an endpoint in quadrant 3 or 4 as $W_{j,1}$. And we set $\varphi_{j,0}$ and $\varphi_{j,1}$ which satisfy $-2\pi < \varphi_{j,0} < -\pi$ and $-\pi < \varphi_{j,1} < 0$. Also, we consider a dummy wall j' which satisfies $W_{j',0} = W_{j,0}$, $W_{j',1} = W_{j,1}$, $\varphi_{j',0} = \varphi_{j,0} + 2\pi$ and $\varphi_{j',1} = \varphi_{j,1} + 2\pi$, and judge visibility of walls j and j' separately. However, we assume that a wall j and j' does not disturb a measurement each other. If both j and j' are measurable, then we can judge that an original wall is so.

5. Some Solutions to Various Requests

In shape measurement planning of outdoor constructions, various requests may be occurred. In this section, we explain some solutions to real-world problems. These solutions are categorized in two: one is the modification of mathematical programming models, the other is the modification of the value of parameters.

5.1 Modification of Mathematical Programming Models

In (2), we define the amount of data about a wall by the sum of multiple scan density. However, we can define it by the best measurement when a wall is scanned from multiple viewpoints. In such a case, (2) should be modified as follows:

$$\begin{array}{ll} \text{maximize} & \sum_{i\in I, j\in J} a_{ij} y_{ij} \\ \text{subject to} & \sum_{i\in I} d_{ij} y_{ij} = 1 \ (\forall j \in J) \\ & \sum_{i\in I} y_{ij} = 1 \ \ (\forall j \in J) \\ & y_{ij} \le x_i \ (\forall i \in I, \forall j \in J) \\ & \sum_{i\in I} x_i \le r \\ & x_i \in \{0,1\} \ (\forall i \in I),\ \ y_{ij} \in \{0,1\} \ (\forall i \in I, \forall j \in J) \end{array} \tag{3}$$

In (3), we introduce a new 0-1 variable y_{ij}. This means as follows:

$$y_{ij} := \begin{cases} 0, & \text{a candidate point i is unadopted as a viewpoint } (x_i = 0) \\ & \text{or i does not correspond to a wall j,} \\ 1, & \text{a candidate point i is adopted as a viewpoint } (x_i = 1) \\ & \text{and i corresponds to a wall j,} \end{cases}$$

where ``i corresponds to j" means that measurement from i is the best of all the measurements about j. The objective function of (3) is to maximize the sum of best measurements for each wall. Also, the first and second constraints of (3) play an important role to extract the best viewpoint for each wall. Moreover, the third constraint means that a condition $y_{ij} = 1$ implies that $x_i = 1$ holds.

5.2 Modification of Value of Parameters

In (1) and (2), we assume that we have to measure all the walls. However, we may consider the case that we do not have to measure some walls. To deal with such a case, we can consider J as the set of walls which need a measurement, and check visibility considering all the walls in the target area. This way of thinking can be apply for the case in which there are some obstacles in the target area.

Moreover, in Algorithm 2, a wall is measurable as long as the angular distance is a little bit larger than 0. However, we may consider that a wall whose angular distance is less than we expect is unmeasurable. We can deal with such a case if we set $d_{ij} = 0$ and $a_{ij} = 0$.

When the distance between a candidate point i and a wall j is longer than a range of a 3D scanner, it is realistic to consider that j is unmeasurable from i. In such a case, we also set $d_{ij} = 0$ and $a_{ij} = 0$.

In addition, Algorithm 2 decide that a whole wall is invisible if any part of it is so. However, this judgement is stricter than the situation as it is. To avoid this problem, it is effective to divide a wall into some parts and check the visibility for each part. This approach can reflect the practical visibility more.

6. Numerical Results for Practical Applications

In this section, we report some numerical results for practical applications. They are obtained by the proposed method. In this section, two target areas have been used: one is a part of Kansai University (Osaka, Japan), and the other is Minami-Sotobori of Osaka castle (Osaka, Japan), where "Sotobori" means an outer moat. There were 22 constructions in the former example, and we would like to measure stone-walls of outer moats in the latter example. In this section, we explain results for these two examples in turn.

6.1 Example 1: Kansai University

6.1.1 Settings

First, as we explained in Section 4.1, we have extracted constructions from a ground plan of the target area (Figure 7, left: 640×480 pixels, 1 pixel ≅ 0.7m). And then, we have found outlines of constructions from this picture, and approximated them by line segments. As a result, the walls were approximated by 124 line segments (Figure 7, right).

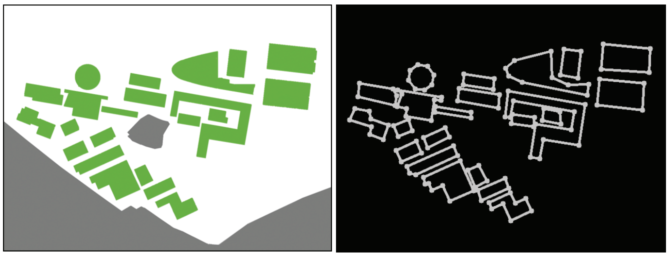

Figure 7: Extraction of constructions and approximation of walls by line segments

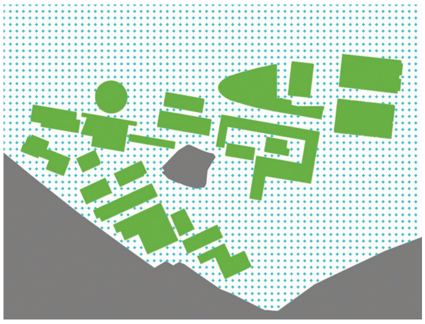

Figure 8: Layout example of candidate points (grid interval: 10 pixels)

Next, we have placed candidate points of measurement. In this experiment, we have placed them on a grid in the region which is available for setting up a 3D scanner (white area of Figure7, left). We have used three patterns of grid interval: 5, 10 and 20 pixels (Figure 8).Table 1 shows the number of candidate points of each pattern.

Table 1: Grid interval and the number of candidate points

Grid interval (pixels)	5	10	20
The number of candidate points	7327	1846	474

Table 2: Experimental environment

PC	Lenovo ThinkPad X200s
OS	Windows XP Professional SP3
CPU	Intel Core2 Duo L9300 @ 1.60GHz
Memory	2.96GB
Solver	GLPK LP/MIP Solver version 4.42

Using the positional information of walls and candidate points, we have calculated the value of d_{ij} and a_{ij} with Algorithm 2. And then, we have solved (1) and (2) to determine the optimal viewpoints. Table 2 shows the environment which has been used for this experiment.

6.1.2 Results and Consideration

First, we have solved (1) to find the least number of measurements. After that, we have set $r \coloneqq$ (the optimal objective value of (1)), and solved (2) to determine the optimal viewpoints. Table 3 shows the computational time of calculation of parameters, the computational time to solve (1) and (2) by a solver, and the least numbers of measurement which are obtained by (1).

Table 3: Computational time and the least number of measurements

Grid interval (pixels)	5	10	20
Computational time to calculate parameters (sec.)	6.2	1.6	0.5
Computational time to solve (1) (sec.)	8.0	0.9	0.0
The least number of measurements by (1)	19	20	infs.
Computational time to solve (2) (sec.)	28.0	0.1	--

infs.: (1) is infeasible

Table 4: Minimal angular distance and the least number of measurements

Minimal angular distance (deg.)	0	5	10	15	20
The least number of measurements (grid interval: 5 pixels)	19	24	28	32	35
The least number of measurements (grid interval: 10 pixels)	20	26	31	38	41

We have obtained optimal viewpoints within a practical computational time for grids whose interval are 5 or 10 pixels. Otherwise, we have found that (1) was infeasible for a grid whose interval is 20 pixels. This may be caused by the rough grid of candidate points, then walls whose intervals are narrow would be unmeasurable.

Figure 9 shows optimal viewpoints obtained by (2) for grids whose intervals are 5 and 10 pixels.

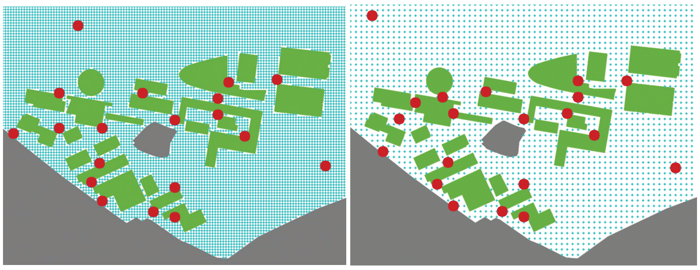

Figure 9: Optimal viewpoints (left: grid interval = 5 pixels, right: 10 pixels)

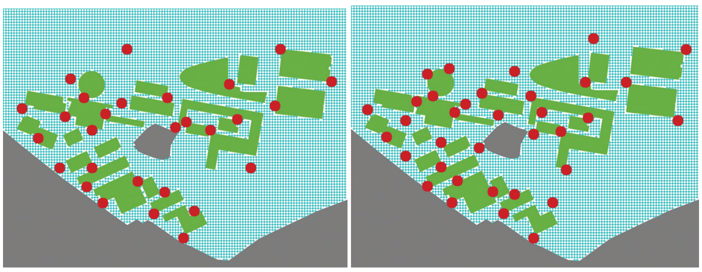

Figure 10: Optimal viewpoints (5 pixel-grid, left: minimal angular distance = 5 deg., right: 10 deg.)

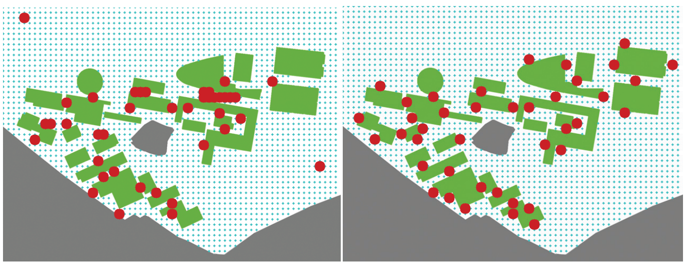

Figure 11: Optimal viewpoints (left: obtained by (2), right: by (3))

In all experiments for Table 3, we have set $d_{ij} = 1$ as long as an angular distance from a candidate point i to a wall j is even a little bit larger than 0.However, sometimes we want to judge that a wall is unmeasurable when an angular distance is too small for adequate scanning density. Then, we had done some experiments in which we set $d_{ij} = 0$ and $a_{ij} = 0$ if an angular distance is less than a threshold. Table 4 shows the relationship between minimal angular distances and the least numbers of measurements. The optimal viewpoints of two cases in Table 4 are depicted in Figure 10. As shown in Table 4, an increase of a minimal angular distance causes that of the least number of measurements, because constraints of (1) get stricter.

On the other hand, we have set $r :=$ (the optimal objective value of (1)) in experiments of Table 3.However, we can set r larger than it. In such a case, we will obtain optimal viewpoints better than normal cases in view of the objective function, that is, the sum of scanning density. For example, the least number of measurements is 20 under the condition that a grid interval is 10 pixels and a minimal angular distance is 0 degree (see Table 4). Contrary to this, we have set $r = 40$ and solved (2) (computational time: 0.1 sec.). Figure 11, left shows the optimal layout of viewpoints. As shown in this figure, optimal viewpoints have been placed unevenly somewhat. This is because (2) is just to maximize the sum of scanning density for each wall. On the other hand, Figure 11, right shows optimal viewpoints which is obtained by (3) (computational time: 318.7 sec.) under the same parameter settings. The objective function of (3) adopts the best measurement for each wall, so optimal viewpoints have been placed more evenly.

From these experiments, we have shown that the proposed method can make a view plan for practical problems. Especially, we can make a view plan even with a laptop PC, which has been used in these experiments, so we can cope with change of requests on site.

6.2 Example 2: Osaka Castle

6.2.1 Settings

Figure 12 (1000×400 pixels, 1 pixel ≅ 0.7m) is a ground plan of Minami-Sotobori and its neighborhood of Osaka castle. In Figure 12, a blue area is a place of an outer moat, and a green area is a set of measurement points. In the same way as the former example, we have extracted an outer moat from this picture. And we have approximated stone-walls of a moat by line segments. As a result, we have found 40 line segments.

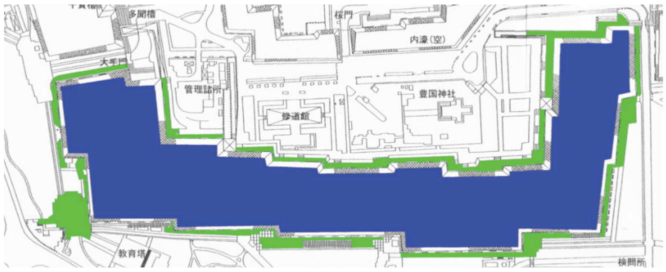

Figure 12: Minami-Sotobori of Osaka castle

At this time, we have to pay special attention to deal with this example. Generally speaking, outdoor constructions are on the ground, and stone-walls of outer moats are underneath the ground. This fact makes some difference as follows (Figure 13): walls of outdoor constructions between a 3D scanner and a measured wall cause occlusions definitely, but stone-walls of outer moats in the same situation do not cause occlusions necessarily. To treat such a situation, we have added the following processes to the proposed method:

- Consider the orientation of walls when we judge the visibility
- Set that walls within a certain distance from a 3D scanner are unmeasurable
- Set that walls within a certain distance from a 3D scanner do not occur occlusions

We can calculate the visibility in this example by applying these conditions to Algorithm 2.

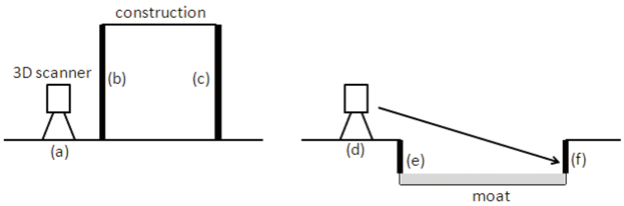

Figure 13: Diffrence between an outer construction and a moat

Left: When we measure a wall (c) from a position (a), a wall (b) occludes a measurement.
Right: When we measure a stone-wall (f) from a position (d), a stone-wall (e) does not occlude a measurement.

Moreover, we have placed candidate points of measurement in the green area of Figure 12. We have used a grid pattern (interval: 5 pixels), which is the same as the former example. The number of candidate points was 722. Also, we have used the same experimental environment as the former example, and set minimal angular distance as 0 degree.

Figure 14: Optimal Viewpoints for Minami-Sotobori

6.2.2 Results and Consideration

Figure 14 is an optimal measurement plan for Minami-Sotobori under conditions which are explained in Section 6.2.1. We can confirm that the added processes function well and a plan is practically executable for this scene.

Moreover, we have tried to find an optimal plan under the condition that minimal angular distance is 5 degree. However, we have found that (1) is infeasible. The reason was that angular distances of some small walls are always less than 5 degree from any measurement points.

7. Conclusion

In this paper, we have proposed a method to make a viewplan to measure all the walls of outdoor constructions in the target area with a 3D scanner. One of the most difficult problems to collect complete data of outdoor constructions is to avoid self and mutual occlusions. For this purpose, we solve two mathematical programming problems: one is to determine the least number of measurements without lack of data, the other is to find an optimal layout of viewpoints in view of scanning density. Our method is based on a 2D diagram that would be available as a ground plan or a geological plan of the target area beforehand. Numerical experiments for practical applications show the good property of the proposed method.

Future work is to make a model which deals with 3D property of constructions and the target area. In this paper, we assume that we can use only a 2D diagram. However, we can suppose that some 3D data is available in some cases. For such cases, we have to improve the proposed method.

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VISUAL MODELING OF OUTDOOR CONSTRUCTIONS BY DATA FUSION OF LASER SCANNING AND STRUCTURE-FROM-MOTION

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ABSTRACT: *A 3D scanner is a surface imaging system based on accurate distance measurement by an electro-optical sensing device. Lately, this type of equipment has been extending its measurement range to facilitate digitizing "existing" constructions, and used for examining and designing landscapes of towns and preserving cultural sites as well. One of the most difficult problems to collect complete surface data of outdoor constructions is to avoid self and mutual occlusions, even if conducting measurement from multiple viewpoints. Moreover, multiple measurements require plenty of time and labor, and each measurement may produces millions of redundant data points for easily visible surfaces, but consequently, miss-scanned surfaces still remain in many cases. Our approach is to utilize the combination of wide angle laser scanner and highly mobile video camera for achieving complementary surface measurement. A single video camera is not really capable of capturing 3D information by itself, but consecutive frames of moving camera can reconstruct a sparse set of image feature points and its camera path in 3D space, using structure-from-motion (SFM) method based on multi-baseline stereo. We apply a simple optimization for registering SFM data and the scanned range data. After registration, taking advantages of the handy-cam's mobility and its great number of frames, reduction of nose, compensating missing texture and shape in scanned range data is available by using the visibility consistency. Straightforward way to implement the visibility consistency check is creating visual hull which is intersection of multiple view volumes. We implemented interactive system for the experiment, whose results showed the effectiveness of the proposed approach through semi-automated processes.*

KEYWORDS: *Outdoor scene, Laser Scanner, Video Camera, Structure-from-motion, 3D model, View Volume*

1. INTRODUCTION

We can obtain digital surface shape data of physical objects by a laser scanner that performs a number of independent ranging. A high-resolution digital still camera is usually equipped and calibrated with the scanner for capturing the visible color information for each data point. Lately, this type of device has been extending its measurement range and density to facilitate digitizing or virtualizing "existing" outdoor constructions, and used for designing landscapes of towns and preserving cultural sites. (Ikeuchi and Miyazaki 2007, Shibuhisa et al. 2007). One of the difficulties in collecting complete surface data of outdoor constructions is to avoid self and mutual occlusions. For scanning overall surface of the target scenes, number of methods have been studied for examining view planning techniques, that mainly focuses on next best view (NBV) in 3D scanning for one after another (Pitto 1999, Pulli 1999, Grabowski 2003, Asai et al. 2007, Blaer 2009). Still multiple surface visibilities relative to variable multiple viewpoints is a complicated and unavoidable problem. Even if an elaborate measurement plan is available, missing detailed parts and artifact noises must be remained in the measured data, because of very local obstacles such as plants nearby and temporal artifacts of cars and pedestrians. Therefore, laborious manual work for data correction is often necessary for completing 3D shape modeling.

2. APPROACH

We focus on the advantageous mobility of a handy-type video camcorder. Lately, high-definition quality has become popular even in consumer camcorder market and each device becomes so small-sized that a long and high-quality footage is available in anywhere a person can walkthrough. 3D scanner provides dense point clouds for the visible surface of the objects, but limited number of viewpoints gives many missing parts. A handy camcorder can easily shoot such missing parts of the scenery by flexibly sneaking around the visual obstacles on foot. Using the camcorder footages, structure-from-motion (SFM) is capable of reconstructing the 3D geometries of both feature points on the objects and a camera path; a sequence of camera positions and orientations. SFM is a 3D reconstruction technique from multiple images based on multi-baseline stereo measurement using epipolar geometry constraints and image feature tracking.

3. CONSISTENCY IN DIGITIZED SPACE

3.1 Camera Path and 3D Reconstruction by Structure-from-Motion

A physically static scenery has a consistency of visibility for observations from different viewpoints in different timing. Our motivation is to proactively utilize the visual consistency for reducing noise and interpolating missing data. The simple realization of the visual consistency is to examine intersection of the view volumes from multiple viewpoints. Single 3D scanning may cause artifact noise like dots in the air, for example, that can be eliminated by comparing with another scan from a different viewpoint which would never yield noises in exactly the same 3D position. Especially for outdoor scenes, walking people and passing cars may leave their ghost-like noises caused by being partially scanned, but a consistency of visibility between multiple scanning in different timing is able to erase the temporary existences of the noises as well. Employing a 3D scanner which is capable of 360 degrees panoramic scanning is effective for covering wide angle with limited number of viewpoint. However, self and mutual occlusion of the objects' surface is inevitable. Furthermore, for compensating the occlusion, multiple use of the panoramic scanner enormously produces redundant data in easily visible surfaces in the scene. After scanning whole surfaces of the constructions in the target area, dispersed small miss-scanned regions can be covered with patches for completing surface modeling. As mentioned previous section, we use a mobile single camera for compensation rather than a scanner. Single video camera movement can be reconstructed by SFM technique.

3.2 Coordinates Transformation

Acquiring geometrical relationship between the video frames and the scanned 3D data set capturing the same scene requires corresponding points within both data. We selected some candidate landmark points from the feature point set used in SFM using the video frames, then finding the corresponding points in scanned 3D points. Considering the low density of the feature points in SFM and visible color features, corresponding pairs are determined manually. From these corresponding pairs, transformation matrix can be found as the best combination of rotation, translation and scaling by an optimization method. Let A as a transform matrix that transforms the 3D coordinate Wp reconstructed by SFM the 3D scanner coordinate Wq. Arbitrary pair of vector $p = [p_x, p_y, p_z]^T$ on W_p and $q = [q_x, q_y, q_z]^T$ on W_q satisfies equation (1).

$$q = Ap \tag{1}$$

The transform A can be represented as a 4×4 homogeneous coordinate matrix with multiplication of 3 rotations $R_x(\theta), R_y(\phi), R_z(\psi)$ and 3 translations $T_x(t_x), T_y(t_y), T_z(t_z)$ and scaling matrix $S(s)$, which contains 7 variables as shown in equation (2). Here, R_x denotes rotation around x-axis and T_x denotes x-direction translation, respectively. When n pairs of p and q are given, the squared error E of equation (1) can be shown in equation (3). For minimizing equation (2), we use steepest descent method, that requires differentiations respect to 7 variables.

$$A = S(s)R_x(\theta)R_y(\phi)R_z(\psi)T_x(t_x)T_y(t_y)T_z(t_z) \tag{2}$$

$$E = \Sigma_{i=1}^{n}(q_i - Ap_i)^2 \tag{3}$$

Steepest descent method needs differentiation of error function E, that is a partial differentiation vector relative to 7 variables shown in equation (4). The partial differentiation vector updates the 7 components of transform A according to equation (5).

$$\frac{\partial E}{\partial A} = \frac{\partial \Sigma_{i=1}^{n} (q_i - Ap_i)^2}{\partial A} \tag{4}$$

$$(A)^{new} = (A) - \alpha(\frac{\partial E}{\partial A}) \tag{5}$$

3.3 Texture Interpolation

Scanned range data can be registered with color texture. Some devices equipped with combination of range and color sensing for each pixel to produce a colored range image as shown in Fig. 1. We implemented a software tool to select a region of interest (ROI) in the color image and pick up the range data or 3D coordinate associate with the ROI. This tool allows the user to select the missing range data region as a ROI and to extract the 3D coordinate of the contour points of the ROI. As described in the previous section, reconstructed sparse 3D data by SFM can be registered with the dense scanned range data. Eventually, actual camera path with 3-dimensional camera position and direction for shooting each frame is registered in the range data space. This result enables to project scanned 3D points onto the video image frames. And thus the occluded region in range data can be overlaid on arbitrary video frames on the camera path. The missing range data region can be specified as a ROI on a video frame which can be selected so that the ROI is visible.

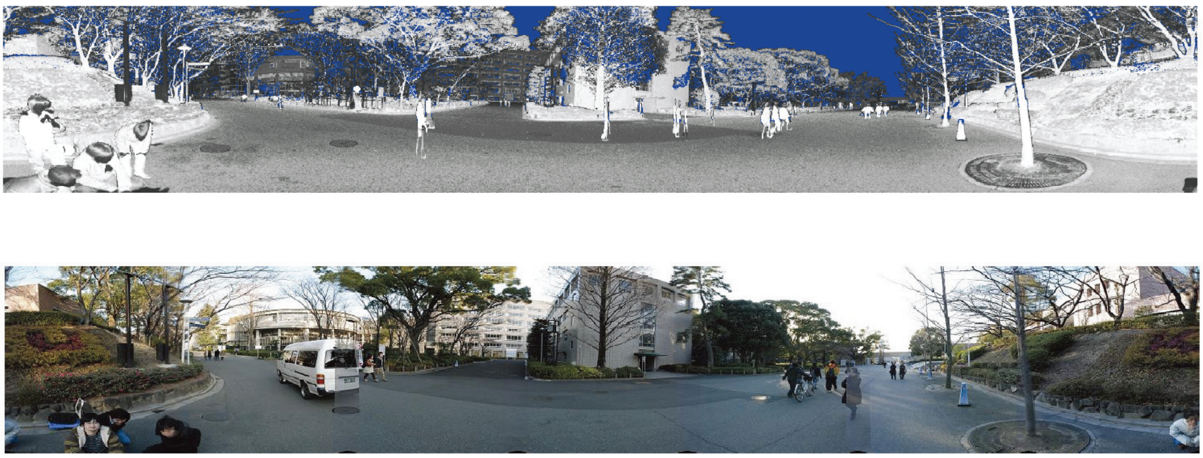

Fig. 1 panoramic 3D scanning data: range image (upper) and color texture (lower)

3.4 Voxel Data with Octree Structure for Visual Hull

A visual hull is generated as an intersection of the view volumes from different viewpoints. A view volume can be specified by a silhouette of the existing object determines on a camera image plane as a possible existing region of the target object in 3D space. For implementing computation of the visual hull, quantized sampling point in the 3D space is projected onto the image plane for checking whether the sampling point is within/without the view volume. The product set of the sampling points between different viewpoints produces visual hull. Visual hull forms approximate 3D shape of the object. This research employs octree technique for dividing region to prepare voxles. Octree technique hierarchically and recursively divides each voxel into 8 sub-voxels and is capable of adaptively defining the voxel size arrangement according to complexity of the objet shape or silhouette. This is advantageous in terms of not only less memory consumption but also low computation cost for checking wheter each voxel is included in the view volume. For silhouette extraction, number of image segmentation techniques can be applied. We use traditional watershed algorithm implemented in OpenCV library for interactively define the target object regions on several video frames (Meyer 1992).

3.5 Surface Model with Marching Cubes over Octree Voxels

Based on the previous implementation of the visual hull, the object existing volume is expressed by a set of voxels. Each of the voxels is cube shape that gives aliased jaggy appearances. We employ Marching Cubes method for surface representation (Lorensen and Cline 1987). Though octree voxel structure is composed of different size of voxels according to their hierarchy in the tree, assigning 0 or 1 for each vertices of all of the voxel cubes in the object space, according to the view volume checking. Referring to the vertex value of 0 or 1, 2^8=256 patterns of surface definition exist. Just like as the original Marching Cubes technique, the pattern can be simplified and decreased down to 14 patterns, considering topological identity, rotational symmetry and identifying two sides of the surface, and thus it is easy to implement for rendering. Overall process flow of the proposed approach is depicted in Fig.2.

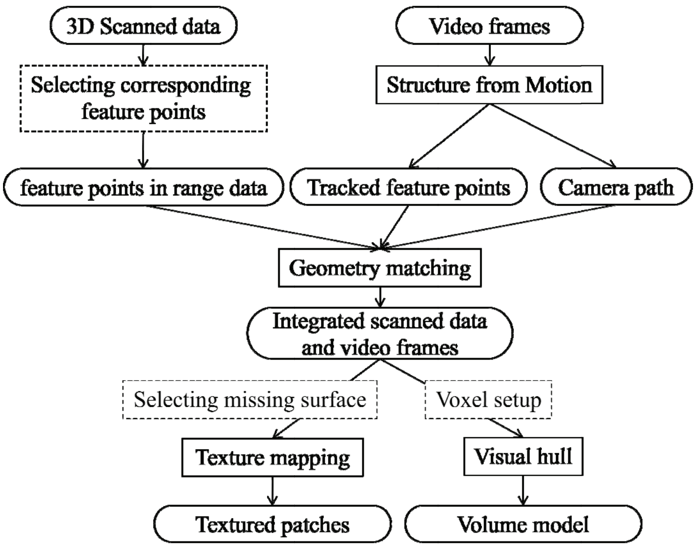

Fig. 2 Process flow: The normal and the dashed squares show automatic (software) and manual processes, respectively, and the rounded boxes show the data.

4. EXPERIMENT

4.1 Setup

We used RIEGL LMS-Z420i for scanning the actual building surface shapes and a Sony handy-cam, HDR-XR520V for capturing the video frames for the same scenery. A match-move software, Boujou Bullet (2d3 inc.) is used for conducting SFM. Specifications for the computational devices are shown in Table.1. Computational condition is shown in Table 2. Scanned surface data shown in Fig. 1. is used for the experiment. A video footage is shown in Fig. 3. Either object is in the campus in Kansai university. Scanned data contains 1555 points with 3D coordinate and 24bits RGB color information. Acquired video footage has 720 x 404 resolution and 711 frames length. Walking with a handy-cam, the footage was filmed around the tree so that the occluded building surface from the scanner viewpoint can be captured in the frames. SFM reconstructed 3D feature points and the video camera path by using Boujou Bullet as shown in Fig. 4. The feature points are show as blue points in both picture in Fig. 4. The left picture shows overlaid reconstructed 3D feature points and right picture shows the reconstructed camera path with a red line. Starting from these data, we targeted interpolating the missing range data of the building wall behind the tree and reconstruct the tree shape itself. We selected a video frame from the footage and corresponding points for acquiring the proper transformation A, that brings SFM data into range data space. For updating the iterative computation, $\alpha = \frac{0.0001}{s}$ we set the updating ratio as using scale component s in equation (5). The minimum residual $\epsilon = 0.00001$ error value was settled as for the threshold of convergence for terminating iteration. The initial values of the 7 component of matrix A are zero and acquired transform matrix is as shown in equation (6).

$$A = \begin{bmatrix} -0.57380 & 0.01921 & -0.00135 & -15.05941 \\ -0.00058 & 0.02291 & 0.57367 & -2.24504 \\ 0.01925 & 0.57335 & -0.02288 & -0.87603 \\ 0.00000 & 0.00000 & 0.00000 & 1.00000 \end{bmatrix} \tag{6}$$

Table 1. Video Camera Specifications

Product name	HDR-XR520V (Sony inc.)
Signal type	HDTV 1080/60i
Recording type	MPEG4-AVC/H.264 AVCHD
Imaging sensor	6.3mm (1/2.88') CMOS
Aspect ratio	16:9

Table 2. 3D Scanner Specifications

Product name	LMS-Z420i (RIEGL inc.)
Precision (1σ@50m)	$\pm$10 mm
Measurement range	1000 m, 80 deg (vert.), 360 deg (hori.)
Angle step	0.0025 deg (vert.), 0.004 dev (hor.)
Scanning rate	1-20 line/sec, 0.01-15 deg/sec

4.2 Reconstruction of Occluded Region

In this experiments, we interactively picked up the miss-scanned region in the range data manually. We prepared a software on which you can select the points surrounding the region to make a polygon patch to cover the missing data by connecting the selected points. The mean residual between the polygon patched ant the scanned range data points was 26.5 mm and proper color texture is mapped onto the polygon patch from one of the video frames. Since the texture colors between video frames and the scanner images, we adjust the hue of the video frame colors beforehand, using photo retouch software. The result example is shown in Fig. 5. Applying the silhouette images of right column in Fig. 6 to visual hull computation, reconstructed volume model of the tree shape with voxel expression is shown in Fig. 7 (right) and surface expression by Marching Cubes is shown in Fig.7 (left). Green wired box is the boundary volume for creating visual hull. This boundary was also set manually beforehand. Both models are rendered with the scanned range data.

Table 3. Computational Conditions

OS	Windows XP
CPU	Intel Core i7 2.8GHz
Memory	3062 MB RAM
GPU	HDDNVIDIA GeForce GTS250
Programming	C/C++
Library	OpenGL/OpenCV

Fig. 3 Target scene: 3D scanning data (left) and video frame (right) .

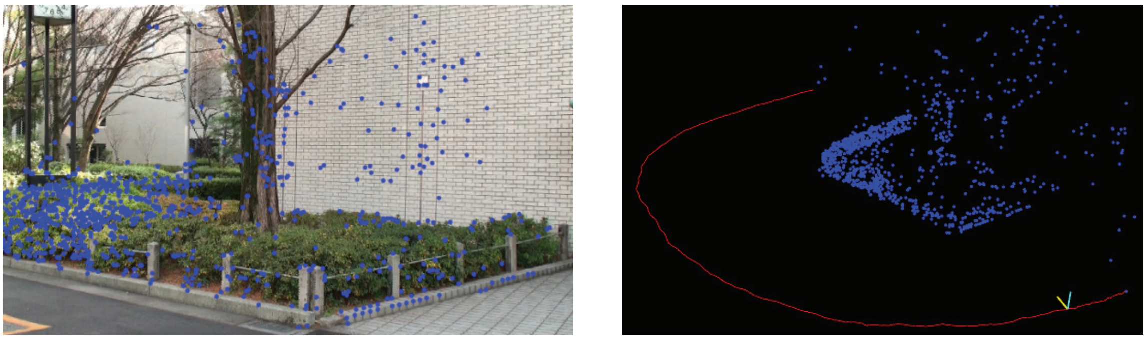

Fig. 4 Reconstructed feature points (blue points in both figures) and camera path (red line in the left) .

Fig. 5 Miss-scanned region behind the tree (left) and interpolated texture (right)

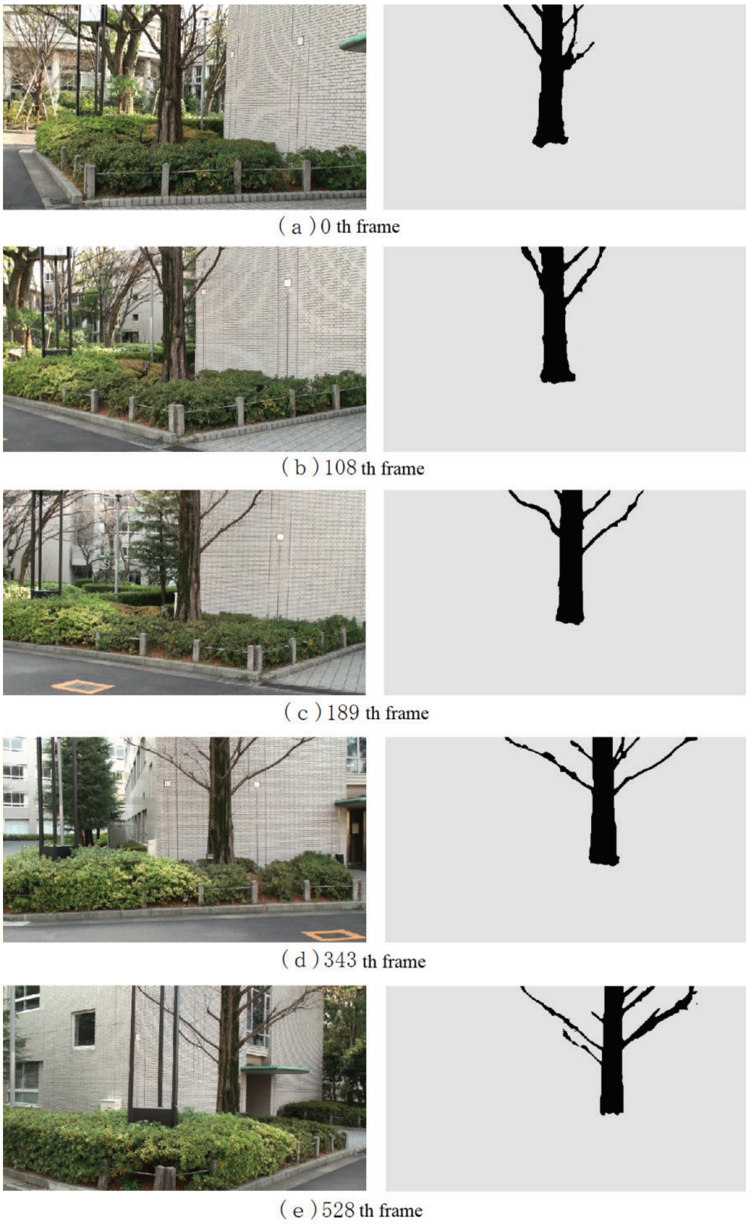

Fig. 6 Video frames (left column) and extracted silhouettes of a tree (right column)

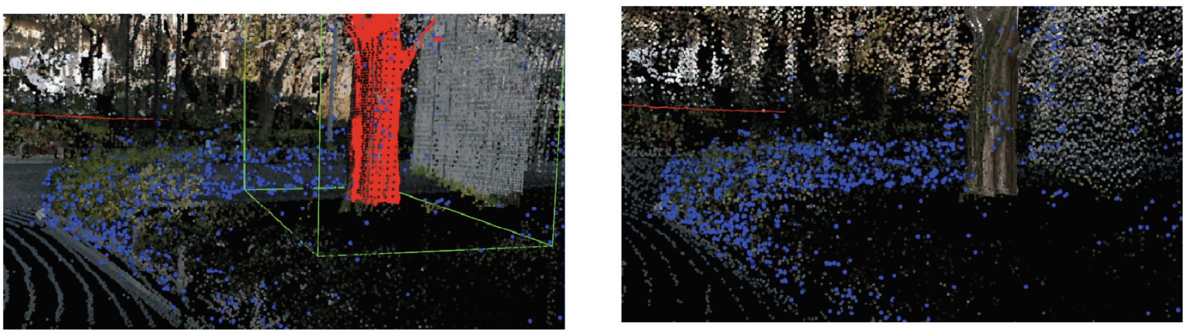

Fig. 7 Reconstructed tree represented by red octree voxels (left) and textured surface (right)

5. CONCLUSIONS

The experimental results showed that the proposed approach works effectively, based on the combination of different types of image sensing. SFM technique only generates 3D information of natural image feature points that are not necessarily what we want to target for modeling, but utilizing high resolution images to extract color information and object contours function that we want to pad and patch the missing textures and shapes. Clear silhouette extraction works as noise reduction as well. In this paper, our implementation includes several steps of manual works, that include selecting corresponding points for registration of scanned and SFM data and setting interpolation region and visual hull area. We need to provide N easy-to-use user interface for these process. The modeling precision depends on the 3D reconstruction by SFM technique. Clarifying the suitable shooting manner for the video footage is also within our focus.

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Optimizing system from 3D laser scanner data to a VR model for urban design study

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ABSTRACT: *In the field of architectural design and city planning, physical scale model (SCMOD) and virtual reality (VR) are acknowledged as effective tools for communication among stakeholders. However, they are often made using different processes so that much labor and high costs are involved. Therefore, an automatic 3D digital modeling system based on a SCMOD is needed. In this study, a VR modeling flow from the SCMOD to the digital data by using 3D Laser Scanner (3DLS) is established. Three problems in this flow were pointed out, namely that the scanning data has too many vertexes and polygons, there are jagged ridges on the edge of the scanned data and spotted losses. Thus, software for resolving these issues, "Poly-Opt" is developed.*

KEYWORDS*: 3D Scanner, Urban physical model, Virtual Reality, Polygon Optimization, Simplification, Point clouds*

1. INTRODUCTION

1.1 Background

In the field of architectural design and city planning, the opportunities for a variety of stakeholders to participate have increased. Therefore, a communications tool that everyone intuitively understands is requested. Hence, a SCMOD is often used together with CG/VR as a tool that can be understood easily. Moreover, the support of an effective workshop by using SCMOD and VR together is anticipated by reflecting the design idea studied by using SCMOD in VR in design workshops. Previous research shows that an effective design workshop can be managed by using VR and SCMOD together [M. Koga, et al. 2008]. However, SCMOD and CG/VR are often made in different processes. Therefore, much labor and high costs are involved.

Consequently, it is thought that the requisite labor and cost could be reduced if modeling were carried out automatically from a SCMOD to digital data. 3DLS is used as a method of making digital data from an existing object, such as a SCMOD, with high accuracy.

Recently, research using 3DLS has increased in the architecture, engineering and construction field. For instance, a 3D digital archive of historical buildings in Taipei is made by using 3DLS [H. Cheng, et al. 2009]. By using mobile mapping technology, a texture-mapped 3D city model is automatically constructed by image data captured by using CCD camera and building shape data measured by using 3DLS [Konno, et al. 2000]. Moreover, there has been research into the image-based modeling as a method of digitalizing objects without 3D scanner [Q. Pan, et al. 2009].

3DLS can provide accurate and complete details, but is expensive and not portable for a person to carry. Additionally, it isn't efficient for scanning large objects. On the other hand, image-based modeling can apply to various environments, but is not good at scanning objects with unmarked surface and modeling automatically [S.F. El-Hakim, et al. 2003]. 3DLS has been used because of the necessity of high accuracy in this study.

1.2 Purpose

In general, when a shape is made by using 3DLS, the volume of data becomes enormous. On the other hand, because real-time rendering (more than 10fps (frames per second)) is required in VR, it is necessary to reduce the volume of data of the vertexes and the polygons, etc.

There has been much research into polygon reduction to find a method of decreasing the number of polygons while keeping the shape of the solid as far as possible. For instance, to minimize energy, polygons were deleted by using the energy function had been defined by the each of the vertex coordinates and the vertex coordinates in the neighborhood [H. Hoppe, 1999]. However, because from hundreds to thousands of vertex coordinates are needed to decide one vertex coordinate, enormous computational complexity is involved. Moreover, a surface or a line that becomes a standard for a certain polygon group is generated, and polygons are deleted corresponding to the distance from the surface or the line to each vertex [W. J. Schroeder, et al. 1992]. Moreover, there is the QEM (Quadric Error Metrics) method of decreasing the number of polygons by deleting the ridge line where the square sum of the distance to surface that is adjacent to the each vertex is minimized [M. Garland, et al. 1997]. However, no system has been developed that considers the loss that exists in the scanned data by using 3DLS, or that considers the shape of the edges of the SCMOD that resemble a staircase when scanned by using 3DLS.

Therefore, the purpose of this study is to construct a VR modeling flow that generates optimal VR data from a SCMOD by using 3DLS. In this study, VIVID910 (Konica Minolta Sensing, Inc.) is used as 3DLS.

2. CONSTRUCTION OF A VR MODELING FLOW THAT GENERATES OPTIMAL VR DATA FROM SCMOD BY USING 3DLS

2.1 The current VR modeling flow and its problems

This section describes the general current VR modeling flow. First of all, the SCMOD is scanned by using 3DLS. 3DLS cannot scan a hidden surface. Therefore, the SCMOD must be rotated in steps, and must be scanned from 360 degrees. Next, a set of the scanned data is synthesized on "Polygon Editing Tool Ver.2.3" which is the software accompanying VIVID910. This data is output by a general VRML97 (Virtual Reality Modeling Language) format and scanned data is created.

However, there are three problems with using scanned data on the VR application. First, there are much more polygons and vertexes than needed. Therefore, it is difficult to draw shapes and to influence the rendering speed of VR. Secondarily, scanned data is output as mesh data, and the shape of the edge of the SCMOD resembles a staircase. Therefore, there is a problem that the edge of the SCMOD is not expressed accurately. Thirdly, part of the scanned data is lacking. This is because it is impossible to scan parts where the laser cannot penetrate or where the CCD (Charge Coupled Device) is invisible. Moreover, even for parts where the laser can penetrate and where the CCD is visible, scanned data is sometimes lacking, for example in the macula. Figure 1 shows the result of surface rendering and wireframe rendering of the scanned data generated from a cube with 49mm sides.

Thus, it is necessary to convert scanned data into optimal scanned data to solve these problems. The replacement of polygons with planes is effective because many objects that compose a SCMOD consist of planes. Therefore, a polygon optimization system "Poly-Opt" that automatically converts scanned data into optimal scanned data has been developed.

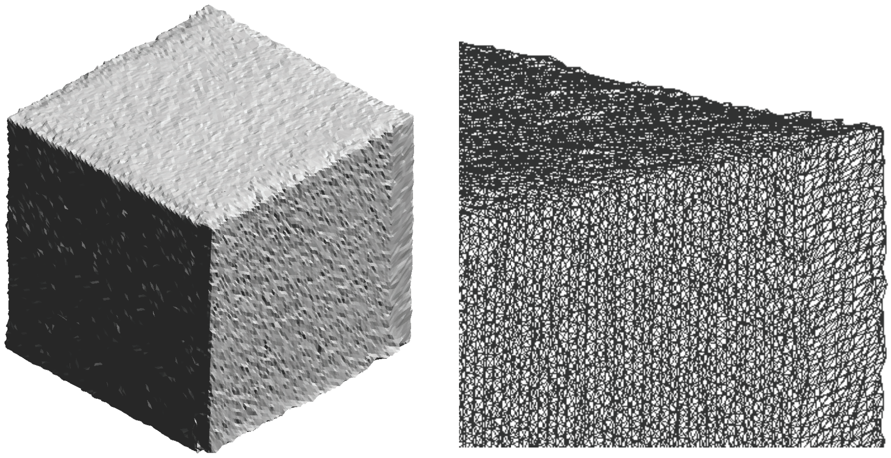


Figure 1: Scanned data generated from a cube: Surface rendering (left) and wireframe rendering at the edge (right)

2.2 Development of polygon optimization system: "Poly-Opt"

2.2.1 Outline of system

Figure 2 shows the processing flow of Poly-Opt. First of all, to carry out the VR authoring easily, the rotation transformation is done from the original coordinate axis of scanned data to the horizontal and vertical coordinate axis (section 2.2.2). Next, the planes including each surface of scanned data are generated. Then, the vertex that becomes the edge of the object is calculated by making a simultaneous equation for each generated plane and obtaining the solution (section 2.2.3). Finally, the polygon is generated by uniting the obtained vertex groups by the Delaunay triangulation method (section 2.2.4). The argument when Poly-Opt is executed described as follows. *k*: Index of arbitrary vector; θ (degree): Permissible angle of extracted normal vector; L_1 (mm): Distance in the perpendicular direction between planes that are separated; L_2 (mm): Distance in the horizontal direction between planes that are separated; *R* (mm): Composure given to codomain obtained by the plane equation.

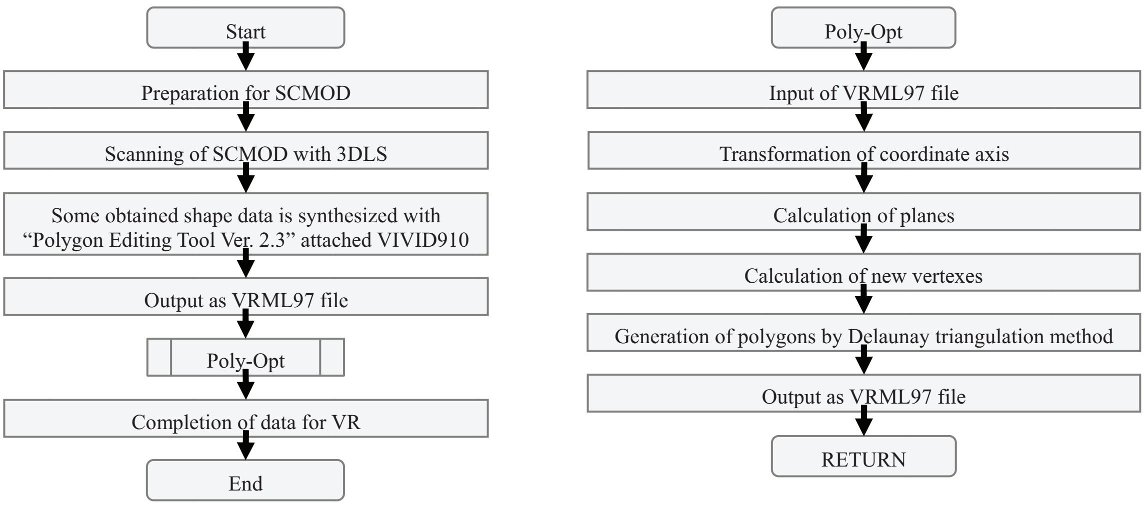


Figure 2: The entire VR modeling flow (left) and the entire Poly-Opt flow (right)

2.2.2 Transformation of coordinate axis

First of all, the polygons of the triangle and the quadrangle exist together in scanned data. Then, all polygons are divided into a triangle.

As for the coordinate axis defined by scanned data, the z axis is set in the direction where it faces 3DLS from the scanned object. Because 3DLS is set up to look down at the scanned object diagonally, the inclination of the coordinate axis is different from the vertical and horizontal relation of a real space. Moreover, the original point of the coordinate axis is defined in the laser irradiation part of 3DLS. Because 3DLS and the scanned object are several tens of centimeters apart, the absolute value of the coordinate value of scanned data usually has a high value. A problem at the following VR authoring stage appeared in the definition of such a coordinate system.

Then, the inclination of the coordinate axis and the distance between the original point and scanned data are corrected. Affine transformation is carried out on all the vertex coordinates, and the coordinate axis of scanned data is transformed.

2.2.3 Calculation of planes

At this stage, a plane equation including scanned data and the codomain is calculated. First, the polygon group P_A is extracted whose angle generated from each normal vector $\boldsymbol{v}_U(i)\ (i = 1,2,\cdots,n(P_U))$ of all polygons (polygon group P_U) and the normal vector $\boldsymbol{v}(k)$ of the certain polygon $P(k)$ is less than θ. Next, the element of each normal vector of the polygon group P_A is calculated by the arithmetic average method, and $\overline{\boldsymbol{v}}$ is calculated. As a result, a plane equation T which passes the gravity center $G(k)$ of the polygon $P(k)$ and has a normal vector $\overline{\boldsymbol{v}}$ is generated.

Next, the polygon group P_B is extracted, by which the distance with each gravity center $G_A(i)\ (i = 1,2,\cdots,n(P_A))$ of the polygon group P_A and the plane T becomes less than L_1. The coordinate value $G_B(i)\ (i = 1,2,\cdots,n(P_B))$ of each gravity center of the polygon group P_B is calculated by the arithmetic average method, and point $\overline{G}$ is calculated. As a result, a plane equation X which passes the point $\overline{G}$ and has a normal vector $\overline{\boldsymbol{v}}$ is generated.

Finally, information on the codomain that defines the area of the plane X is added to the decided plane equation. If the codomain is not set, a plane equation is defined in an infinite range. The method of deciding the codomain of the plane X is as follows. The perpendicular is extended from gravity center $G_B(i)\big(i = 1,2,\cdots,n(P_B)\big)$ to the plane X, and the intersection is defined as $H(i)\ (i = 1,2,\cdots,n(P_B))$. The point at which the distance from point $H(k)$ is less than L_2 is extracted from point group $H(i)$, and is defined as point group $H_0(i)$. Next, the point at which the distance from point $H_0(i)$ is less than L_2 is extracted from point group $H(i)$, and is defined as point group $H_1(i)$. This procedure is repeated until the extracted point does not exist. The point finally obtained is defined as point group $H_{codomain}(i)$. Point group $H_{codomain}$ is made polygonal the convex hull. Then, the polygonal shape is expanded by R and is defined as the codomain of the plane X.

Scanned data and the plane X are displayed in the overlay. When the user selects an appropriate substitution plane candidate, the plane X is added to the array that stores the plane group. Then, the user selects arbitrary vector $P(k)$ again, and repeats the operation for the other surfaces. When the user judges that substitution of all planes is complete, the process shifts to the next step. Figure 3 shows an example of displaying the substituted plane and the codomain.

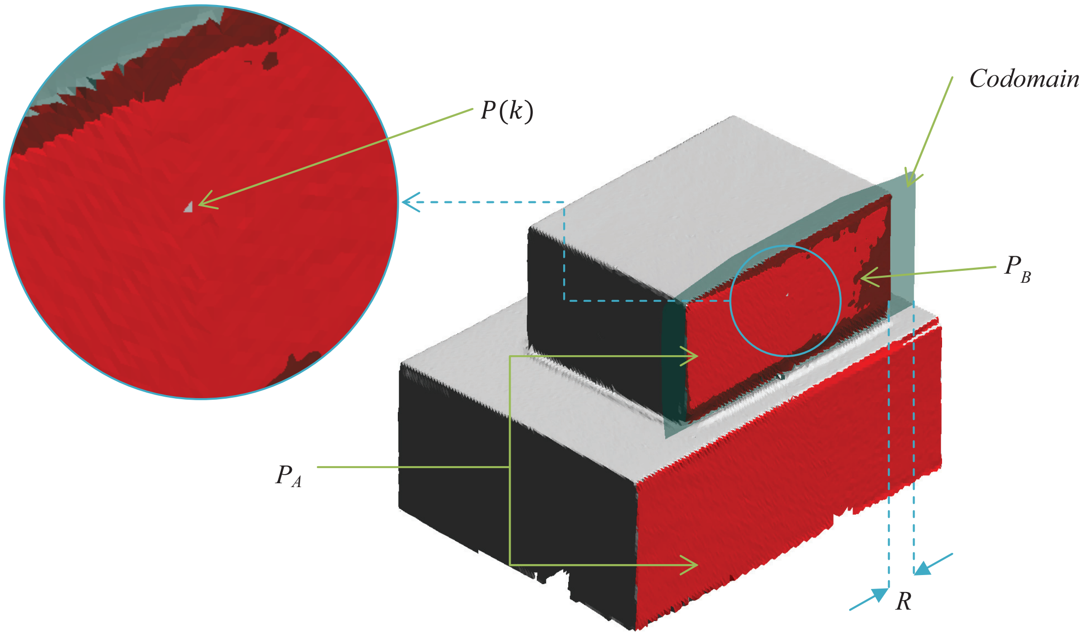


Figure 3: The display of the substituted plane and its codomain.

2.2.4 Calculation of the new vertex and polygon generation

The vertex is calculated from the plane equation calculated in the preceding clause. The coordinates of the vertex are calculated by solving the simultaneous equations that used the three calculated plane equations. When the coordinates in the calculated vertex do not exist in the codomain defined in the preceding section, the coordinates are annulled. This inside and outside judgment of the vertex is calculated by the outer product of the vector because the codomain is the convex polygon, and all the vertexes of the convex polygon exist on flush. First of all, point group $H_{codomain}(i)$ is sorted to be unicursal. Next, the orthogonalization coordinates (vw plane) of two dimensions are defined on the plane. Then, the projection conversion is done, and each vertex $H_{codomain}(i)$ of the convex polygon and coordinates of point S are defined in the vw plane respectively as $\mathrm{H}'(i) = (v_i, \ \ w_i, \ \ 0)$ and $S' = (s_v, \ \ s_w, \ \ 0)$. Here, z coordinates are defined as 0. Then, the outside product of the vector $\overrightarrow{H'(\iota)H'(\iota+1)}$ composed of two adjoining points and vector $\overrightarrow{H'(\iota)S'}$ composed of one of the points and the vertex are calculated. The vertex exists in the codomain if all signs of the z coordinates of the obtained vector are the same. Otherwise, the vertex exists outside of the codomain.

Finally, a triangular polygon is generated from the vertex with the Delaunay triangulation method which is the way of dividing plane by generating triangles from a point group on flush. This system acquires the coordinates of the vertex by solving the three plane equations as a simultaneous equation. Therefore, the Delaunay triangulation method can be used because there is a guarantee that all the vertexes obtained from the same plane are sure to exist on flush.

3. EXPERIMENTS FOR EVALUATION

This chapter verifies the accuracy and the data reduction of optimal scanned data by executing Poly-Opt for scanned data. The sample scanned data are primitive solids (solid A, B and C) and plural cubes that are used in the SCMOD.

3.1 Method of verification

3.1.1 Accuracy verification

A cube with 41mm sides (made of Styrofoam) was scanned by using 3DLS and scanned data was made. A TELE lens (focal length = 25mm, degree of accuracy = 0.10mm ~ 0.22mm) with the highest accuracy was used for 3DLS. Afterwards, Poly-Opt was executed and optimal scanned data was generated. Then, the accuracy of Poly-Opt was verified according to the actual measurement value, the measurement value of the scanned data, and the measurement value of the optimal scanned data. Compared items were the length of a side and the angle generated with planes.

The length of a side of the scanned data generated its bounding box, and the length of a side of the bounding box was measured. The angle of the scanned data was not measured because it is too difficult to do so.

3.1.2 Verification of data reduction

Analysis of how data can be reduced is carried out by the developed Poly-Opt software. The amount of reduction of the size of the file, the number of vertexes, and the number of polygons is calculated for scanned data and optimal scanned data of three kinds of solids (solid A: a wooden cube with 49.3mm sides) / solid B: a wooden quadrangular pyramid whose base plane is a 49.5mm square and whose height is 48.5mm / solid C: a complex which is composed of two hexahedrons (120×90×50mm and 80×60×40mm) made of styrene board) used with SCMOD. In addition, the accomplishment rate to an ideal value of the optimal scanned data is calculated (1).

$$(The\ accomplishment\ rate) = \frac{(The\ ideal\ value)}{(The\ value\ of\ optimal\ scanned\ data)} \times 100 \quad (1)$$

3.1.3 Application for SCMOD

In this section, Poly-Opt is executed on a SCMOD (1/500 reduced scales) with arranged plural solids. The three hexahedrons of 15×50×50mm, 25×53×67mm, and 31×31×50mm are set at intervals of 2mm or 12mm (see Figure 4), which is assumed to be the interval between one building and the next without a road, and the interval between one building and the next with a road in an urban street.

Here, a plane definition method of expressing ground in Poly-Opt is described. In Poly-Opt, the new vertex is calculated based on the plane intersection substituted by the calculated polygon group. Therefore, ground is defined only by the polygon that connects the low-side vertexes of each building mutually. Then, the size of ground is defined by the user selecting the plane that becomes ground, and adding the anchor of the codomain as the vertex.

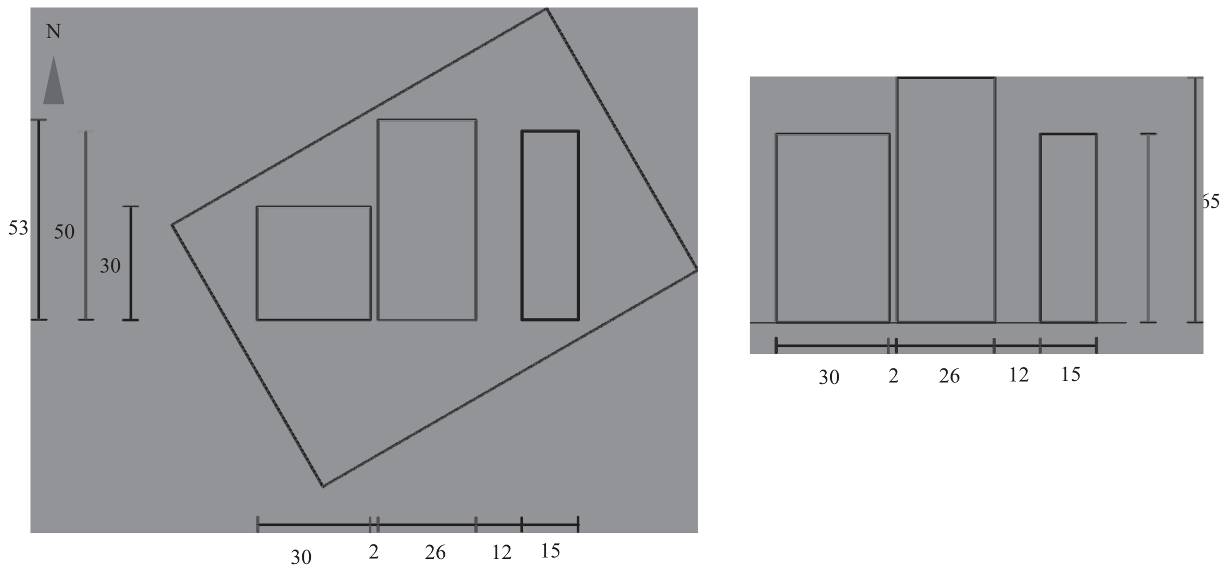


Figure 4: top view (left) and front view (right) of SCMOD (unit: mm).

3.2 Results and discussion

Table 1 shows the result of accuracy verification. The range error between the actual measurement value and the value of the optimal scanned data is maximum: +3.13mm, minimum: -0.52mm, average: +1.25mm and standard deviation: 0.95. The angular error is maximum: +2.78 degrees, minimum: -1.92 degrees, average: -0.01degree and standard deviation: 1.39. The range error of 3.13mm on the SCMOD in 1/1000 scale which is a general scale becomes a gap of 3.13m. This is larger than the gap in the process of producing the SCMOD and is difficult to allow. On the other hand, the angular error of 2.78 degrees becomes a gap of 1.99mm from a right point, 41mm ahead, and is smaller than the range error. It must be clarified that the error originates in 3DLS or Poly-Opt, and making the error margin smaller is a future work.

Next, the range error between the actual measurement value and the value of the scanned data is maximum: +13.38mm, minimum: +3.79mm, average: +7.65mm and standard deviation: 4.13. This range error is more than that between the actual measurement value and the value of the optimal scanned data. The bounding box is thought to become larger than the actual solid because there is ruggedness in the surface of the scanning data and the scanning measurement value is larger also.

Table 1: Result of accuracy verification.

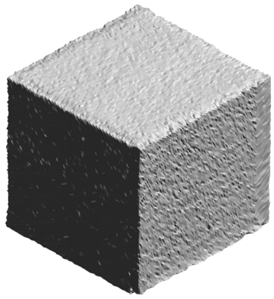
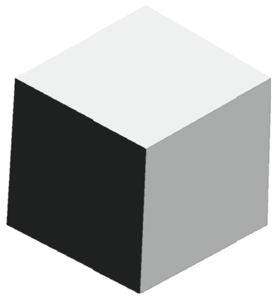
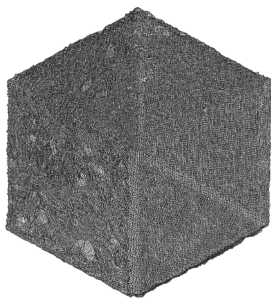
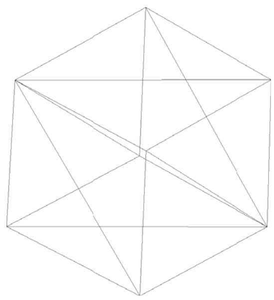
		Actual measurement value	**Scanned data**			**Optimal scanned data**		
Surface rendering								
Wireframe rendering								
			Value	**Difference from actual measurement value**	**Ratio to actual measurement value**	**Value**	**Difference from actual measurement value**	**Ratio to actual measurement value**
Range error (mm)	**Maximum**	41.0	54.39	+13.38	+32.65%	44.13	+3.13	+7.73%
	Minimum	41.0	44.80	+3.79	+9.26%	40.48	-0.52	-1.26%
	Average	41.0	48.65	+7.65	+18.66%	42.25	+1.25	+3.04%
	Standard deviation	0	4.13			0.95		
Angular error (degree)	**Maximum**	90.0				92.78	+2.78	3.09%
	Minimum	90.0				88.08	-1.92	-2.13%
	Average	90.0				89.99	-0.01	-0.01%
	Standard deviation	0				1.39		

Table 2 shows the result of reduction of data size. The value of the optimal scanned data can be reduced in terms of the file size, the number of vertexes, and the numbers of polygons by 99% or more. Moreover, the accomplishment rate is 100%. In data reduction, it can be said that Poly-Opt is effective.

Table 2: Result of reduction of data size

		Scanned data	Optimal scanned data	Reduction rate	Ideal value	Accomplishment rate
Solid A	**File size**	795 KB	973 B	99.88%		
	Number of vertexes	11,111	8	99.93%	8	100.00%
	Number of polygons	22,218	12	99.95%	12	100.00%
Solid B	**File size**	584 KB	803 B	99.86%		
	Number of vertexes	8,305	5	99.90%	5	100.00%
	Number of polygons	16,356	7	99.93%	7	100.00%
Solid C	**File size**	4,559 KB	1.29 KB	99.97%		
	Number of vertexes	60,063	16	99.97%	16	100.00%
	Number of polygons	119,044	30	99.97%	30	100.00%

Table 3 shows the result of application for a SCMOD. The surface rendering and wireframe rendering of the scanned data and the optimal scanned data is shown in Figure 5. The Optimal scanned data can be reduced in terms of file size, the number of vertexes, and the numbers of polygons by 99% or more for the SCMOD. Moreover, the buildings located at intervals of 12mm can be distinguished, though the buildings located at intervals of 2mm cannot. On the other hand, the accomplishment rate is not 100% because the expected shape cannot be obtained from the L-shape solid. This is why the Delaunay triangulation method is used when the polygon is generated, and it will be necessary to search for the more suitable algorithm in the future.

Table 3: Result of application for the SCMOD

	Scanned data	Optimal scanned data	Reduction rate	Ideal value	Accomplishment rate
File size	9.86MB	3KB	99.97%		
Number of vertexes	95,807	27	99.97%	27	100.00%
Number of polygons	188,500	58	99.97%	57	98.28%

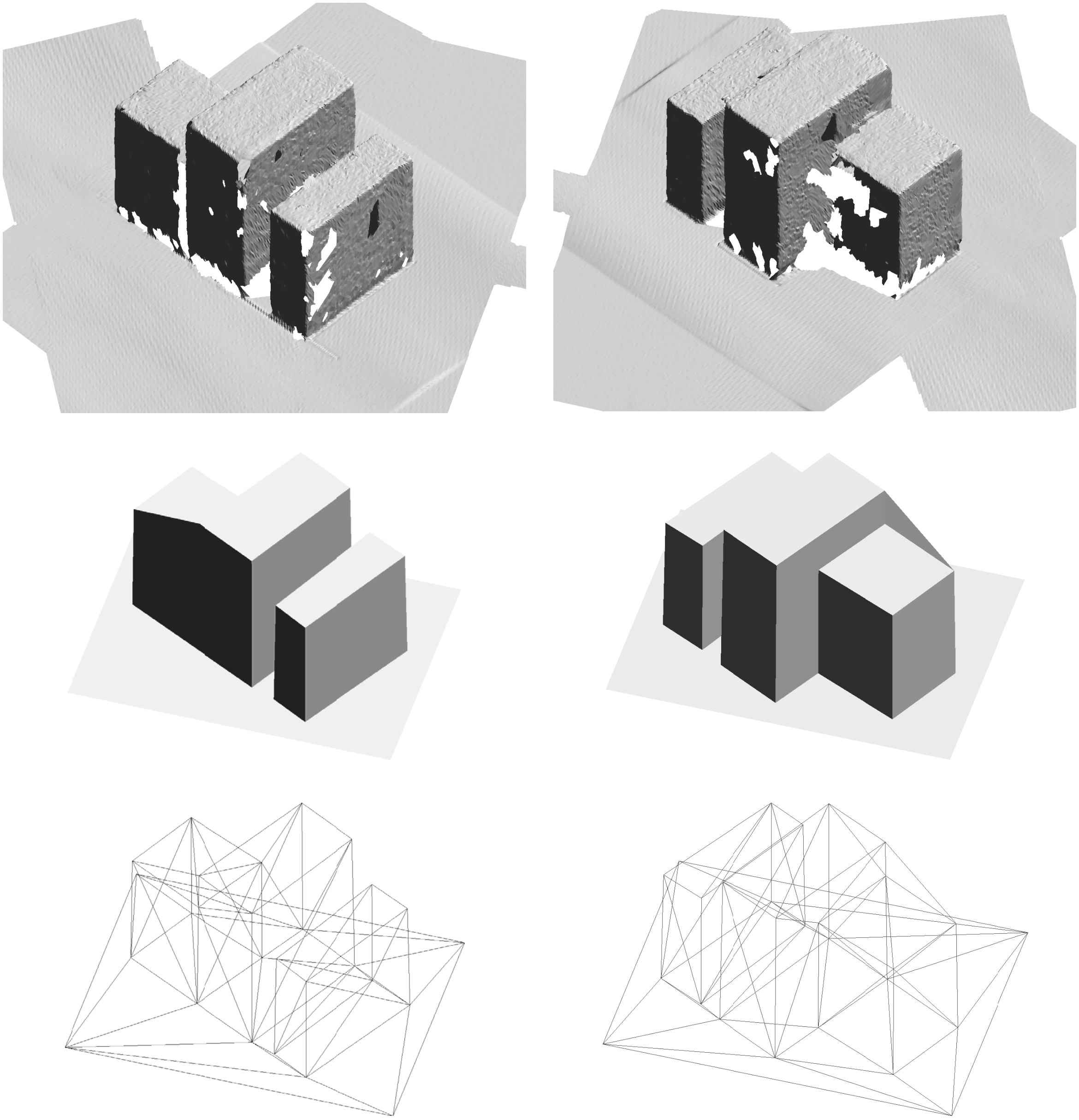


Figure 5: Surface rendering of the scanned data (top), and surface rendering (middle) and wireframe rendering (bottom) of the optimal scanned data (left: south view; right: north view).

4. CONCLUSION AND FUTURE WORK

The achievements of this study are as follows.

- Three problems in the current VR modeling flow are pointed out, namely that scanned data has more vertexes and polygons than needed, the edge of the model has a stair-like shape, and the spotted losses. The polygon optimization system "Poly-Opt" for solving these issues is developed.
- In the solid object that composes a SCMOD, the range error between the actual measurement value and the value of optimal scanned data is maximum: 3.13mm, minimum: -0.52mm, average: +1.25mm and standard deviation: 0.95. The angular error is maximum: 2.78 degrees, minimum: -1.92 degrees, average: -0.01 degree and standard deviation: 1.39. The range error is difficult to allow, but it is necessary to clarify the cause of the large angular error and to minimize it.
- In the solid object that composes a SCMOD, the authors succeeded in reducing the scanning data by 99%

or more. The generation result of the vertexes and the polygons was ideal, and the issues of the stair-like shape of the edge and the spotted losses seen in the scanning data could be solved.

- In the typical SCMOD where plural solids exist, the authors succeeded in decreasing the scanning data by 99% or more. On the other hand, the accomplishment rate was not 100%; in the L-shape solid the generated polygons were not applicable. It will be necessary to search for the more suitable algorithm beyond the Delaunay triangulation method.

Future work following this study will be as follows.

- Because it requires great care for user to fix each plane manually, it is necessary to be able to automate this process.
- Scanned data with curved surfaces has not been considered yet. It is thought that using an algorithm for general polygon reduction would be effective for a curved surface. Therefore, the function to distinguish a plane surface part from a curved surface part is necessary.
- 3DLS used in this study has a function that can acquire texture data. However, Poly-Opt is non-compliant to texture mapping because the texture coordinate cannot correspond to generated vertexes and polygons after Poly-Opt.
- There is a possibility that scanned data is oversimplified, and then jagged ridges on the edge which should be kept are omitted as the case maybe. A function of level of detail should be developed.
- The operating process in this system cannot be visualized. For example, a user cannot find the polygon identified by the argument *k*, index of arbitrary vector. Then GUI (Graphical User Interface) should be developed.

5. ACKNOWLEDGEMENTS

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RESEARCH ON GENERATION OF A 3D MODEL USING BREAKLINE FROM POINT CLOUD DATA

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ABSTRACT: *For the purpose of promoting efficiency and assuring quality of public work projects, it is encouraged to arrange environment using Information and Communication Technology (ICT) such as CALS/EC and intelligent construction. In this context, the authors established a workshop about the establishment of data distribution environment in a collaborative way in Kinki Regional Development Bureau, Ministry of Land, Infrastructure and Transport (MLIT) to perform joint research aiming to realize intelligent construction in river projects using 3D data. Intelligent construction requires 3D models with high precision that represent actual conditions of terrains faithfully. However, there are problems; a problem that arises in reading a large amount of point cloud data, and a problem of causing fault extraction to breakline in treating natural land forms. This paper solves these problems by proposing a method for generating a 3D model in consideration of cross-sectional change point using point cloud data. Then experiments are performed to compare with existing methods to prove validity of the proposed method.*

KEYWORDS*: Point cloud data, 3D model, CAD, Intelligent construction.*

1. INTRODUCTION

For the purposes of ensuring transparency of public works projects, improving business efficiency, and assuring quality, public institutions including MLIT are working on the measures for constructing a data circulation environment using ICT such as CALS/EC and intelligent construction (MLIT 2006, MLIT 2007, MLIT 2009, and MLIT intelligent construction promotion conference 2009). With these measures promoted, efforts to apply in product models such as development of Road Alignment Data Exchange Standard (Kanazawa 2007), as well as advanced efforts for intelligent construction (Committe on earthwork compaction control intelligent construction 2009, Kanazawa 2009, MILT 2008, Shiiha 2009, Tanaka 2009) are being made under the initiative of public institutions. Cases of the advanced efforts for intelligent construction include as-built management technologies using Total Station (TS) and Global Navigation Satellite System (GNSS), and a construction management case using a compaction record of fill earthwork. In the former case, construction management is performed by a method of managing finished work quality by measuring road surface width, slope length, and the standard height using TS, and a method of automatically managing cut and fill volumes. In the latter case, construction management is performed by a method of monitoring operating situations of the site facilities and the location of the excavating machinery in a large-scale earthwork to help optimum machinery arrangement. It is considered that for these cases, offering high-precision 3D models that reproduce the present topography will contribute to further advancement of construction management.

In this context, the authors set up a workshop on establishing a data circulation environment for river projects in Kinki Regional Development Bureau, MLIT to perform joint research for the purpose of promoting new technology development with industry-academic-government.

Specifically, we aim at generating high-precision 3D models that reproduce the present topography of rivers with ease, and applying them to intelligent construction in order to improve work efficiency and construction quality.

On the other hand, the method to generate a 3D model that reproduces present topographic features has been devised in the existing research. One of the past works that is helpful is a method of generating 3D models automatically from point cloud data (Fukumori 2009) measured by a highly precise scanner (Fukumori 2009, Furuya 2004, Gumhold 2001, Kobayashi 2009, Otsu 2007). Presently measurement devices for point group coordinate data show remarkable performance, so introducing them into intelligent construction will lead us to enjoying their effects in various scenes. However, to generate 3D models with raw point cloud data collected by laser scanners and use them in construction management, there is a problem that the number of point cloud data measured by the laser scanner is too enormous for common CAD or CG software programs to read. So some approaches to this have been devised in existing research, including a method to generate mesh data by automatically thinning out the point cloud data acquired by the laser scanner, and a method to generate a 3D model by thinning out the measured point cloud data, keeping the characteristic information alone such as break lines and removing redundant point clouds. The method to generate mesh data by automatically thinning out the point cloud data uses a gridlike filter with constant intervals, narrowing down processing objects using the window method at every intersection point of the grid, and interpolating them to obtain a collection of points, from which thinned-out point cloud data is generated. This makes it possible for common CAD software programs to read the data.

As a result, point cloud data that were measured at irregular intervals are arranged like a grid. Therefore, it allows to generate an intuitively easy-to-understand 3D model that precisely reproduces the characteristics of the object by adjusting grid intervals. The precision of the 3D model generated by this method depends on the grid interval. However, in treating the enormous number of point clouds for large-scale construction, it is necessary to reduce the amount of data by widening the grid interval. In this case, there is concern that it is unable to reproduce boundaries between surfaces on a 3D model, still leaving a problem that it is assumed to be unable to recognize the road surface or slope faces, which are important in intelligent construction.

To cope with this problem, existing research has devised methods to use relative positions of point clouds or to use color information added to the point cloud data in order to extract break lines. For the method of using relative positions of point cloud data, a method of using mesh normal vectors, a method of using curvature, and a method of using angles (MLIT 2003) have been studied. These methods are effective when generating a geometric 3D model with clear boundary surfaces. However, in the case of river embankment, clear boundary lines may not exist between the road surface and the slope. Furthermore, noise of gravel or vegetation may affect extraction of breaklines to cause errors. In addition, the method of using color information added to point cloud data is effective in generating a 3D model for the conditions where there are such markings as a centerline or side strips. However, it may be difficult to distinguish from color information if there is no clear identifier to show the boundary of surfaces such as a side strip.

Based on these problems, the aim of this research is set to suggest a method to automatically generate a 3D model that correctly recognizes the boundaries of surfaces of a river embankment from a relative positional relationship of the point cloud data collected by the laser scanner.

2. OVERVIEW OF RESEARCH

2.1 Goals

This paper proposes a method of automatically generating a 3D model using point cloud data, which has solved the problem that boundaries between surfaces cannot be recognized when the point cloud data is thinned out, as discussed in the previous chapter.

First, breaklines are extracted from the input point cloud data. Next, the breaklines are overlapped with a grid filter to create a breakline filter. Using the filter, interpolation processing of the point cloud data is performed. Then, a 3D model is generated using the point cloud data that are left behind. At this time, the proposed method controls extraction errors of breaklines by specifying the area of extracting breaklines.

The result of this research will allow the commercial 3D CAD software packages to read in point cloud data and to generate a detailed 3D model in which the boundaries of surfaces can be recognized.

2.2 Flow of process

The process of generating a 3D model in this research comprises a function of breaklines extraction and a function of thinning out point cloud data. The point cloud data that are output using these two functions realizes a method of generating a 3D model, making the best use of a special feature of highly precise point cloud data. The procedure of each function proposed in this research is shown below.

3. FUNCTION OF BREAKLINES EXTRACTION

The function of breaklines extraction works to extract breaklines by entering the point cloud data acquired by the laser scanner and the Digital Mapping (DM) data. Here we assume the point cloud data acquired by the laser scanner as $P=\{p_1, p_2, p_3, ..., p_i\}$. This function solves the problem of extraction errors of breaklines discussed in Chapter 1. The following are the details of each process.

3.1 Process of limiting the extraction range

Figure 1 shows the concept of the process of limiting the extraction range. In this process, we acquire a road line from the DM data and nominate it for a breakline. Polygonal line elements to indicate road lines (element number 2101 and 2106) are adopted for the road lines based on the real implementation rules and various standards (MLIT 2005). Next, we create a rectangle area from the starting point of the nominated breakline for every distance s with width w and height h. Then we extract point cloud from within the created area. We assume the area obtained from this process as $RC=\{rc_1, rc_2, rc_3, ..., rc_j\}$, and the point cloud data included in rc_j as $Pj = \{pj_1, pj_2, pj_3, ..., pj_k\}$.

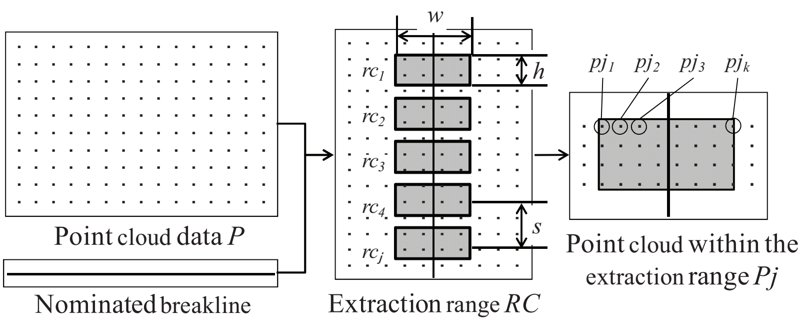


Fig. 1: Concept of process of limiting extraction range

3.2 Process of acquiring cross-sectional change points

In the process of acquiring cross-sectional change points, in order to make section line from each area rc_j of the area RC acquired by the process of limiting the extraction range, we compress point cloud data Pj into a 2D space using each point pj_k and the distance from the input line. Specifically, as shown in Figure 2, let elevation be the vertical axis, and the length of the perpendicular of each point for the input line be the horizontal axis, we perform projection transformation of the 3D point cloud. At this time, the points within the Distance t from each point pj_k are removed. We assume the 2D point cloud data acquired from this process as $P'j=\{p'j_1, p'j_2, p'j_3, ..., p'j_l\}$.

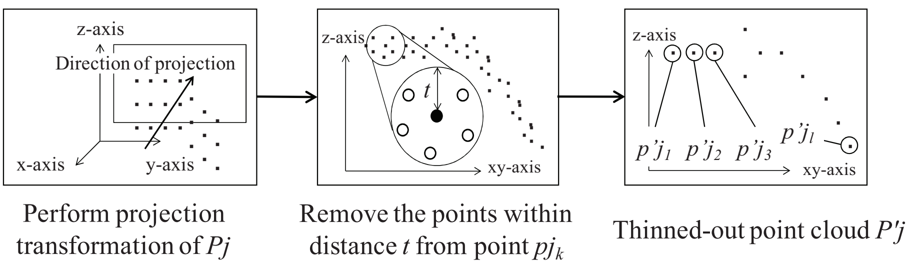


Fig. 2: Concept of projection transformation to 2D space

Next, we make an approximation of the section line from the 2D point cloud $p'j_l$. In making an approximation, we make a polygonal line that connects 2D point cloud $p'j_l$ and $p'j_{l+1}$ together to indicate the section line, as shown in Figure 3. If there are more than one points that are at equal distances from $p'j_l$, the point with higher elevation is adopted as pj_{l+1}.

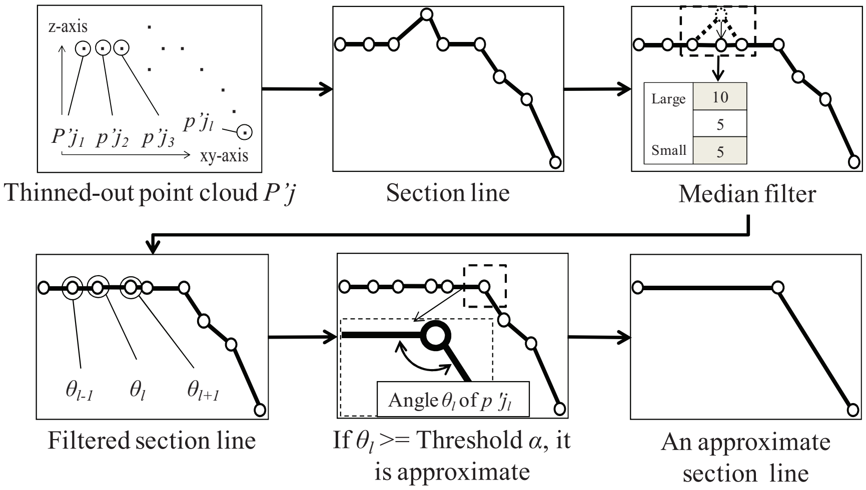


Fig. 3: Concept of section line approximation

Subsequently we smooth the values of the vertical axis of the polygonal line by the median filter (Pratt 1978). The median filter is a noise removal method to use the medians of the value of interest $p'j_l$ and the values before and after it, $p'j_{l-1}$ and $p'j_{l+1}$, as effective values. Therefore, unlike smoothing with the arithmetic mean, smoothing with the median filter can acquire the result of removing the influence of the pulse noise. Here, if the angle θ_l of vertex of the polygonal line $p'j_l$ is greater than the threshold α, we make linear approximations of the two lines containing vertex $p'j_l$.

Finally, from each approximated segment, we acquire cross-sectional change points. In acquiring cross-sectional change points, as shown in Figure 4, first from the approximated section line segment, we extract section line segments to which the angles from the horizontal line is within the threshold β. Next, from among the end points of the extracted horizontal lines, we acquire the nearest point to the input line in distance as a cross-sectional change point. Then we apply the process of acquiring cross-sectional change points to every area rc_j. We assume a set of the cross-sectional change points obtained from this process as $Px=\{px_1, px_2, px_3, ..., px_j\}$.

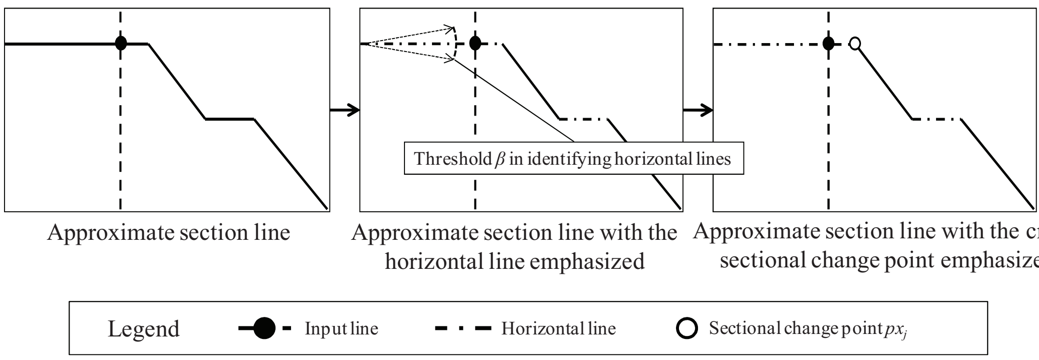
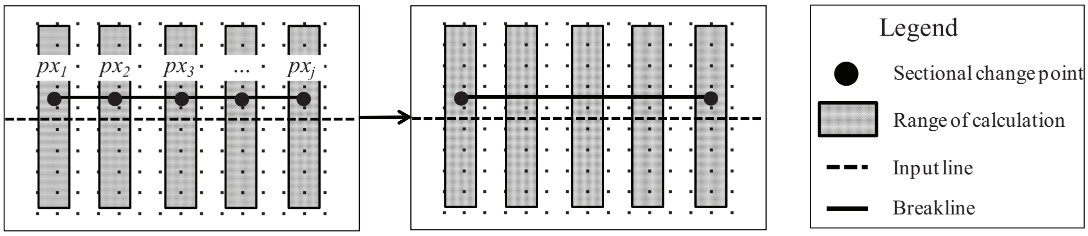


Fig. 4: Concept of acquiring cross-sectional change points

3.3 Process of creating breaklines

In this process, a breakline is created with the acquired cross-sectional change points Px. Specifically, as shown in Figure 5, we create a polygonal line by connecting each point px_j of a cross-sectional change point Px.



Set of cross-sectional change points *Px* Breakline *L*

Fig. 5: Concept of process of creating breaklines

Next, let the distance from the starting point of the input line of the area where each point px_j was acquired be the horizontal axis, and the length of the perpendicular of each point from the input line the vertical axis, smoothing is performed using the median filter. This process makes it possible to remove cross-sectional change points extracted by mistake due to noise such as gravel or vegetation. Then we make a breakline *L* with the sequence of points *Px* of the smoothed cross-sectional change points as vertices.

4. THE FUNCTION OF THINNING OUT POINT CLOUND DATA

The function of thinning out point cloud data is used to perform processes of thinning out the points *P* acquired by the laser scanner. The following are the details of each process.

4.1 The process of creating a filter

In this process, a grid filter is created with an interval *g* containing the input point cloud data p_i. We assume that each intersection point of the grid filter obtained in this process is $F=\{f_1, f_2, f_3, ..., f_n\}$. Then the grid filter $BF=\{bf_1, bf_2, bf_3, ..., bf_o\}$ that considers the breaklines proposed in this research is calculated using the next formula (1).

$$BF = F \cup L \tag{1}$$

4.2 Process of interpolation of the point cloud data

In this process, we extract point cloud data $Pw=\{pw_1, pw_2, pw_3, ... pw_q\}$ from the point bf_o, which is contained in the filter *BF* obtained by the process of creating a filter using "Window method" (Murai 1999). The window method is a narrowing method to assume point cloud data p_i contained in the rectangle area with the intersection point bf_o as its center and with the length of one side *g* as a processing object. Next we acquire the value of the elevation in bf_o by way of interpolation process using the weighted mean from the point cloud data *Pw*. The interpolation process using the weighted mean is calculated with Formulae (2) and (3). Assuming *x*, *y*, and *z* coordinates in bf_o and pw_q in Formula (2) as bfx_o, bfy_o, bfz_o, pwx_q, pwy_q, pwz_q, we obtain the weight parameter $weight(Pw_q)$ for each point. Next, we obtain the elevation of bf_o, Z_{bfo}, with Formula (3).

$$weight(Pw_q) = \frac{1}{\sqrt{(pwx_q - bfx_o)^2 + (pwy_q - bfy_o)^2}} \tag{2}$$

$$bfz_o = \frac{\sum weight(Pw_q) \bullet pwz_q}{\sum weight(Pw_q)} \tag{3}$$

Interpolation calculation is a calculation technique to estimate the value of any given point pa_{r+1}, when there are 3D data $Pa=\{pa_1, pa_2, pa_3, ..., pa_r\}$, the number of which is *r*. This research derives an elevation of bf_o by applying a weighted mean to the data, which are *Count(Pw)* in number, included in a rectangular area with the center point bf_o and side length *g*, using the window method. The weighted mean is a technique of calculating a mean in consideration of the weight of each value, unlike a general arithmetic mean. At this time, the weight parameter for each value is assumed to be the horizontal distance from any given point bf_o to each point pw_q. Then by removing those except the 3D point cloud data for which an elevation was given to each intersection point bf_o, they are converted into the point cloud data that are thinned out and arranged in a grid shape.

5. EXPERIMENT TO GENERATE A 3D MODEL

We carried out an experiment to generate a 3D model in order to verify the usability and effectiveness of the method of generating a 3D mode using point cloud data devised in this research. In the experiment, we used both simulation data representing a simple geometry and point cloud data collected by measuring an actual river embankment.

5.1 Experiment environment

Table 1 shows the specification of the equipment used in this experiment. In this experiment, we generate a 3D model from two kinds of thinned-out point cloud data: one is the data output by the proposed method that takes breaklines into consideration, and the other by a conventional method that applies only a grid filter. In generating a 3D model, we use AutoCAD Civil3D 2010 of Autodesk with functions of reading in point cloud data and generating Triangulated Irregular Network (TIN), along with UC-Win/Road ver3.04.12 of FORUM 8. Note that UC-Win/Road was used in this experiment with a function of reading in point cloud data newly developed.

Table 1: Experiment environment

Type	Equipment	Item	Value
Hardware	Machine for the experiment	CPU	Inter® Core™2 Duo CPU 2.50Ghz
		Memory	4.0GB
		HDD	280GB
Software	Developing environment		Visual Studio 2005
	Language		Visual C++
	CAD Software		AutoCAD Civil 3D 2010
	CG Software		UC-Win/Road ver.3.04.12

5.2 Experimental conditions

In this paragraph, we set seven parameters: s, w, h, t, α, β, g to use in the proposed method as experimental conditions. For the five parameters of s, w, h, t, and g, we empirically set the value according to the result of the preparatory experiment. The following are the properties of each parameter derived as a result of the preparatory experiment.

5.2.1 Setting Parameter *s*

Parameter s is a value for setting extracting intervals of the cross-sectional change point in "process of limiting the extraction range". As a result of the preparatory experiment, when a small value was set for the parameter s, the intervals of an output breakline got narrower, while the precision tended to decrease under the influence of vegetation and so on. On the other hand, when a large value is set, the number of acquired cross-sectional change points decreased, and the tendency was seen that the influence such as of vegetation was strongly reflected in the breakline. Therefore we adopted $s = 0.5$(m) in this experiment.

5.2.2 Setting Parameters *w* and *h*

Parameters w and h is a value for setting the extracting range of the cross-sectional change point in "process of limiting the extraction range". As a result of the preparatory experiment, when a small value was set for each of the parameters w and h, the precision tended to decrease under the influence of vegetation and so on. On the other hand, when a large value was set for each of the parameter w and h, the precision of the cross-sectional change point tended to decrease. It seems that this is because it is influenced more strongly by the noise as the acquisition area gets larger. Therefore we adopted $w = 2.0$(m) and $h = 1.0$(m) in this experiment.

5.2.3 Setting Parameter *t*

Parameter t is a value for setting intervals in thinning out the point cloud within the extraction area in "process of interpolation of the point cloud data" As a result of the preparatory experiment, when a small value is set for parameter t, the precision of the cross-sectional change point improves, while it becomes more subject to be affected by small noise such as gravel or the measuring error. On the other hand, when a large value was set, the precision of the cross-sectional change point tended to decrease in proportion. It seems that the measuring precision gets lower than the original precision as the point cloud density falls down. Therefore we adopted t = 0.01(m) in this experiment.

5.2.4 Setting Parameter g

Parameter g is a value for setting the interval of the grid filter in "process of creating a filter". When a small value is set for parameter g, the precision of the 3D model to be generated tends to improve, while the data volume to be output also increases.

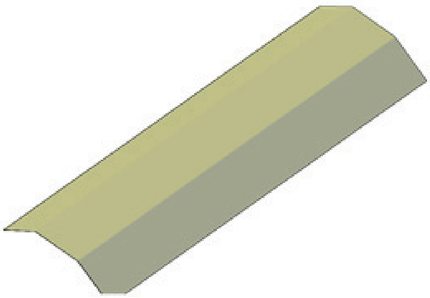
On the other hand, when a large value was set, the precision of the 3D model to be generated tends to decrease. In addition, it is generally required to have the interval of the grid g larger than that of the breakline. Therefore we adopted g = 2 in this experiment. Note that the precision of this value is approximately 20 times as precise as that found in the as-built management standard provided by MLIT.

5.2.5 Setting Parameters α and β

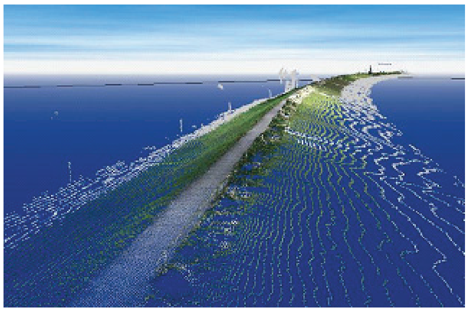
Next, we discuss the role of parameters α and β and the values adopted for them. Parameter α and β are threshold values to use in identifying the gradient of the road in the process of acquiring cross-sectional change points. Therefore in this experiment we adopted 5% (2.9 degrees), which is the maximum value of the cross falls in Article 24 of Road Structure Ordinance.

5.2.6 Experimental data

In this research, we used as experimental data both the artificially created data and the point cloud data measured using Mitsubishi Mobil Mapping System (MMS) in order to evaluate the precision of generating a 3D model. The simulation data was created by entering an ideal embankment shape (Figure 6-a) and generating a point cloud, assuming 20mm spacing from each surface and a 10mm absolute error. And for the point cloud data from MMS, we adopted the result of measuring (Figure 6-b) when driving on a path along the embankment surrounded.



a) Visualization result of ideal embankment geometry



b) Result of visualizing MMS point cloud data (G-Viz Lite1.0, Mitsubishi Electric Corporation)

Fig.6: Experimental data

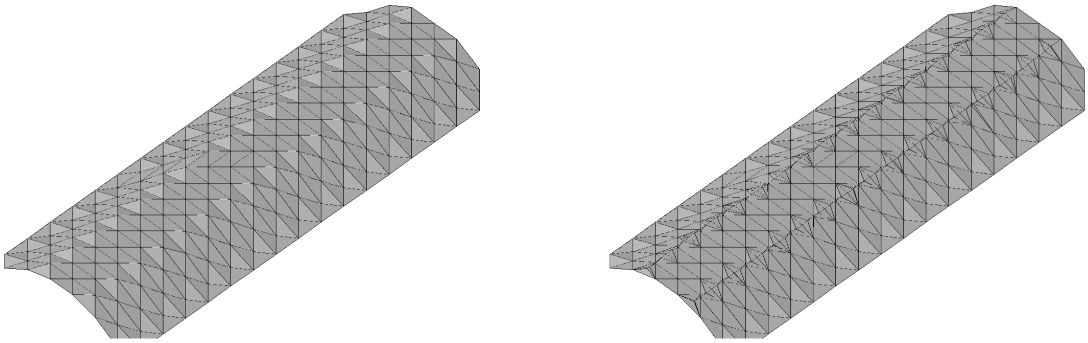
5.3 Contents of Experiment

In this experiment, we generate a 3D model using the thinned out point cloud data that takes into consideration the breakline that is output with the proposed method. Then we compare its result with the 3D model created using the thinned out point cloud data that does not take the breakline into consideration, according to the conventional method. We discuss the comparison and evaluate usability and effectiveness. In evaluation, we check whether the generated 3D model reproduces an original shape correctly. In addition, in the experiment we use simulation data and the point cloud data collected by actual survey to evaluate the precision of each one.

6. EXPERIMENTAL RESULTS AND DISCUSSION

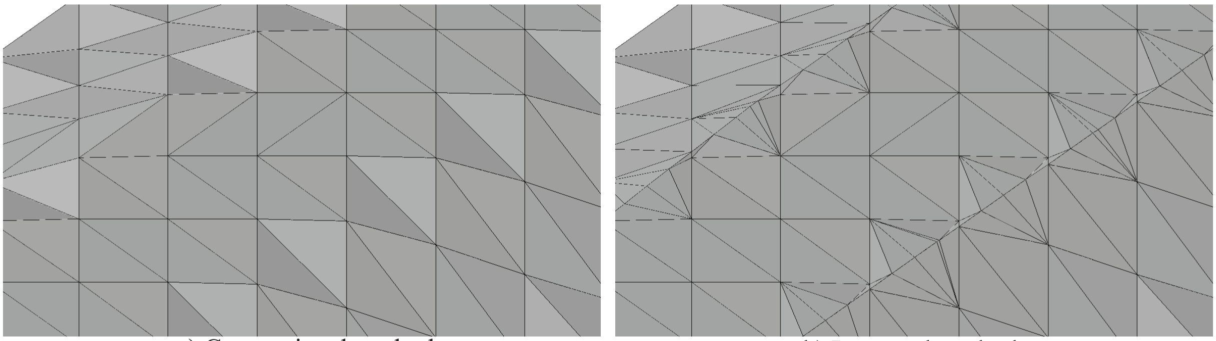
6.1 Experiment to generate a 3D model using simulation data

Figures 7 show the result of generating a 3D model from the point cloud data that are generated from the simulation data using each method. In comparing this figure, it is found that the proposed method of this research (hereinafter referred to as "the proposed method") is able to reproduce the shape according to the one in the original Figure 6a more precisely. Checking the result of enlarging the part of the cross-sectional change point for each method (Figures 8), it is found that the proposed method is able to represent the breakline precisely, solving the problem of the conventional method.



a) Conventional method b) Proposed method

Fig. 7: 3D model generated from simulation data

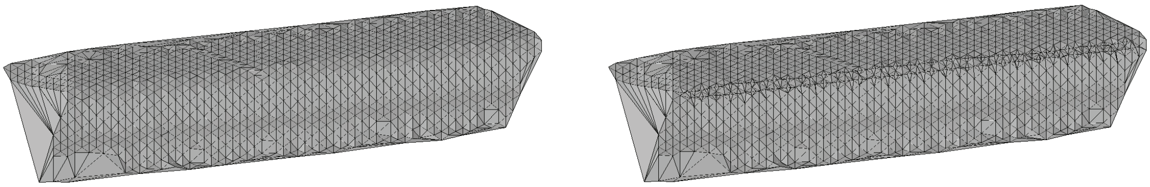


a) Conventional method b) Proposed method

Fig. 8: Scale-up of the part of the cross-sectional change point

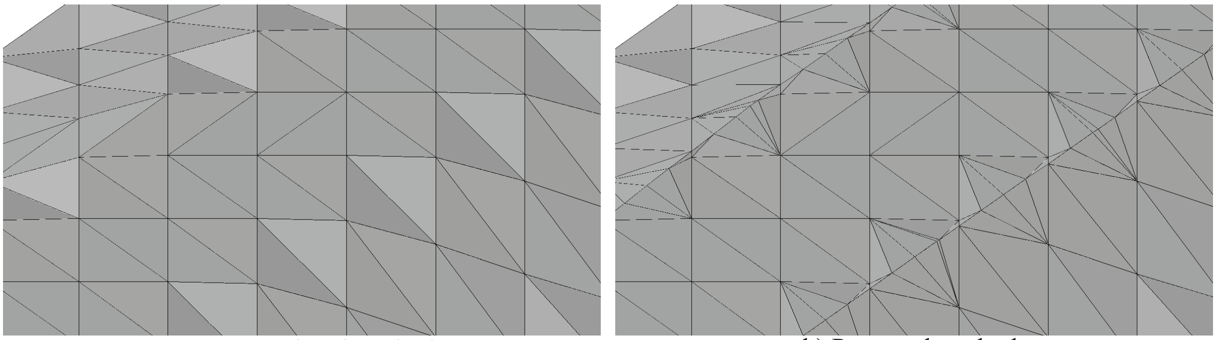
6.2 Experiment of generating 3D model using point cloud data collected by actual survey

Figures 9 show the results of generating a 3D model using the point cloud data collected by an actual survey with MMS. When comparing the results of Figures 9, it is found that the proposed method makes it possible to confirm the upper surface easily compared with the conventional method. Figures 10 reveal that the proposed method is able to represent the breakline precisely, solving the problem of the conventional method.



Conventional method Proposed method

Fig. 9: 3D model generated from point cloud data



a) Conventional method b) Proposed method

Fig. 10: Enlarged view of the road surface area

7. CONCLUSION

This research proposed a method for generating a 3D model in consideration of cross-sectional change points using point cloud data collected by the laser scanner. Under the proposed method, a 3D model is generated using the data processed by extracting breaklines and the point cloud data processed by thinning out with a grid filter. As a result, we solved the problem that boundaries between surfaces cannot be recognized when the point cloud data is thinned out. In other words, it may be safe to say that the proposed method contributed to technological development to generate a 3D model from the point cloud data collected by the laser scanner. In addition, the result of demonstrative experiments proved that it is useful for generating a 3D model with a precision available for intelligent construction. In other words, it can be said that the proposed method of this research contributed to realizing "generation of point cloud data that can be read into commercial CAD software" and "Reproduction of the present geometry from which one can recognize boundaries of surfaces using commercial CAD software".

This research also produced the following next challenge: Nominated breaklines are required. In future, we will solve this problem, aiming to generate a 3D model with high accuracy from point cloud data. Moreover, we will perform an experiment of intelligent construction that applies 3D models to clarify its practical applicability and effects.

This paper is an outcome of the activities of "Workshop on establishing a data circulation environment for river projects" set up in Kinki Regional Development Bureau, MLIT for the purpose of promoting new technology development with public and academic sectors as its core.

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VIII. SIMULATION AND VISUALIZATION

Utilization of VR Technology in Highway Safe Driving Education

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ABSTRACT: *Realistic driving simulation with cannot be experienced without the high quality realization of both VR space and driving simulator system. Therefore, there are few driving simulators which allow experiencing driving with high degree of realism. We have produced a highway driving simulator with reality specializing in the simulation on highways*

This simulator realizes the simulation with the real-car-like feeling by the realistic representation of driving behavior with VR, the employment of 6 DOF motion unit which uses the real-car parts steering system and the wide view by 3 channel LCD.

VR data used in simulation must have the high quality reality. This time, we have collected data of the existing toll gate by taking still and motion pictures and created road signs, toll gate booth and buildings in rest areas. For the highway driving simulator this time, we used UC-win/Road Ver4.0 to create and represent VR space.

For the hazardous events to be reproduced, we have created the data for customers to experience high quality and realistic feelings. For the section on main highways where congestion is produced, we tried carefully to make the jam on sagged or curved sections, not on simple straight sections.

Driving log was used for the evaluation of driving behavior, which have collected the data of examinees' driving behaviors. As driving log, time lapse from the start, current position, winker application, and the distance from the road center. By analyzing parameters in driving log, evaluation are made by finding rapid acceleration or rapid braking.

KEYWORDS: *Highway, road safety, driving simulator, driving log, Measures for safety driving*

1. Introduction

Highway driving simulator is designed to promote safety driving by reproducing hazardous events which can cause accidents on highways, being experienced by drives and evaluating the driving behavior at the simulation.

It is crucial for experiencing driving simulators to experience the driving with the same feeling as the real driving. In VR space, highly precise reality is required in the driving of other vehicles as well as road structures, surrounding buildings and road facilities like traffic signals. For the highway driving simulator for this time, we have used FORUM 8 UC-win/Road Ver4.0 for the creation and representation of the highway driving simulator.

For the hardware, examinees can experience the DS (driving simulator) with real driving feelings by driving the simulator which can reproduce the similar environment to the real car. Since simulator should be good at reproducing the sense of sight, hearing and balance, the simulator of figure 1 was chosen. The simulator realizes wide vision by 3 channel display, presence by 5.1 channel surround system and the body by 6 DOF motion unit. It allows the simulation with realistic feelings by linking the data to VR system

This paper is made to report the trial process of the Highway Driving Simulator which focuses on the highway simulation.

Figure1: 3ch driving simulator system

Figure2: Screens for the 3 channel display

2. Creation of VR course data

For the highway driving simulator, we have created the driving course as below by driving 20km highway main line, with toll gates and rest facilities.

2.1 Alignment of the highway

We have made a virtual highway course based on the Tohoku Highway. Another kind of road structures and facilities of Joban Highway was also referred. Highway main line has basically 2 carriage ways for 1 way with 3 carriage ways in the section close to toll gates. Tunnel section and bridge section were also made in mountainous sections. Snow section was set in some mountain sections, where snowed road surface, trees and houses were created.

We also created smart interchange as well as highway toll gate and rest facility. About the virtual course where other drawing materials can not be referred, road alignment was made based on the Road Structure Regulations. We made the road carefully not to make sharp curve nor low visibility road by setting curvature radius, vertical curve, and transverse slope.

Figure 3: Toll gate

Figure 4: Rest facilities

2.2 Creating highway related facilities

About the highway facilities to be created, we referred to drawing materials and collected data by taking still and movie pictures, reproduced toll gate booth, building in rest facilities and smart interchange booth, which was made to look like real one by seeing the models from the simulation route.

2.3 Placing road facilities

For the road furniture, we tried fully to reproduce the real ones. We made guiding signs to SA, service areas and IC, interchange, road surface marking at Service Areas, guiding signs to smart interchanges, based on the collected pictures. In addition, we placed road lamps and information board. To tunnel section on the highway, tunnel fans, fire hydrant and fire alarms are placed and pier and streamer are placed

We are reproducing realistic VR space by placing an over bridge above the highway and placing trees and houses by the road side.

2.4 Reproducing hazardous evens

About the hazardous events, we created carefully to reproduce the reality as road alignments. To choose the event and the order to be experienced, hazardous events are set one by one.

2.4.1 Hazardous event on highway

Various hazardous events were set on highway. In order not to make unrealistic events, various real hazards are produced.

For the section on main highways where congestion is produced, we tried carefully to make the jam on sagged or curved sections, not on simple straight sections and placed the signboard, which looks like the real environment.

In addition, we made the weather change smoothly, for example, to make the low visibility because of the fog after exiting the tunnel.

Figure 5: Congestion section

Figure 6: Foggy section

2.4.2 Hazardous events at toll gate

For this simulation course, we created 2 types of toll gate: ordinary type toll gate and toll gate on main line for all driving vehicles. For each type, the course is set to drive along the ETC lane and the bars are set to open only when the passing vehicle is observing the speed limit. The way the bars are opening and its timing is made by referring to the collected movie.

In addition, the number of lanes increases temporarily at the toll gate and the number decreases after passing thorough the booth. It may cause collision because of the congestion. To reproduce the situation a number of driving vehicles are set.

Figure 7: Going through the ETC lane

2.4.3 Hazardous events at rest facility

As resting facility, service area with smart interchange is made. Smart interchanges are types of interchanges set only for vehicles with ETC to enter or leave the highway at SA or PA (Parking area). Those drivers who use smart interchanges have to stop the carat the bar, it is different from that of usual ETC lane of the toll gate. Because of the difference, road signs and road surface markings are usually set to collect attention.

In addition, since rest facilities are the only place where vehicles may collide with pedestrians on highway, one pedestrian model is set to cross in front of the car at the time of driving in the rest area.

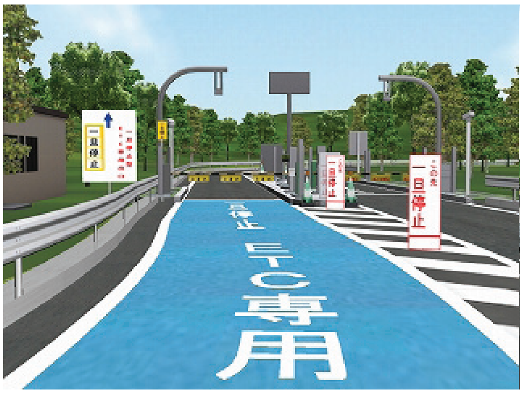

Figure8: Smart Interchange

Figure9: Crossing pedestrian in SA

2.4.4 Hazardous event at merging point into main line

The hazardous event at the zone between rest area and merging point into main line are re-enacted. In the route which merges from rest area into main route, a driving vehicle is set every 100m in the main route, it is expressed as a hazardous event to merge with high difficulty.

Figure10: Merging into main line

2.4.5 Hazardous event at branching point from main line

The hazardous event at the zone between branching point from main line into toll gate is also re-enacted. A driving vehicle is set every 100m in the main route before branching into ramp, and the congestion is expressed by reducing other vehicles speed to 40km/h.

In **contrast,** the event in which driving vehicles are reduced **is** created. The long straight line continues after branching into ramp, therefore the hazardous event that the vehicle at the same speed as main line cannot turn at the curve and crashes into concrete barrier curb is re-enacted.

Figure11: Ramp congestion

Figure12: Overspeed

2.5 Driving route

In general, the highway doesn't have the branching point other than toll gate, rest area, and junction. This simulator is designed for users to experience the hazardous event, therefore the voice guidance as well as the guide image such as figure 12 shows them to drive predefined route.

It is set to restart just before branching point in case the wrong driving route is selected.

Figure13: Example of driving route sign

2.6 Cockpit model creation

Although the simulation vehicles in VR space are set with the steering wheel on the right side, the simulator body is designed on center. Therefore when user is trying to drive at the center of road, they might drive a little on the left in VR space. Figure14 and 15 represent the driver's view and the overhead view from the above while driving in the center of traffic lane. Though the figure 14 shows that the vehicles are running in the center of traffic lane from the driver's viewpoint, the overhead view shows that they are running on the left from the center line.

This phenomenon affects driving result, thus the driving screen is displayed by creating the cockpit model with bonnet to view the driving position.

Figure14: Driving at the center of traffic lane

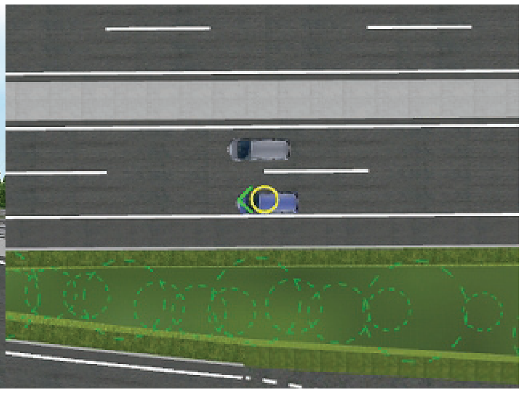

Figure15: Overhead view

2.7 Sound effect setting

The quality of drawn landscapes and re-enacted hazardous events is extremely important, but the sound effect is also meaningful in VR space. It is thought for example, the engine sound of vehicles, talking voice in rest area.

Therefore the engine sound of own vehicle and passing vehicle(bike, truck), sudden braking sound, talking voice of people, the sound occurred when vehicles hit other vehicle or road obstructions such as toll gates are set to create VR space as realistically as possible.

2.8 Frame rate retaining

As this simulator is designed to output from a PC into 3-display monitors to be processed the image into each side mirror and rear-view mirror, VR data is required to be set simple structure to reduce the burden on PC. The polygon is set hidden at the point invisible from simulation route or the extra polygons are not generated in road structure for it. In addition, LOD function is used by VR space are restriction to ease the load on PC.

In addition, when driving experience was performed without retaining frame rate, it was found that time-lag was occurred between the operation and reaction in VR space, and the motion movement was not smooth, then it resulted in less satisfactory results for experimental simulation.

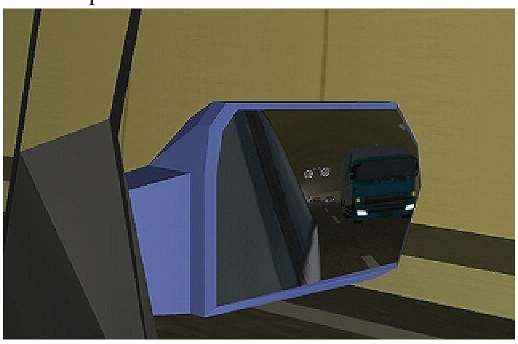

Figure16: Side mirror display

3. Driving behavior assessment

The driving logs in which the driving behavior of each experimental subject are recorded and used to assess the driving behavior after simulation. This starts to be recorded when the simulation starts, and ended when the simulation ends. This log includes the passing time from driving start point, the position information of own vehicle, the right/left turn signal status, and the distance from the center of road. The carefulness of driving operation is assessed by analyzing each parameter on the driving log; sudden-acceleration tendency from acceleration table, sudden-brake tendency from brake table, unnecessary lane change tendency from lane change number, sudden-steering tendency from steering speed.

For example in accidents with other vehicles and human models, the speed level and the handle rotation angle will be evaluated in each event.

The analysis of driving experiment result allows to judge the tendency of traffic accident including the type of road structure to use it for the safety driving in future.

Though the simulation course is created as the virtual road, some tendencies can be found by collecting of the driving experience results; many accidents tend to occur in the sag area due to the congestion and in the area where the number of lane is reduced in the tollbooth.

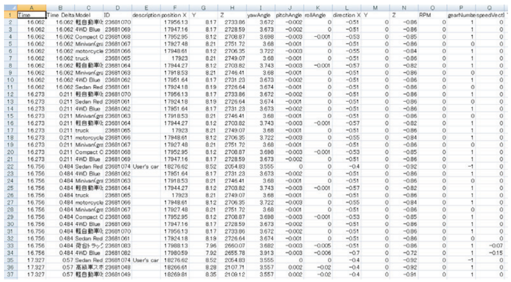

Figure17: Output example of driving log

Figure18: Output example experiment result

4. Conclusion

The hazardous events which can occur while driving in 3D space including the traffic highway can be safely experienced by using VR technologies. The driving behavior could be assessed by analyzing the driving movement of each experimental subject from the driving log. This simulator has been already applied in traffic safety campaigns in various regions in Japan, and they have been experienced by various highway drivers. The validation of road construction for safe driving can be performed by accumulating and analyzing the driving experiment results.

Driving simulator is becoming the tool which raises awareness of the safe driving, and it is expected to be used more widely as a measure to validate road construction issues.

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UC-win/Road Ver.4 Reference Manual , Forum8 Co.Ltd , URL:http://www.forum8.co.jp/

APPLICATION OF VIRTUAL REALITY TECHNOLOGY TO PRE-PROCESSING FOR 3-D FINITE ELEMENT SIMULATIONS

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ABSTRACT: *This paper presents a mesh visualization and modification system based on virtual reality technology for the pre-process of the three dimensional finite element simulations. The aim of the system is to understand the three dimensional mesh structures and to improve the numerical accuracy and stability. The CAVE library and OpenGL are employed for the development of the system. Users can check and modify the mesh quality interactively by using the controller in VR space. The mesh modification method based on the node relocation method is employed. The linear and second order tetrahedral elements are available. The present system is applied to the pre-process for the large scale wind flow simulation in urban area.*

KEYWORDS*: finite element simulation, mesh visualization, mesh modification, mesh quality, node relocation*

1. INTRODUCTION

The finite element method is a powerful tool for planning and design of various construction projects. The three-dimensional finite element simulation became more popular in accordance with the development of hard- and soft-ware of computers. However, the following problems are pointed out in practical computations of this type of problems as: 1) it is difficult to check the quality of mesh for the complicated spatial domain; 2) it is difficult to modify the mesh to improve numerical accuracy and stability, since the shape model and mesh are normally visualised on the two dimensional screen or display. In order to overcome the first problem, the present authors developed a mesh visualization system based on the virtual reality technology (Takada and Kashiyama, 2008, Kashiyama et al, 2009).

This paper presents a system to overcome both problems for the pre-process in three dimensional finite element simulations. The system consists of two functions; mesh visualization and mesh modification. The system is developed to understand the details of three dimensional mesh structures and to improve the numerical accuracy and stability in finite element simulations. The mesh modification method can be classified into three methods; the node relocation method, the mesh refinement method and the replacement method using higher order element (Kikuchi, 1986). In this system, the node relocation method is employed for the mesh modification method. For the finite element, the linear and second order tetrahedral elements are available. The CAVE library (Kageyama and Ohno, 2000, Ohno et al., 2007) and OpenGL are employed for the development of the system. The present system is applied to the pre-process for the large scale wind flow simulation in urban area in order to investigate the efficiency of the system.

2. VR ENVIRONMENTS

The present system is designed for the use of virtual reality system such as CAVE. FIG. 1 shows the exterior view of the VR system “Holostage” of Chuo University based on IPT (Immersive Projection Technology). This system consists of a PC cluster (a master-PC and four slave-PCs), three projectors, three large VR display and a motion tracking system. The stereoscopic image from the arbitrary viewpoint of observer can be displayed in VR space (CAVE room) by the motion tracking system. The details of the VR system are described in the references (Takada and Kashiyama, 2008, Kashiyama et al., 2009).

The binocular parallax is employed for the stereoscopic view. The stereoscopic view is realized in VR space by creating the image that corresponds to binocular retinal images. The active stereo method is employed for the method of stereoscopic view.

(a) (b)

FIG.1: VR system based on IPT

3. MESH VISUALIZATION AND MODIFICATION SYSTEM

3.1 Overview

Users can check the details of three dimensional mesh structures and modify the shape of mesh interactively in VR space by the present system. The present system consists of two functions; mesh visualization and mesh modification. FIG. 2 shows the flow chart of the present system. The system is developed by the VR programming languages, Open GL and CAVE library. For the finite element mesh, the four nodes linear tetrahedral element and the ten nodes second order tetrahedral element are employed.

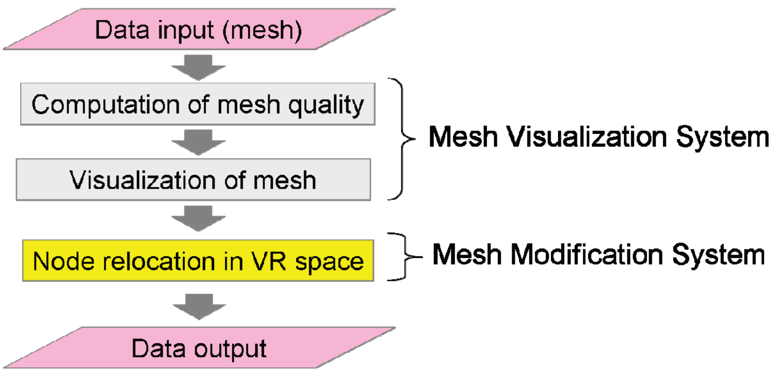

FIG.2: Flow chart

3.2 Mesh quality

The mesh quality can be evaluated by the following equation (Freitag and Knupp, 2002).

$$Q_m = \frac{\left(\sum_{i=1}^{6} L_i^{\,2}\right)^{\frac{3}{2}}}{8.4796\,V}$$

where L_i denotes the length of the edge of the element, V is the volume of the element. The mesh quality is to be 1 if the element is to be a regular tetrahedron and the value is to be big value if the element becomes a bent element. In this system, the elements which exceed the setting value for mesh quality are displayed by the red color in VR space.

3.3 Boundary condition for node movement

In order to avoid the violation of the geometrical shape by the node relocation, the node movement condition must be specified for the nodes on the boundary. The condition is prepared by the geographical information, which is obtained by the mesh data. The nodes of the mesh can be classified into four kinds, nodes at apex point, nodes on the edge-line of the boundary, nodes on the surface of the boundary and nodes in the computational domain (see FIG. 3). FIG. 3 shows the example for the mesh around a cubic structure. The nodes at the apex are assumed to be fixed point. The nodes on the edge-line of the structure can move on the edge-line only. The nodes on the surface of the structure can move on the surface of the boundary (tangential direction) only. The nodes in the computational domain can move to any direction. In this system, if the element violates the geometrical shape by the node relocation, the element is displayed by the green color in VR space.

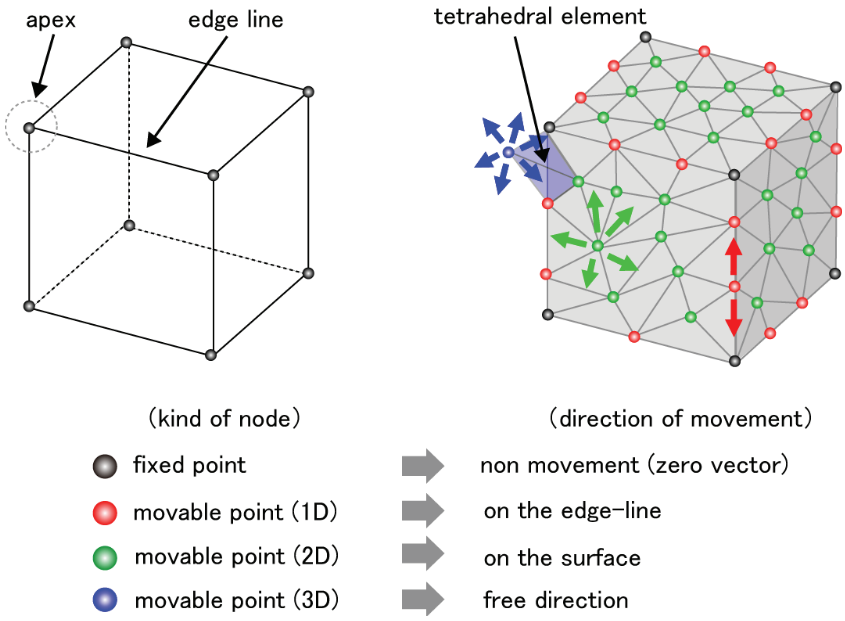

FIG.3: Condition of node movement

3.4 Menu and function of the system

The menu for the present system is shown in FIG. 4. This menu is displayed at five feet front from users in VR space. The functions of the system can be classified into four categories; “VIEW”, “SHOW”, “CLIPPING” and “EDIT” functions. The “VIEW” functions are for the viewing method, navigation (“NAVIGATION”), zoom (“ZOOM”) and rotation (“ROTATION”) functions for mesh. The “SHOW” functions are for the method of visualization of mesh as follows; “SHOW BAD MESH” shows the bad shaped elements which exceed the setting value for mesh quality only, “SHOW ALL” shows all of elements and “SHOW SURFACE” shows the elements on the surface only. User can check the mesh idealization and quality by using the “VIEW” and the “SHOW” functions in VR space. The “CLIPPING” function is also for the method of visualization of mesh. The function “CLIPPING ON” shows the elements around the tip of beam generated by the controller. The “EDIT” function is for the mesh modification method, “NODE MOVE” denotes the mesh modification based on node relocation. Users can modify the mesh structures using “CLIPPING” and “EDIT” functions.

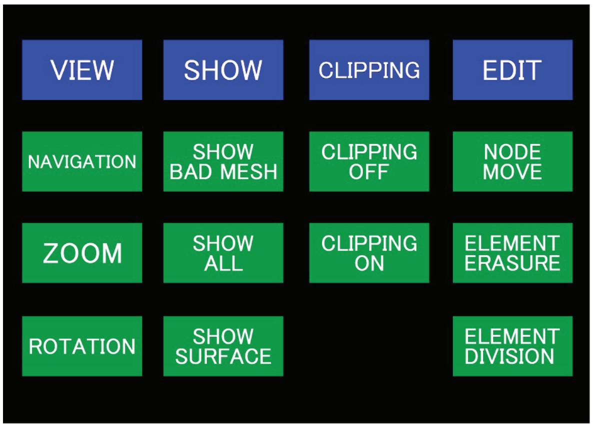

FIG.4: Menu of the present system

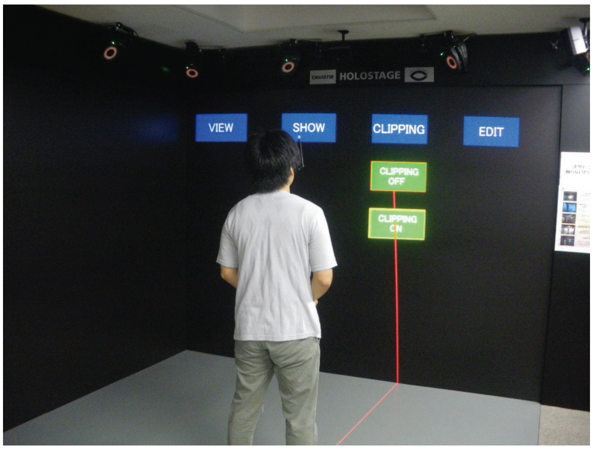

FIG.4: The scene user select menu item

FIG. 5 shows the scene the user select the menu item using the controller. FIG. 6 shows the scene the user select the “NODE MOVE” function. If the tip of beam generated by the controller captures a node, the node color is changed to yellow and the observer can move the node under the boundary condition for node movement. In FIG. 6, the red color elements denotes the elements which exceed the setting value for mesh quality. If the element violates the geometrical shape by the node relocation, the element is displayed by the green color in VR space.

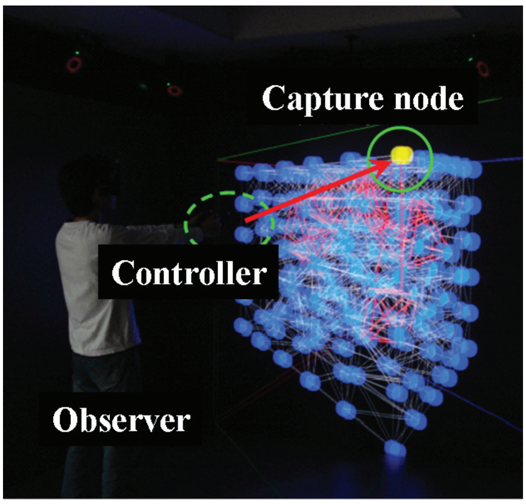

FIG.6: Method of mesh modification

4. APPLICATION EXAMPLE

The present system is applied to the pre-processing for the large scale simulation of wind flow in urban area. FIG. 7 shows the aerial-photo (Google) of the studied area, Nihon-bashi, Tokyo, and the circle area denotes the modeling area. For the modeling method, the method using GIS/CAD data is employed for creating the shape model and the Delaunay method is employed for the mesh generation based on unstructured grid (Takada and Kashiyama, 2008, Kashiyama et al, 2009). For the data for buildings, the GIS data (Mapple 2500) which is developed by the aerial-photo and survey is employed. For the land elevation data, the digital elevation map issued by the Japanese geographical survey institute, which is developed by the aerial-laser survey, is employed. The stabilized parallel finite element method is employed for the wind simulation (Kashiyama et al., 2005).

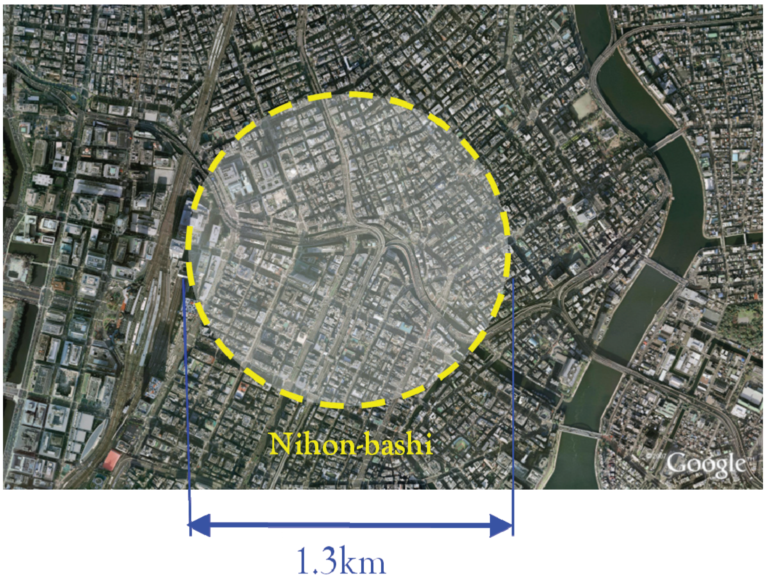

FIG.7: Studied area, Nihon-bashi, Tokyo

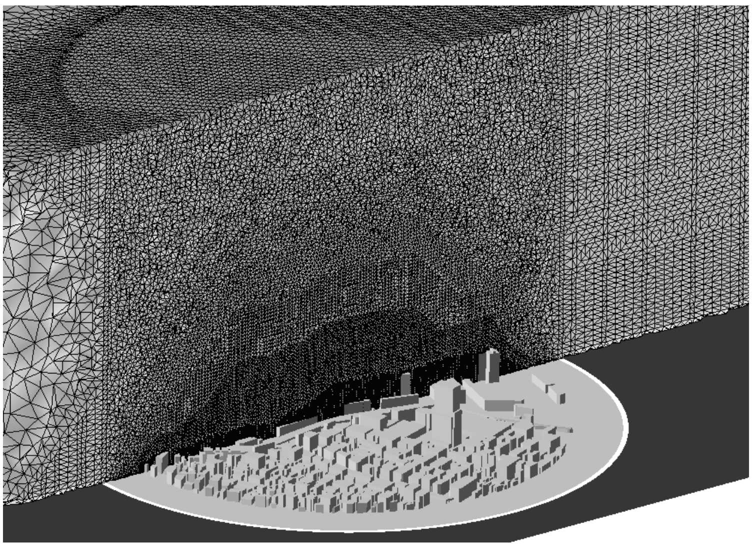

FIG.8: Mesh idealization for wind flow simulation

FIG. 8 shows the finite element mesh idealization based on the four nodes linear tetrahedral element. The fine mesh is employed near the ground and buildings. The total number of nodes and elements are 2,458,388 and 14,115,104 respectively. From this figure, it can be seen that; 1) it is difficult to check the quality of the shape model and mesh idealization for the complicated spatial domain by the visualization based on two dimensional expressions using the perspective drawing. 2) It is difficult to modify the mesh to improve numerical accuracy and stability.

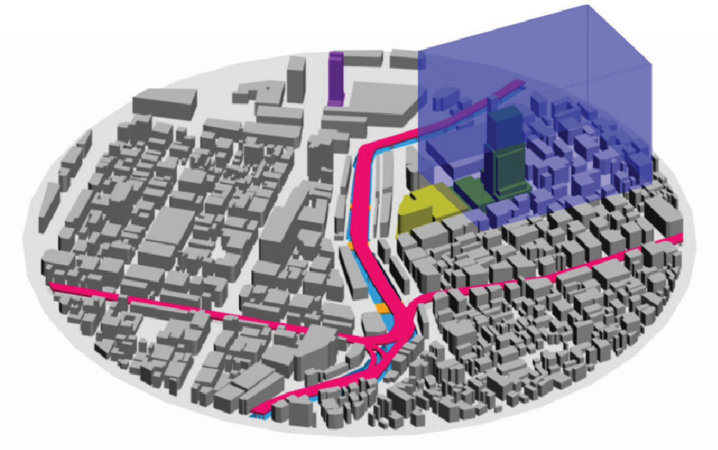

FIG.9: Shape model and application area

In order to overcome both problems, the present system is developed by the VR programming languages; Open GL and CAVE library. The present system is applied to the mesh visualization and modification for the box region in FIG. 9.

FIG. 10 shows the visualization of mesh by using the "SHOW SURFACE" and "SHOW BAD MESH". From this figure, the surface mesh and bad shaped element are shown by white and red colors respectively. FIG.11 shows the visualization of mesh by using the "SHOW BAD MESH"; in that case only the bad shaped element is displayed by the red color.

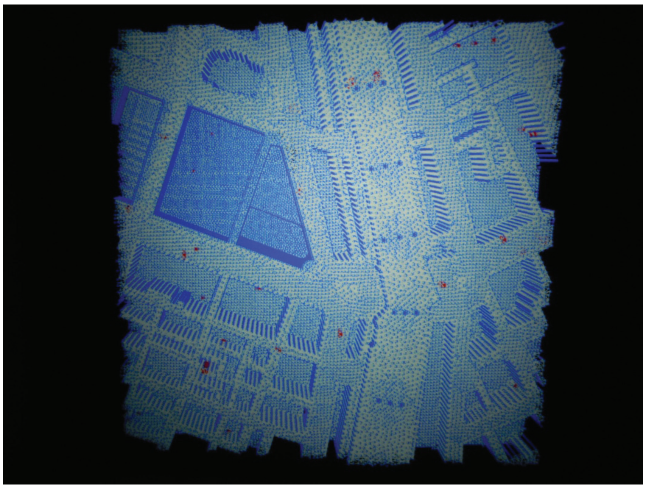

FIG.10: Mesh visualization using "SHOW SURFACE" and "SHOW BAD MESH"

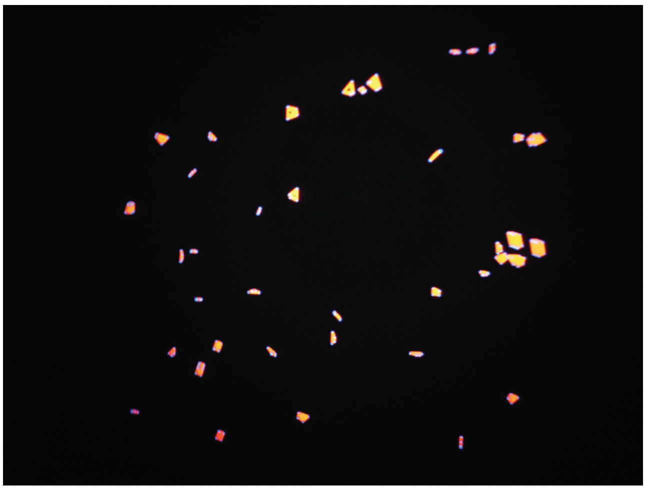

FIG.11: Mesh visualization using "SHOW BAD MESH"

Using the results of mesh visualization, the mesh modification functions “CLIPPING” and “EDIT” are applied. FIG. 12 shows the scene the user modifies the mesh idealization using functions “CLIPPING ON” and “NODE MOVE”. From this figure, it can be seen that the bad shaped elements are displayed by the red color and the elements around the tip of beam are shown by the white color by the function “CLIPPING ON”. By using the function “NODE MOVE”, the user can change the position of nodes of the bad shaped elements interactively. In case of the ten nodes second order tetrahedral element, the apex node of the element is movable and the position of mid-nodes on the edge-line is interpolated linearly by using the position of apex nodes.

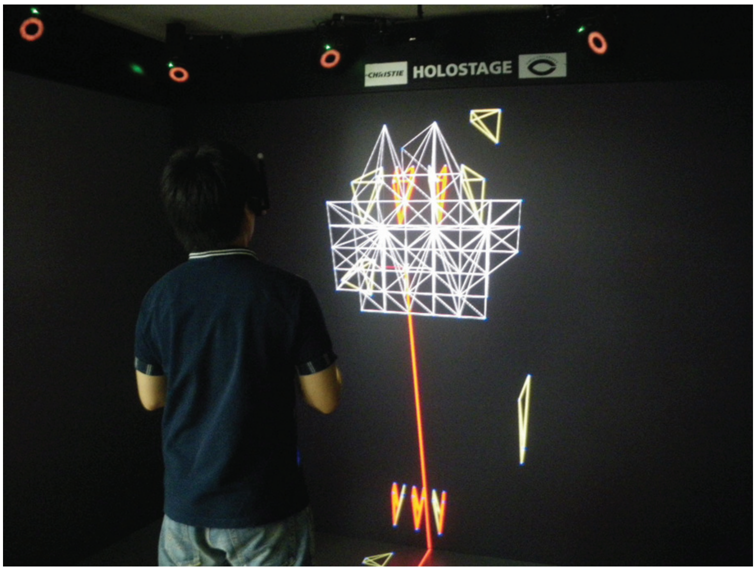

FIG.12: Modification of mesh using “CLIPPING ON” and “NODE MOVE”

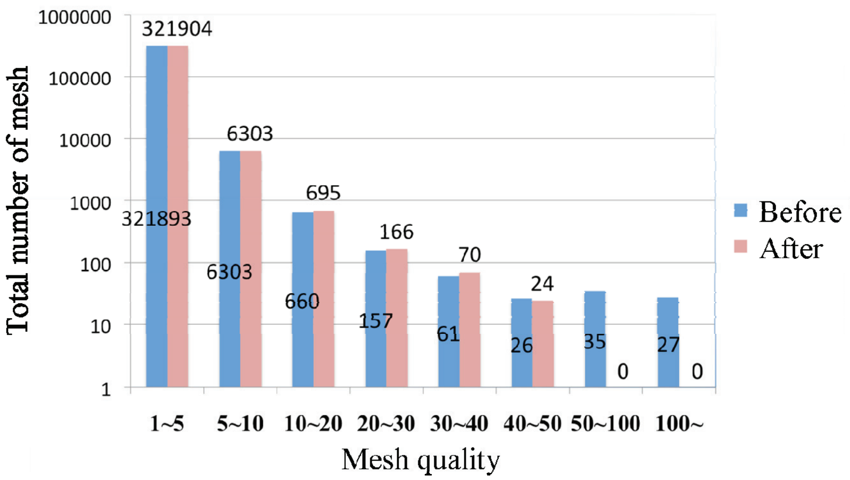

FIG.13: Distribution of mesh quality before and after “NODE MOVE”

FIG.13 shows the distribution of mesh quality before and after the application of node relocation function “NODE MOVE”. In this case, the bad shaped elements which exceed the mesh quality values “50” are modified by the present method. From the figure, it can be seen that the bad shaped elements which exceed the mesh quality values are erased perfectly. The operation time to correct the bad shaped mesh (total number of elements are 62) was about 10 min.

5. CONCLUSIONS

A mesh visualization and modification method based on the virtual reality technology has been presented for the pre-process in the three dimensional finite element simulations. The present system has been developed by the VR programming languages; Open GL and CAVE library. The key features of the present system are as follows.

- Users can check and modify the mesh idealization interactively and easily by using the controller in VR space. From this. users can understand the three dimensional mesh structures and improve the numerical accuracy and stability by using the present system.

- The mesh modification system based on the node relocation method has been successfully developed. For the finite element, the four nodes linear tetrahedral element and the ten nodes second order tetrahedral element are available.

From the results obtained in this paper, it can be concluded that the present system provides a useful tool in the pre process for three dimensional finite element simulations. The modification method based on mesh refinement will be investigated in the future work.

6. ACKNOWLEDGEMENT

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3D VISUALIZATION OF ARTICULATED MICRO-TUNNEL BORING MACHINE DURING PIPE-JACKING OPERATIONS

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ABSTRACT: *This paper presents a generic real-time 3D visualization methodology to improve the equipment tele-operations in construction site environments. Microtunneling is a typical construction operation that lacks visual information for steering the tunnel boring machine in a remote control station. The state-of-the-art application of real-time visualization of construction equipment operations requires the development of specific graphic control interfaces, while construction practitioners may not possess the programming skills as required. This has impeded the wide application of computer graphic technology on construction sites. To simplify building construction equipment kinematic models, the proposed methodology alleviates the burden of deriving mathematical equations and developing computer programs by introducing a graphic network modeling technique based on the SimMechanics toolbox in the Simulink environment. As such, construction site objects can be modeled in a virtual reality environment and the 3D animations of the construction operations are driven by sensor data representing the real world operations on site.*

KEYWORDS*: Visualization, Tele-operation, Site data collection, Micro-tunnel boring machine, kinematic model, Transformation matrix.*

1. INTRODUCTION

In recent years, tunnel boring machines (TBM) have been increasingly adopted by the construction industry for developing urban underground pipeline systems, minimizing the disruption to traffic, businesses, and other aspects of the social equity. Micro-tunnel boring machines (MTBM, generally varying from 0.61 to 1.5 meters) are used on microtunneling projects. The main differences between MTBM and large diameter TBM are (1) MTBM is operated remotely; (2) MTBM usually has the tunnel liner pushed behind the machine (the process known as "pipe-jacking"). In a typical microtunneling project, the MTBM advances from a jacking shaft to a reception shaft. Due to the nature of small diameters, the visual information on MTBM operations is very limited. It is a challenge for operators to steer the MTBM and control the tunnel alignment.

Visual perception is the main source of information that operators rely on for making decisions on controlling construction equipment. The insufficient visual feedback to MTBM operators may cause numerous problems including misalignment, trapping MTBM underground, and damage of existing utility pipe in the close proximity, which result in project delays and significantly drive up project cost. It was reported that problems with MTBM operation and alignment check on average account for 24% and 20% delay time respectively in trenchless projects (Hegab & Smith 2007). And the performance of the microtunneling largely depends on the skill of the MTBM operators (Yoshida & Haibara 2005).

Although the computer generated 3D graphics have been applied in the construction industry to visualize building design concepts, project schedules and construction processes, it is still difficult to apply to a dynamic construction site at the operational level. This research proposes a cost-effective virtual reality modeling methodology that is intended to facilitate construction equipment tele-operations, for which site sensor data are used to drive 3D animations of construction operations in the virtual world which reflect the real world motions on site.

This paper is organized as follows: first, the background of this research and the related knowledge obtained from previous research are discussed. Then, given an outline of the methodology, we elaborate on the two components of the methodology, namely, (1) the input: the site data collection, and (2) the controller: virtual reality modeling techniques. Finally, two experiments are conducted to verify the feasibility and effectiveness of the proposed methodology. Conclusions are given in the end.

2. BACKGROUND AND LITERATURE REVIEW

2.1 Visual feedback to TBM operators

It has been reported that construction equipment operators tend to concentrate on processing visual information because they rely on the visual sense as their main recognition means (Hirabayashi et al. 2006). As shown in Fig. 1, the TBM operators count on the visual information obtained from a closed-circuit television (CCTV) and instrument panels to steer the MTBM along the designed tunnel alignment. A laser theodolite set up in the jacking shaft projects a laser beam on the target board fixed at the rear of the MTBM. The displacement of the laser point indicates the alignment deviations. Two inclinometers are installed in the MTBM to give the roll and pitch angles information. The operators watch on the CCTV and the inclinometer readings and make decisions on how to steer the MTBM.

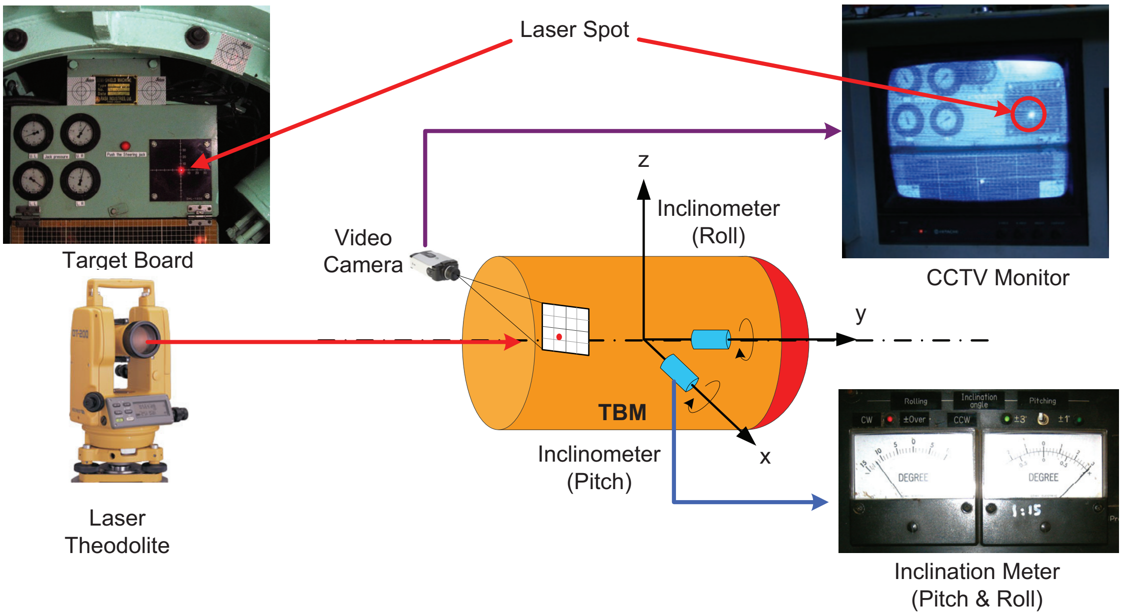


Fig. 1: The commonly used visualization approach for MTBM remote control

Nonetheless, the tele-operation systems with conventional CCTV are unable to generate perfect tele-existence (Hirabayashi et al. 2006). Additionally, the traditional visual feedback does not provide visual information of the cutter head orientations. Thus, operators only count on their experiences to steer the cutter head through "push or pull" operations on control jacks so as to correct any deviations as detected from CCTV.

2.2 Virtual reality in construction applications

Virtual reality (VR) is a generic term for describing technologies about creating a real-time visual/audio/haptic experience. Essentially, virtual reality is about the navigation, animation and manipulation of 3D computer-generated environments, and can be categorized into "Immersive VR" and "Non-immersive VR" (Vince 2004). Virtual reality technologies have been extensively embraced by construction practitioners and researchers in the application areas of dynamic 3D visualization of simulated construction operations (Kamat & Martinez 2001), 4D visualization of construction process/schedule (McKinney et al. 1996), 3D/4D based constructability review (Hartmann & Fischer 2007). However, these applications are largely confined to the design/planning purposes. There is still a lack of documented evidences as well as efficient methodologies for VR technology application in the construction stage, aimed to improve the construction tasks at the operational level such as construction equipment tele-operations. One important impeditive factor is attributable to the enormous efforts needed to model the dynamic construction site operations in the VR world.

2.3 Kinematics of articulated construction equipment

Kinematics is the study of the motion of objects without consideration of the causes leading to the motion (Beggs 1983). It is relatively simple to describe the motion of a single rigid body, which might undergo translation and rotation or a combination of both. A 4×4 homogeneous transformation matrix can be used to express a rigid body's motion (translation, rotations) mathematically (Grigore & Coiffet 2003). However, it is much more complicated to describe a system that consists of a system of rigid bodies connected by joints that constrain their relative movements. The system is called a kinematic chain that can be categorized into open chain and closed chain (Khalil & Dombre 2002). A closed kinematic chain contains at least one link with more than two joints, while an open kinematic chain only has links with one or two joints.

In general, most articulated construction equipment systems can be viewed as open kinematic chains comprised of a finite number of links that are joined together with simple prismatic or revolute joints, each of which typically allows only one degree of freedom in connection with the next link down the hierarchy (Kamat & Martinez 2005). The kinematic chain of a MTBM is a kind of special closed kinematic chain known as parallel robot (Khalil & Dombre 2002). Fig. 2 shows the kinematic chains of a typical MTBM that consists of a rigid rear body linked with a rigid cutter head by three hydraulic cylinders. A hydraulic cylinder can be viewed as combination of a prismatic joint and a spherical joint. Note that different MTBM may have different mechanical configurations. For example, some MTBM has the cutter head control system that is comprised of four parallel hydraulic cylinders.

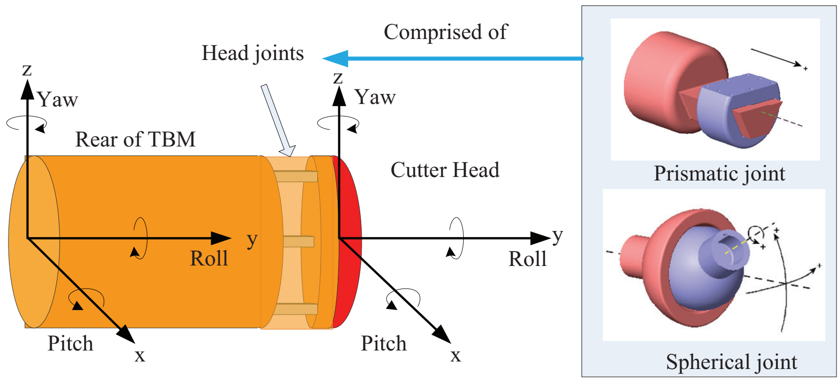


Fig. 2 The kinematic chains of MTBM

At the control station the operators manipulate buttons to push or pull the piston rods of the hydraulic cylinders in order to change the orientation of the cutter head. To update the equipment model based on sensor data, the motion of equipment components should be defined by kinematic models (Seo, J et al. 2000) which are a mathematical representation (i.e. linear equations and differential equations) that reflects the mechanical structure and the geometric arrangement of the joints and links of the construction equipment. Thus, a kinematic model is required to derive the pose of the cutter head based on the length of the piston rods. However, it will be tedious to derive equations and code them in a VR system in an ad hoc fashion considering a wide variety of equipment configurations.

The majority of previous approaches for construction equipment visualization need to derive a set of equations and code specific kinematic models in their visualization systems (Kamat & Martinez 2005; Seo, JW, Haas & Saidi 2007). In this research, a graphic network modeling approach based on Simulink environment in MATLAB is applied to generate the kinematic models for MTBM. Compared with previous approaches, this new method can be easily adapted to various articulated construction equipment without the need of software programming.

3. OVERVIEW OF THE PROPOSED METHODOLOGY

The main goal of this research is to realize on-site 3D visualization of articulated MTBM during pipe-jacking operations in order to support operators in making more informed decisions in steering MTBM remotely. To achieve this goal, the proposed methodology relies on the integration of site sensor data with virtual reality models. Fig. 3 gives an overview of the proposed methodology.

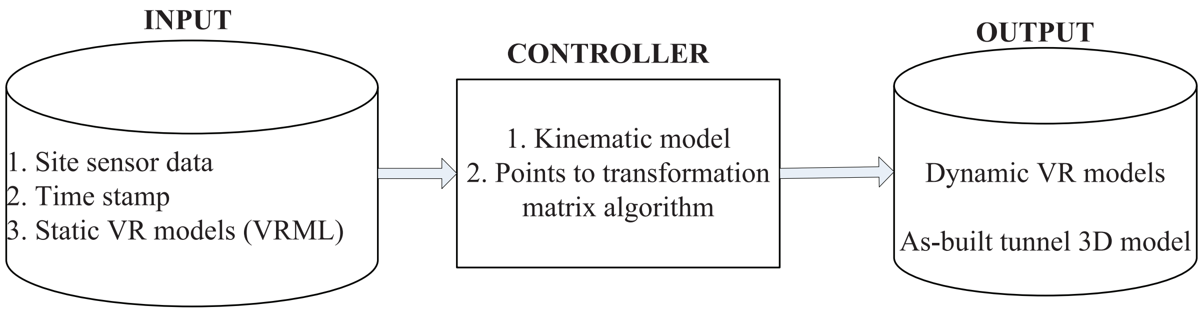


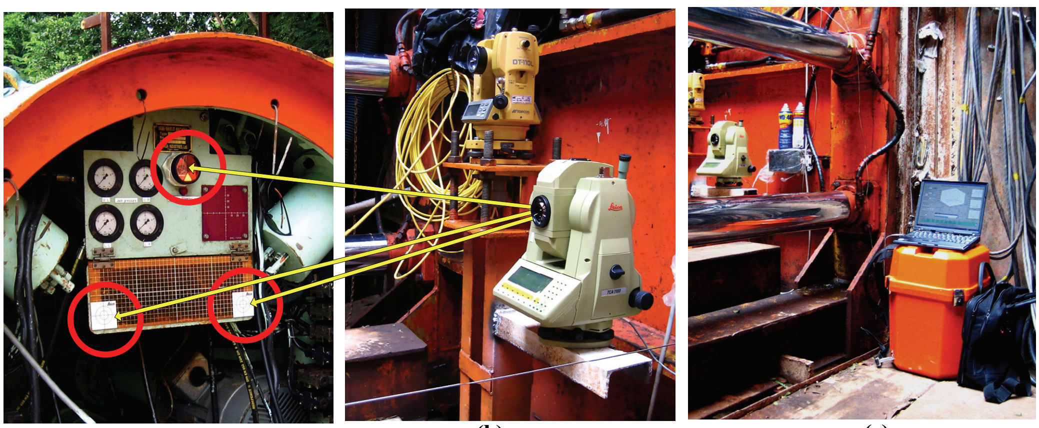
Fig. 3: Overview of the proposed methodology

The integration is achieved through a controller that combines a kinematic model and a "points to matrix" transformation algorithm. The controller performs like a computing engine that translates the site sensor data to the position and orientation information of each equipment component. Thus the equipment 3D geometric models can be updated using the computing results, which generates dynamic VR models which reflect the actual pose of the MTBM working on a site, including the position and orientation of the rear part and the orientation of the cutter head. As a by-product of the dynamic 3D visualization, the as-built tunnel model can be generated automaically.

4. ON-SITE DATA COLLECTION

There are many types of sensors can be used to collect site data to drive the dynamic 3D visualization of construction equipment operations. The commonly used equipment sensors are angle encoders for revolute joints, linear encoders for prismatic joints, gyroscopes for orientation of equipment body, and positioning systems for position and orientation of the equipment base (Seo, J et al. 2000). As discussed in Section 2, a MTBM are composed of a rear part (main body), a cutter head and a control system that consists of several hydraulic cylinders. To visualize the MTBM operations, we need a positioning system to get the position and orientation of the rear part, and linear encoders to obtain the length information for each hydraulic cylinder.

Considering the cost, implementation complexity and computation efficiency, as shown in Fig. 4, we applied a computer controlled total station (Fig. 4 b) which automatically measures the coordinates of targets (Fig. 4 a) mounted on the rear of a MTBM to fix the position and orientation of the rear part of the MTBM. The system was originally developed for automatically tracking and guiding TBM during micro-tunnelling and pipe jacking operations (Shen, Lu & Chen 2010). A program was developed to control the robotic total station through a RS-232 data communication cable (Fig. 4 c),



(a) **(b)** **(c)**

Fig. 4: The configuration of the data collection system

The data collected by the positioning system mainly consist of two parts, namely, the primary data which are the coordinates of positioning points; and the metadata which describe the primary data like the point ID and tracking time. The controller uses the time information to synchronize the dynamic VR model and the site data, and processes the point coordinates to calculate the position and orientation of the rear part of the TBM by using a special "points to matrix" transformation algorithm. In the real situation, the piston rod's length can be measured using linear transducers. But in the experiment discussed later, we only provide a graphic user interface to input the piston rods length information to simulate the data collection from linear transducers.

5. THE VIRTUAL REALITY MODELING

Design of a graphical representation scheme is of great importance for the effective delivery of information on equipment and work environment for remote control (Seo, J et al. 2000). The virtual reality modeling maps the real construction site layout to the virtual world, which includes the geometric modeling and kinematic modeling. Geometric modeling describes the shape and dimensions of objects as well as their appearances, such as texture, surface reflection coefficients, and colour. The geometric modeling generates the static 3D geometry which is not sufficient for expressing the motion of objects in the real world. The kinematic modeling describes the changes of position and orientations (pose) of objects in the virtual world.

5.1 Geometric modeling

There are two types of objects to be modelled, namely, the static objects (i.e. the existing facilities, jacking shaft, receiving shaft, the designed tunnel and surrounding environments like trees), and the moving objects (i.e. the MTBM). Construction engineers can use any 3D CAD (i.e. AutoCAD, 3D MAX, SketchUp) they are familiar with to model these objects. Note each component of the moving object should be modeled as a standalone model, because the components change their relative position and orientation during operations. As shown in Fig. 5, the designed tunnel, the jacking pit, the receiving pit, and the adjacent existing infrastructure are modelled as static objects in the virtual world. The MTBM is modeled as five standalone sub-models, namely the rear part, the three hydraulic cylinders and the cutter head. The models are then exported to a VRML (Virtual Reality Modelling Language) file ready to be used in Section 6. Note the VRML is a standard file format for representing 3D interactive vector graphics (Web3d.org 1997).

Fig. 5: The virtual reality models for a micro-tunneling project

5.2 Kinematic modeling

The SimMechanics toolbox of MATLAB provides a graphic network modeling platform to build mechanical systems within the Simulink environment. Simulink is an environment for multi-domain simulation and model-based design of dynamic systems. It provides an interactive graphical environment and a customizable set of block libraries that allow users to design, simulate, implement, and test a variety of time-varying systems, including communications, mechanics, controls etc. (MathWorks 2007). Instead of deriving and programming equations, the kinematic model can be built by using the provided application blocks, such as bodies, joints and actuators. Fig. 6 shows the kinematic model of MTBM modeled using the application blocks provided by SimMechanics.

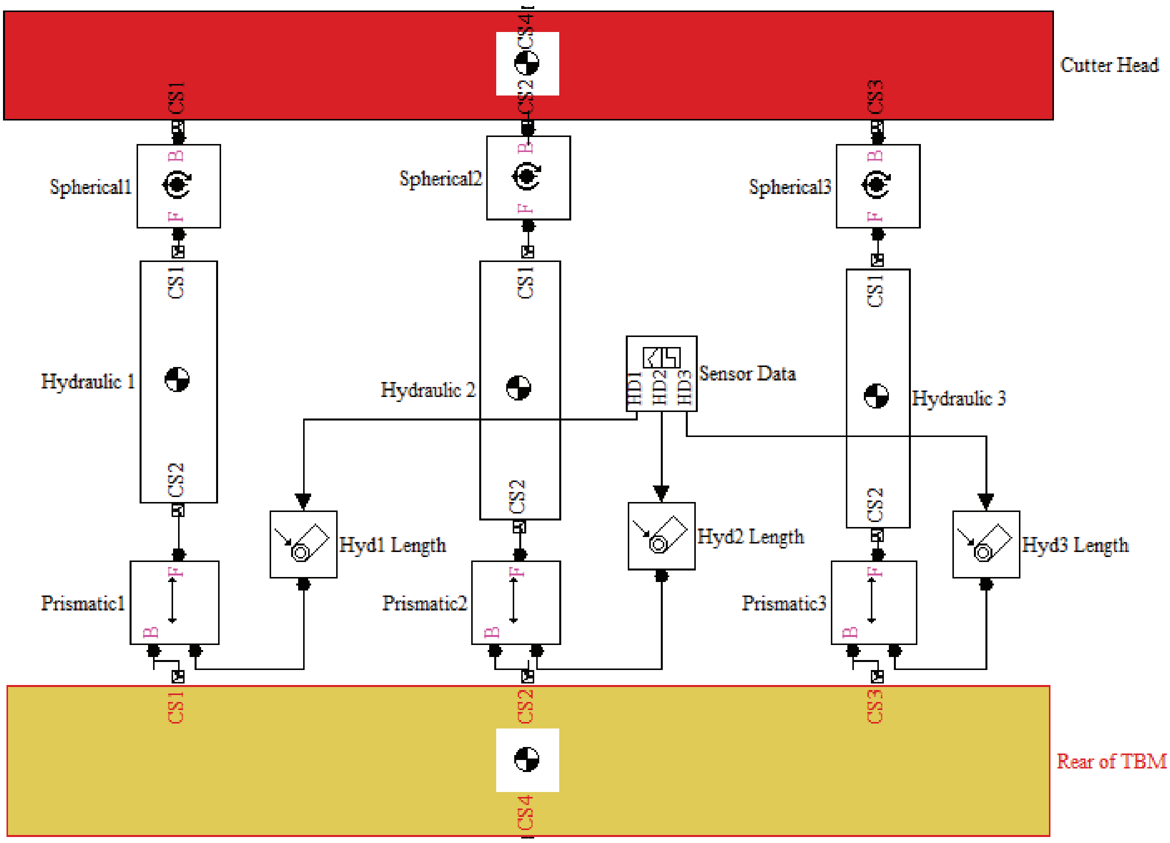


Fig. 6: The kinematic model of MTBM in Simulink environment

A body application blocks represents a user-defined rigid body, which is defined by mass, inertia tensor, and coordinate origins and axes for center of gravity and other user-specified body coordinate systems. As shown in Fig. 6 , the five body blocks represent the rear part of TBM, the cutter head and the three hydraulic cylinders respectively. The rear part of TBM is linked with the hydraulic cylinders by prismatic joints, and the cutter head is linked with the hydraulic cylinders by spherical joints. A prismatic joint represents one translational degree of freedom. The follower (F) body translates relative to the base (B) body along single translational axis connecting body coordinate origins. A spherical joint represents three rotational degrees of freedom. The follower body pivots freely relative to the base body at the collocated body coordinate system origins.

The push or pull operations on the hydraulic cylinders induce the pose changes of the head cutter, which provides a mechanism to adjust the drilling direction. The kinematic model provides an interface for inputting the length information of the piston rods of hydraulic cylinders. By using the information, the Simulink environment performs the forward kinematic computing to obtain the five body elements' position and orientation information which will be linked with the VRML file created in previous section to generate animations.

5.3 "Points to matrix" transformation

The kinematic model discussed in section 5.2 can only give the relative motions between the five body elements. The rear part of TBM is treated as a fixed base in the system. The SimMechanics toolbox does not provide functions to model the position and orientation of the fixed base in a kinematic model. However, the Simulink environment provides user-defined functions that enable us to extend the capability of the existing system. A "points to matrix" transformation algorithm (Liang 2010) is coded as a user-defined function as shown in Fig. 7. The input parameters of the function are the coordinates of three tracking points on MTBM, while the output is the position and orientation information in the form of a 4×4 homogeneous transformation matrix.

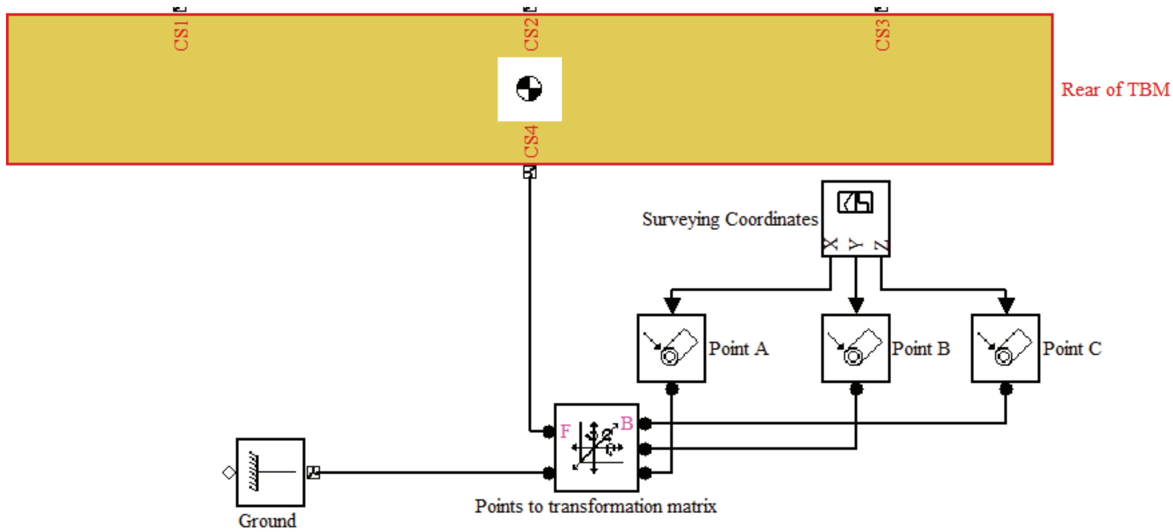


Fig. 7: Coding the “points to matrix” transformation algorithm in user-defined application blocks

6. EXPERIMENTS AND RESULTS

Two experiments were conducted to test the feasibility of the proposed methodology. The first experiment was based on the data collected from a real microtunneling project in Hong Kong. The purpose was to verify the “points to matrix” transformation algorithm. Then based on the position and orientation information results from the first experiment, we conducted a second experiment to test the kinematic models by inputting the piston rods length data simulating the operations on the MTBM.

6.1 Visualization of MTBM’s position and orientation

As the test bed for this experiment, a pipe jacking site for constructing one cross-river tunnel with a length of 220 m and an inner diameter of 1200 mm was selected. The project was commenced in October 2008 and was completed by December 2009. The data were sourced from the field testing of a TBM guidance system (Shen, Lu & Chen 2010). The field testing was carried out in late August 2009 at the pipe jacking site in the New Territories of Hong Kong.

As shown in Fig. 8, the collected data (coordinates of three tracking points) are transferred to the “points to matrix” transformation algorithm which generates the position and orientation information (“**RT**” in Fig. 8) of the rear part of the MTBM. The VR graphic engine uses the computing results to update the 3D model of the rear part of the MTBM. In order to visualize the as-built tunnel, a tracer application block of Simulink is used to generate the 3D models of installed tunnel segments (cylinders having 1200mm diameter and 100mm height) according to MTBM positioning information. The tracer block also provides an interface to change the color of the tunnel segments to be generated during the drilling process (yellow in this experiment). As shown in Fig. 8, the alignment deviations can be visualized according to the real site situation. We can also navigate in the virtual world to check the details of the alignment and the geometric relationship between the tunnel and existing underground facilities. The visualization effects demonstrate that the proposed approach can be applied for effective alignment guidance and “as-built” tunnel surveying.

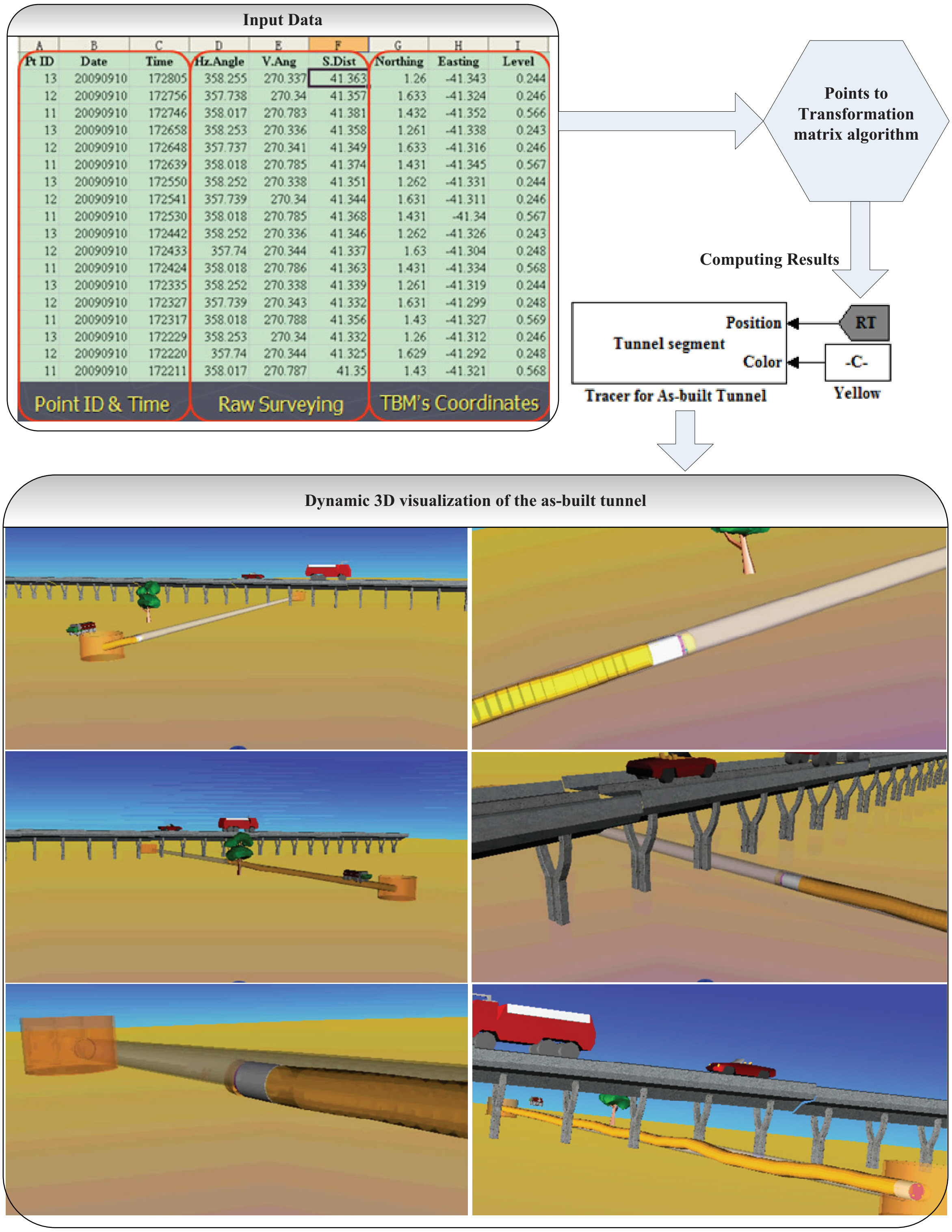


Fig. 8: The data flow and visualization effect of the first experiment

6.2 Dynamic 3D visualization of the cutter head control system

The data flow of the second experiment is given in Fig. 9. Based on the position and orientation information ("RT" and "RR" in Fig. 9) from the first experiment and the piston rods length information, the kinematic model generates ten computing results denoting the position (translation vector) and orientation (rotation matrix) of the five body elements. The computing results are linked with the VRML file to update the 3D geometric models in the virtual reality environment.

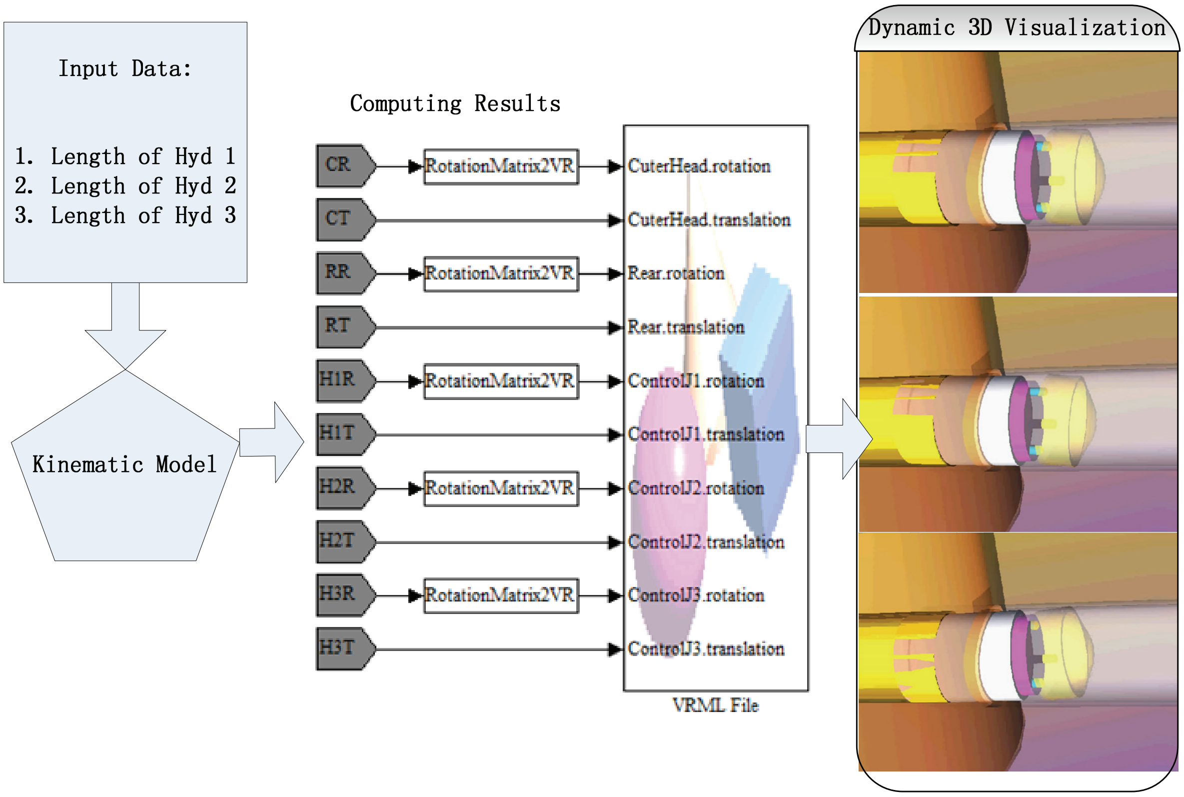


Fig. 9: The data flow and visualization effect of the second experiment

Note that the data structure of the rotation matrix is different from the one used in the virtual reality application. Thus a "RotationMatrix2VR" application block is used to convert the data structure. As shown in Fig. 9, the changes of the piston rods' lengths can be exactly reflected in the virtual reality environment. We can navigate (rotate and scale the 3D view, zoom in and out) in the virtual world to check the orientation of the cutter head. The visualization effects show the significant potential of the proposed approach to support operators in making fast and sound decisions for steering MTBM.

7. CONCLUSION

This paper has proposed a cost effective virtual reality modeling methodology for on-site visualization of articulated micro-tunnel boring machine operations by integrating sensor data, 3D geometric model, kinematic model of the MTBM and a "points to matrix" transformation algorithm. This methodology is generic and can be easily adapted to other construction equipment and operations that desire effective 4D visual aid to operators, e.g., tele-operations, underwater construction.

Two experiments were conducted to verify the proposed methodology. One experiment was based on simulated data and the other was based on real site data. The experiments show that the proposed methodology is effective and efficient to build dynamic 3D virtual reality models that can be utilized to assist in tele-operations of the MTBM as well as tunnel alignment control. Thus, operators can take setter control during the tunneling process.

The implementation of the methodology is based on the SimMechanics toolbox in MATLAB. The tool is originally developed for mechanical systems design, which lacks effective interfaces for real-time data communication. Thus, it is difficult to synchronize automated data collection system and the visualization system for real-time updating. In order to facilitate the application of the proposed methodology in construction, a standalone system should be developed in the future research, including a graphic network modeling platform for creating the kinematic model, a data communication protocol for real-time data transfer between data collection system and visualization system, and a 3D graphic platform to render the virtual reality model.

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DEVELOPMENT OF 3-DIMENSIONAL GEOSPATIAL INFORMATION SYSTEM WITH PANORAMIC IMAGES FOR RAILWAY FACILITY MANAGEMENT

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ABSTRACT: *Railway companies in Japan maintain detailed railway drawings which list rail facilities. These drawings include various specifications of railway facilities and are useful in understanding the environment and surroundings of railroads. These drawings had been recorded on films or paper maps in the past. In recent years, most of these drawings have been transferred to CAD drawings by digital mapping techniques. Nowadays these vector map data are deployed in GIS. In some companies, these maps are visualized layered with corresponding aerialphotographs as background. East Japan Railway Company has been making practical use of these railway drawings since 2003, when we transferred films and paper drawings onto vector map data and utilized them as CAD spreads. In 2009, we conducted a massive renewal of railway drawings applying GIS measurement technology. At the same time, we created an interactive 3-dimensional terrain database along with a panoramic movie database. In this paper, we present the development of our totally new "3-Dimensional Geospatial Information System with Panoramic Images for Railway Facility Management," also called as "Digital Railway Drawing System". There were two major points in the development. First, the integration of aerialphotographs with 3-dimensional geospatial information enabled 3-dimensional terrain views surrounding railroads. Second, the practical use of a 360°-view high resolution camera provided realistic human-eye view of railroads and their surroundings. Accurate information of railroads and their surroundings enhanced by optional functions enabled us to improve facility management; for example, preventing accidents in case of natural disasters, or rapid deployment in case of emergency. Furthermore, the intuitive and simple operation is welcome by staff members who are not used to operating computers. This development is useful not only for the Civil Engineering Division, but also for other maintenance divisions such as those handling tracks, architecture, machinery, electricity, signals, and telecommunication. It is also useful for the Operation Control Center. We expect to integrate this system as a fundamental visual database system for railway companies.*

KEYWORDS*: 3D geospatial information system, disaster prevention planning, sediment disaster, natural disaster, panoramic movie, kilometer posts, location information, orthophotographs, digital terrain model*

1. INTRODUCTION

East Japan Railway Company has been maintaining railway drawings for the purpose of managing railway structures, which is based on Railway Business Act. These drawings include drawings of the area within 100meters on both sides of railways, and show stations and major structures such as railway tracks, kilometer "posts" (which indicate distance from starting point of each route), bridges, tunnels, and station facilities etc. These drawings are maintained by a reduced scale of 1/500 or 1/2500, and the total extent is about 7,500km.

In past years, these drawings had been maintained by long Mylar films and papers. In 2003, they were digitalized into vector data (to facilitate handling as CAD data). As a result, these railroad drawings became seamless "digital drawings." (Figure-1, 2)

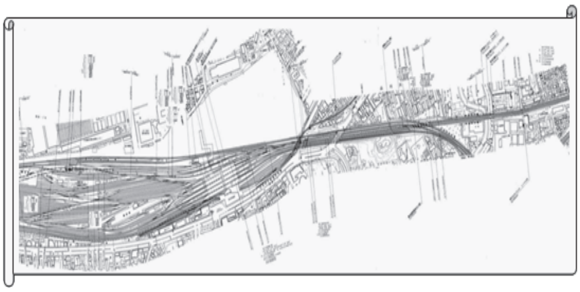

Figure-1 Paper drawing

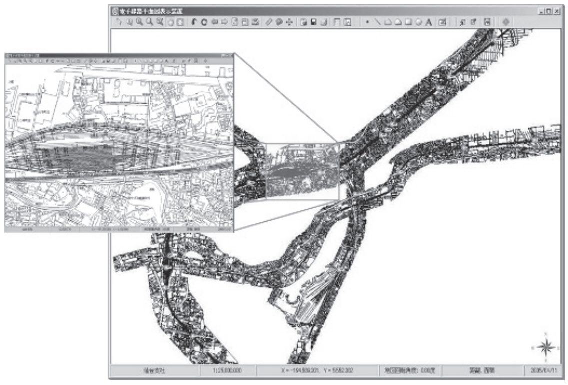

Figure-2 Digital drawing

This enabled us to utilize the data in various systems. Since 2004, we have been utilizing the data as location maps for structural inspection, as part of the civil engineering structure management system.

As we synchronized the map with ledger information, civil structure management has become more efficient, which led to the enhancement and improvement of accuracy of the structure management database.

2. ISSUES AND MEASURES

Five years or more have passed since films and paper drawings were transferred into vector map data.

The surroundings of railroads have changed by improvement of existing facilities and development of areas along railway-tracks, and updates for these changes were required. We set as our aim to assist disaster prevention planning and to achieve rapid deployment in case of abnormal circumstances, and planned to update and improve resolution of railway drawings. We also aimed to enhance additional functions so as to strengthen civil structure management.

We updated railway drawings using high-resolution aerialphotographs. In order to obtain higher resolution, these aerialphotographs were taken at a lower altitude (at 1,000 kilometers high) compared to those taken in previous years (at 2,000 kilometers high).

Additional 3-dimensional geospatial information was obtained by using a GPS/IMU device (Global Positioning System / Inertial Measurement Unit: device that records position and direction of the camera at the moment of photographing, which is installed in the aircraft for taking aerialphotographs) for correcting distortions.

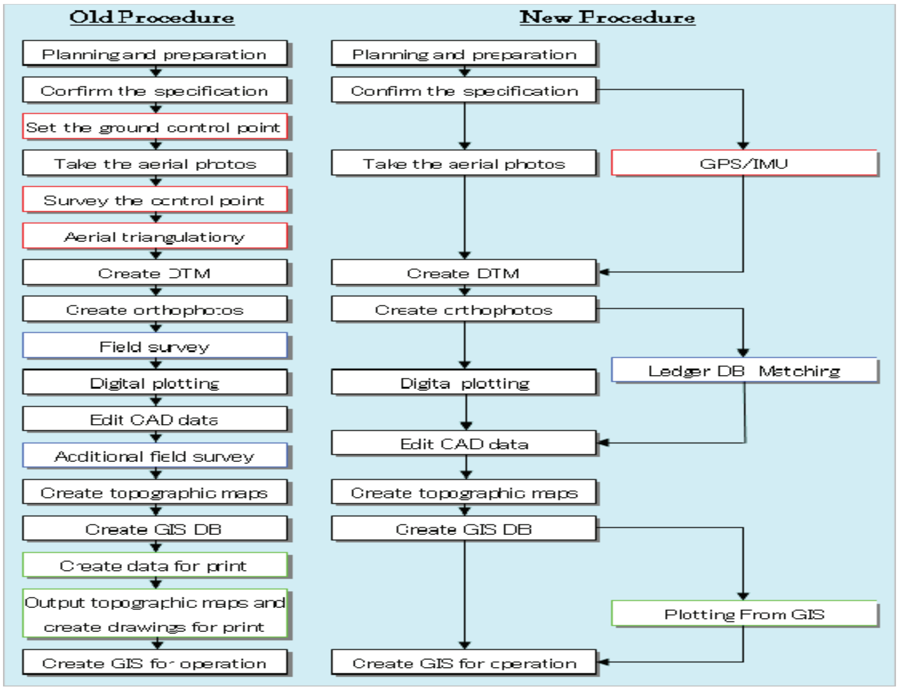

Figure-3 Comparison of work procedures

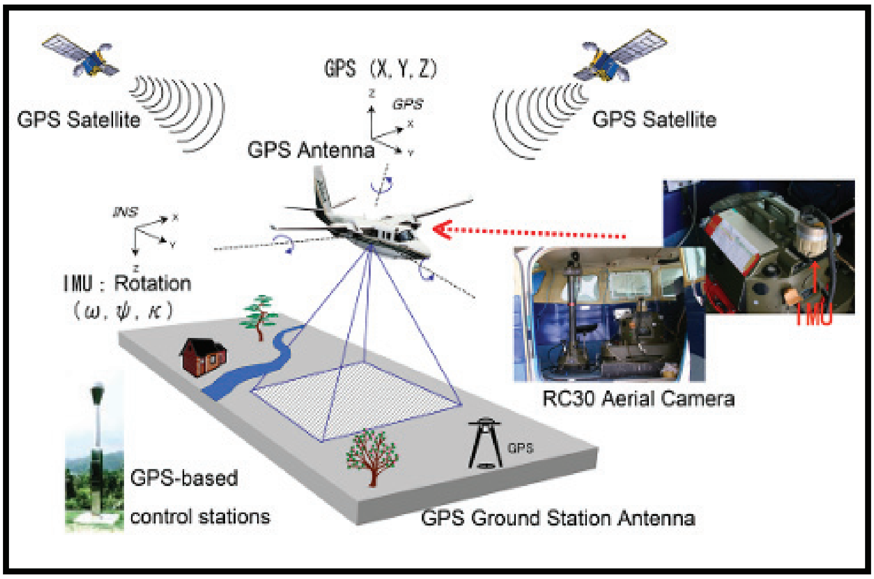

Figure-4 Mechanism of GPS/IMU

3. COMPOSITION OF THE NEXT "DIGITAL RAILWAY DRAWING SYSTEM"

The new "Digital Railway Drawing System" consists of three functions. These are the "Digital Railway Drawing Function", the "3DGIS Function", and the "Panoramic Movie Function". These functions can be synchronized mutually based on location information (information of kilometers from the starting point of each route). We can retrieve drawings by kilometer information, station names, facility names, addresses, or coordinates with common operability.

3.1 Digital Railway Drawing Function

The purpose of this function is to retrieve the required digital railway drawings, to display them by the necessary reduced scale, and to print them out according to the company's rules.

Although a normal map is usually drawn placing north on the top, railway drawings from the Meiji era have been often drawn so that a rail route would be shown horizontally, with the starting point on the left side. A function to rotate drawings instantly according to the azimuth of the railway track is thus indispensable. (Figure-5, 6)

"Hataage" in Japanese is written information of the facility ledger within drawings. Though there are rules to show facility information within digital drawings, it might be hard to distinguish those because they can be very complex according to place or due to reduced scale, and because they differ according to the structure classification. We developed the system to adjust the size of "hataage" automatically, according to reduced scale. (Figure-7, 8)

Considering that the system is operated by a computer mouse, there are functions to move position, to enlarge or to reduce displayed area, to display overlapped layer image of drawing with corresponding aerialphotograph, and to indicate distance between the stations or from the starting point.

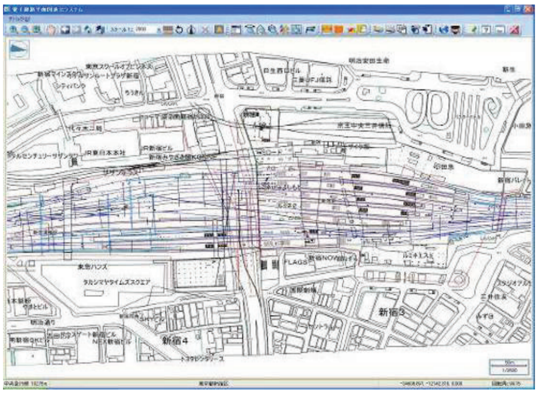

Figure-5 Digital drawing of railroad : scale 1/2500

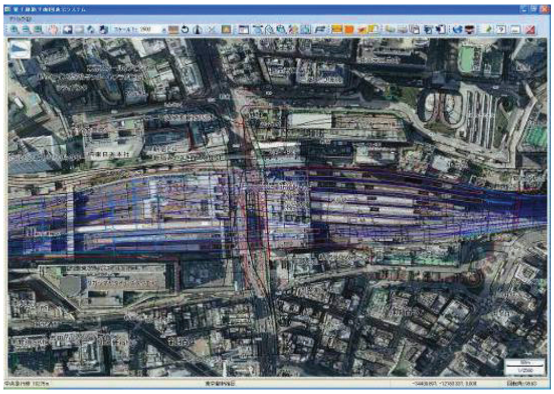

Figure-6 Overlapped layer image of railway drawing and aerialphotograph

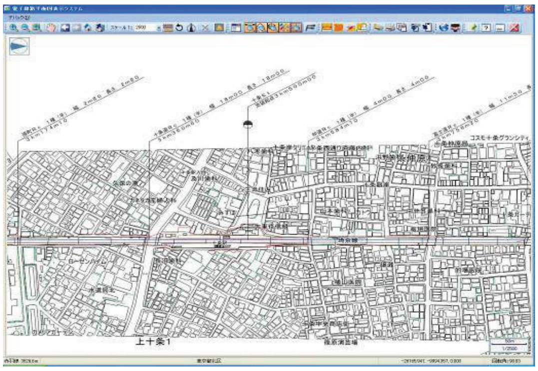

Figure-7 Automatic adjustment of ledger information

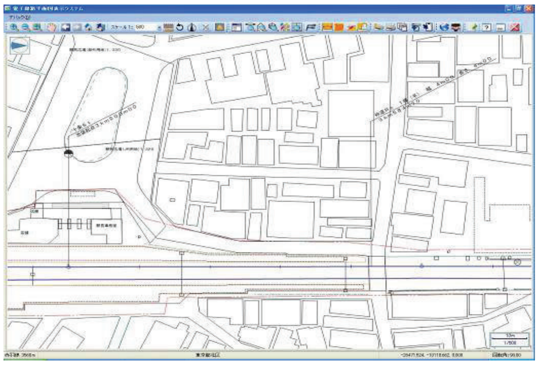

Figure-8 Automatic adjustment of ledger information

3.2 Function of 3-Dimensional Geographic Information System

Stereoscopic 3-dimensional railway information shows relations between railway facilities and surrounding terrestrial conditions. The data of this 3-dimensional railway track information were generated from distortion -correcting data for aerialphotographs. When this data is combined with high-resolution aerialphotographs, we can obtain a 3-dimensional view of railway tracks in a continuous bird's eye view.

At the beginning of our development, we studied using Google Earth (public version) or Google Earth (for enterprises). In the case of the public version, business use was strictly limited by the license permission, and only streaming delivery was allowed, which meant that we could not conduct application development on our own. On the other hand, in the case of the enterprise version, the infrastructure procurement and maintenance of the server, etc. and payment to Google Co. would have been required, which were not affordable. For this reason we gave up applying Google Earth technology for this system.

Table-1 Data comparison of each method

	3DGIS	Google Earth (public version)	Google Earth & Railway (enterprise version)
Service provider	East Japan Railway Company	Google Co	JR East Consultants Company
Digital terrain model	5m-mesh(around railroads) 10m-mesh(additional areas)	90m-mesh United States Geological Survey	50m-mesh Geographical Survey Institute of Japan
Resolution of the image	10cm(around railroads) 1m(additional areas)	According to place	1m
Data form	Data file form (The streaming form is also available)	Streaming form	Streaming form
Suitability for business use	Highly suitable	Unsuitable	Somewhat suitable
Operation of server	Not necessary	Necessary (Operated by Google Co.)	Necessary

We selected 3DGIS engine separately and registered the geographic information data. Though Google Earth uses 90m-mesh altitude data of the United States Geological Survey, high-resolution geographic expression became visually comprehensible by registering a minimum 10m-mesh data, Digital Surface Model (the height data for surroundings of railway tracks by aerial surveying) and 1m-mesh data which was used as a break line in 3DGIS.

When digital terrain data is combined with high-resolution aerialphotographs, we can obtain a 3-dimensional view of railway tracks in a continuous bird's eye view. (Figure-9)

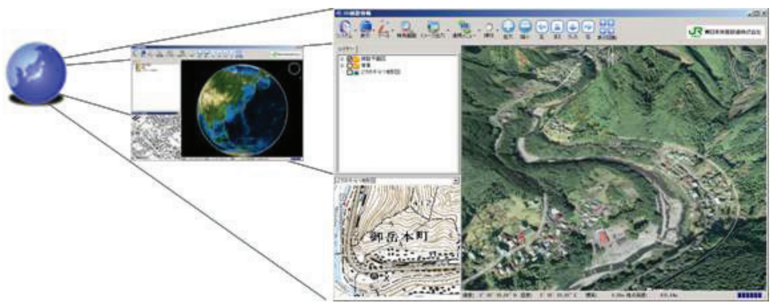

Figure-9 Visualized 3-dimensional information surrounding railroad

These visualized data show in detail the position of slopes facing railway tracks, overhead wiring along or intersecting railway tracks, and roads. The following figures show the features of digital terrain model quite clearly. (Figure-10, 11, 12)

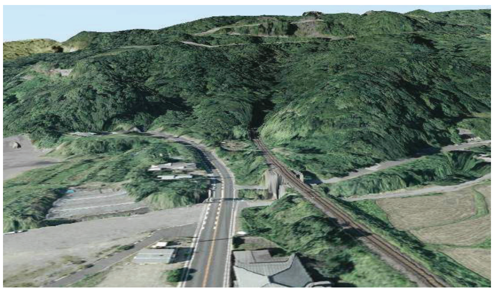

Figure-10 Bird’s eye view near exit of Nokogiri Mountain Tunnel, Uchibou Line

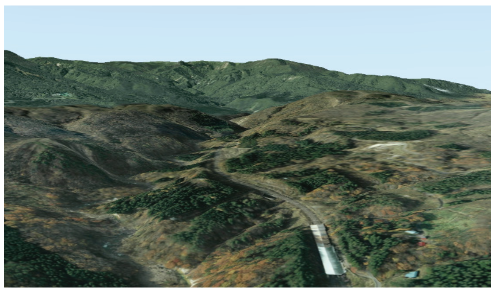

Figure-11 Bird’s eye view near Itaya Pass of Ouu Line

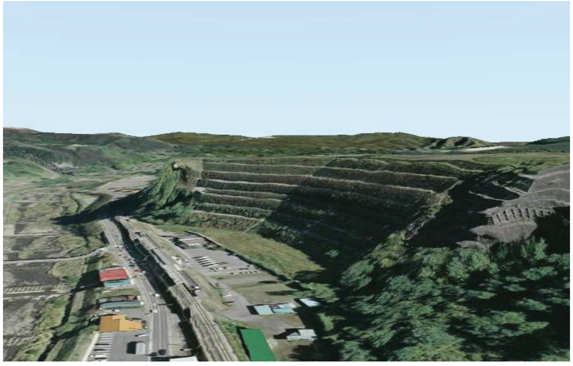

Figure-12 Bird's eye view of Manza-Kazawaguchi Station

In this system, we can produce a cross-section view of any place as the digital elevation data is embedded. In addition, we can measure the distance between two points where height is different, or we can measure vertical intervals. We can also make notes directly on this 3-dimensional view using this system. (Figure-13, 14)

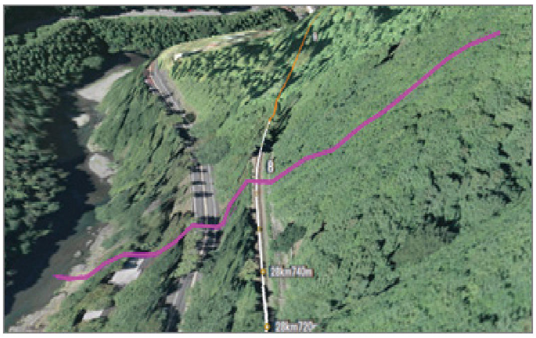

Figure-13 Making cross section (Line in figure)

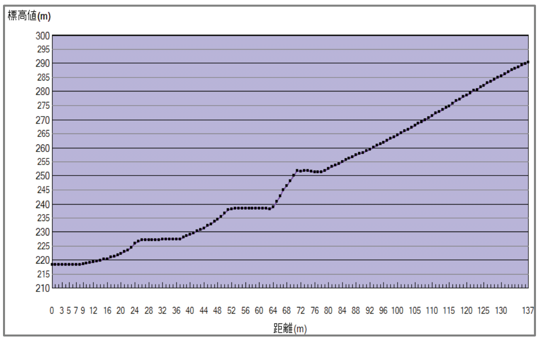

Figure-14 Cross section specified by Figure-13

This enables us to speed up correspondence in case of a disaster or an emergency. We can also share images when planning constructions or developments.

3.3 Panoramic Movie Database

Only limited information can be obtained by taking pictures of railroads from airplanes, even by high-resolution aerialphotographs.

We planned to make use of video images often taken from the driver's room on the train. In addition, we chose to use the panorama camera to improve those images for the structure management.

We compared industrial use cameras for moviemaking when selecting a camera for panoramic movies. Finally, we selected a camera that was able to record high-resolution images in all directions at the same time. (Figure-15)

Figure-15 360°panorama camera

This camera is a complex of six high-resolution CCD cameras set toward separate directions. Images can be projected spherically by converting images captured with each lens.

As software development sets for picture processing are supplied with the camera, we were able to develop software on our own.

Table-2 Parameter of selected camera

Name of camera	Ladybug 3
Manufacturer	Point Grey Research Inc.
Structure	six high-resolution CCD cameras
Dimensions	122 mm × 141 mm
Synthetic pixel count	5,400 × 2,700 pixels
Frame rate	15 frames per second

The selected camera is able to obtain images of six surrounding directions at one time. However, an effective range of image depends on where the camera is set up. (Figure-16,17) In order to reduce a "shielded" or blind region, the best place to set the camera is outside of the train.

We planned to set up the camera outside the train, in front of the train body. (Figure-18)

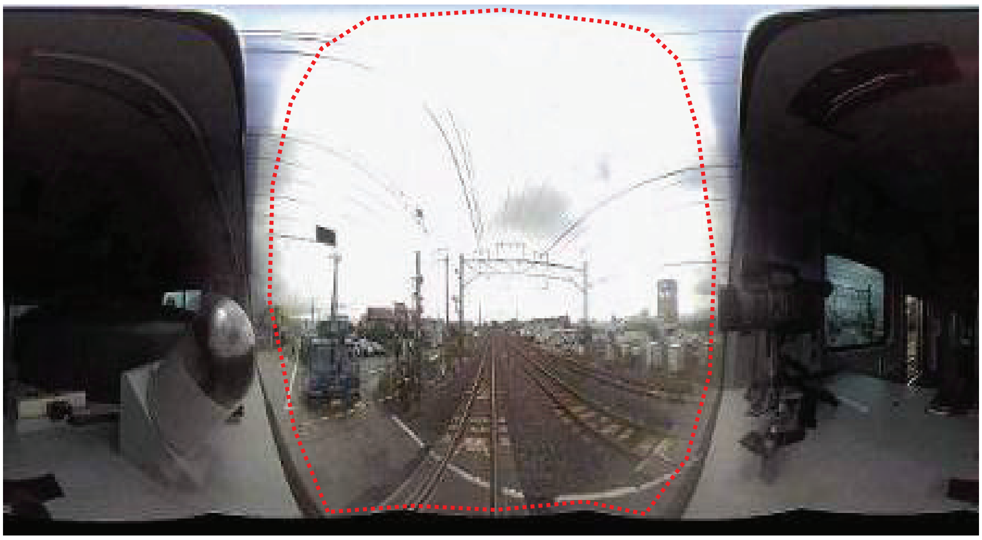

Figure-16 Image when the camera is set up beside driver's seat (Dotted line indicates effective range)

Figure-17 Image when the camera is set up in front of the train (Dotted line indicates effective range)

Figure-18 Installation of camera

After taking movies, we checked those movies, deleted unnecessary frames, and arranged them by routes. Then we linked frames with kilometer information. By this work, we can retrieve images by kilometer information, and do not have to search movies by time-lapse images as in videos.

As those movie files consist of a huge amount of data which is the equivalent of the data of six television, smooth playback of these data by normal PC was quite difficult. In order to improve operation, we prepared two types of data, that is, of high quality and of low quality, and switched these types of data according to operation.

The main operations of the movie-viewer are to play, stop, slow, forward, reverse, skip frames, and so on. We can rotate views on the screen and enlarge / reduce images by computer mouse. We can also search movies by station names, by name of the line, by kilometer information, or by coordinates.

Figure-19 Image of application

The following are images of when the operator stopped panoramic movie temporarily at the position of Figure-19, and rotated the view in 4 directions; left, right, up, and down. (Figures-20, 21, 22, 23)

Figure-20 Viewing left at the point of figure-19

Figure-21 Viewing right at the point of figure-19

Figure-22 Viewing up at the point of figure-19

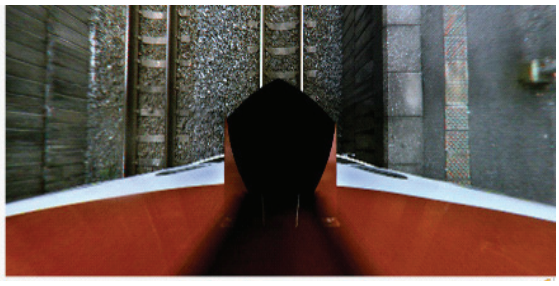

Figure-23 Viewing down at the point of figure-19

Figure-24 Aerialphotograph at the point of Figure-19

Figure-24 is the view of high-resolution aerialphotographs at the same point. We can see the difference between the image of the aerialphotograph (taken at 1,000 kilometers high) and the image of panoramic movie view (taken at several meters above the ground). As the panoramic movie is taken at human-eyes' height, we can see the conditions of the railroads as if we were looking with our eyes.

4. REVIEW OF THE SYSTEM AND FUTURE TASKS

4.1 Technical Novelty

Our challenge was that there was no precedent system for railway operators. Our development was as follows.

- Smooth and seamless view of high-resolution aerialphotograph over a wide range.
- Development of 3-dimensional basic software that enables to retrieve data at high-speed, to operate smoothly, and to display data at desired reduced scale for a planned total extension of 7,500km.
- System and data operating not by streaming-server but in a stand-alone environment with ordinary PCs.
- Iconized kilometer and facility information.

Regarding the panoramic movie database, there were more challenges, such as the followings.

- The camera was installed to take panoramic images in an effective position at sinciput outside the inspection

train.
- Panoramic movie camera was used continuously at an outdoor environment, for about half a year in total.
- Panoramic images were taken at the speed up to 130 km/h, the maximum speed of urban and local railways, and were viable without vibration.
- The movies were taken continuously for eight hours a day, handling a large amount of data (80MB/s).

It should be noted that such existing techniques were conducted as partial study or demonstration. This time, we devoted our energy to attain stable operation of the system for business use at a minimum cost, such as the followings.

- First of all, we confirmed specification of aerialphotograph survey and controlled the process in order to register data without editing or correcting. We also planned thorough inspection of aerialphotographs and related 3-dimensional data.
- We developed three individual application software for three functions and integrated those, from the viewpoint of cost advantage coping with users' operability.

4.2 Future Issues

We are considering how to upgrade and to efficiently improve the following issues by technical solutions.

- As data of panoramic movies is as huge as about 2TB per day, we must change hard disks every day. We believe that we will be able to improve recording efficiency by developing a mechanism to stop and start recording automatically corresponding to the movement of the train.

- Checking movies to match each frame with kilometer information is now conducted manually. We believe that we will be able to speed up the task by using GPS when taking a picture, or by automatically recognizing images of kilometer posts in panoramic images.

- The cost of storage media can be reduced by improving the efficiency of data storage. Technology of data compression and de-compression may be effective in this case. Compressing data is not required when taking movies, but de-compression needs to be carried out in quite a short time, which is quite difficult to be conducted with existing technology.

- In addition, 3DGIS function may be required to add efficient tools for business and analysis, depending on future use at various sites.

5. CONCLUSION

Introduction of the next generation "Digital Railway Drawings System" resulted in improvement of accuracy of digital railway drawings. In addition, it enabled us to confirm site information from various aspects such as aerialphotographs, 3DGIS which is able to catch ambient surrounding like bird's view, and panoramic images. Especially, panoramic images enabled us to understand the outline and surroundings on site promptly at our desk, even if we are not well informed, and we can confirm the site from the driver's point of view.

We will keep studying to make better use of additional functions. We will improve this system to strengthen civil structure management and to achieve rapid deployment in case of abnormal circumstances for safe and stable transportation.

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SIMULATION-BASED APPROACH TO PLANNING TEMPORARY TRAFFIC ARRANGEMENT FOR MICROTUNNELING OPERATIONS IN URBAN AREAS

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ABSTRACT: *Microtunneling and pipe jacking is commonly used in urban areas for constructing subsurface utility tunnels. A jacking pit is generally required to be excavated in a traffic lane in order to launch a tunnel boring machine (TBM) and install pipe sections. This paper addresses the application needs for modeling the traffic-construction interaction and applies discrete simulation modeling to automate the site access layout design and investigate the impact of construction on the traffic. Relevant parameters are generalized for defining site access and layout design in the context of microtunneling construction in a congested urban setting. Based on those parameters, discrete simulation models are generated in the SDESA platform (simplified discrete event simulation approach), which is a cost-effective simulation methodology developed from in-house research to facilitate the operations planning integrated with site layout planning in construction. The resulting SDESA simulation model is conducive to assessing the dynamic characteristics for a given scenario of the complicated traffic-construction system being modeled. Multiple scenarios can be designed and evaluated to address following issues related to construction planning and traffic planning: (1) Planning for the location and size of jacking pit; (2) Planning site access, including the points of ingress and egress and time restriction; (3) Planning for temporary storage or lay down areas near jacking pit. The simulation condenses the simulation results in terms of traffic flow statistics including "Added System Residence Time of Each Car" into a driving delay warning system (amber/red/black color schemes for certain thresholds of traffic delay), leading to effective communications and sound decision making among all the stakeholders of the project in planning the temporary traffic arrangement (TTA) for microtunneling in congested urban areas.*

KEYWORDS*: Construction, Simulation, Traffic Modeling, Temporary Traffic Arrangement, Trenchless Technology.*

1. Introduction

The construction method of microtunneling and pipe jacking is commonly used in urban areas for constructing subsurface utility tunnels. A jacking pit is generally required to be excavated in a traffic lane in order to launch a tunnel boring machine (TBM) and install pipe sections. This paper addresses the application needs for modeling the traffic-construction interaction and applies discrete simulation modeling to automate the site access layout design and investigate the impact of construction on the traffic. Relevant parameters are generalized for defining site access and layout design in the context of microtunneling construction in a congested urban setting. Based on those parameters, discrete simulation models are generated to assess the dynamic characteristics for a given scenario of the traffic-construction system being modeled.

With the simulation tool, multiple scenarios can be designed and evaluated to facilitate the construction planning and traffic planning, addressing following issues: (1) Planning for the location and size of jacking pit; (2) Planning site access, including the points of ingress and egress and time restriction; (3) Planning for temporary storage or lay down areas near jacking pit. This is conducive to effective communications and sound decision making among all the stakeholders of the project in planning the temporary traffic arrangement (TTA) for microtunneling in congested urban areas. The simulation condenses the simulation results in terms of traffic flow statistics including "Added System Residence Time of Each Car" into a driving delay warning system, featuring amber/red/black color schemes to differentiate certain thresholds of traffic delay.

2. Problem statement on TTA impact assessment

Nido *et al.* (1999) addressed the importance of operations simulation in analyzing and improving the system performance of a microtunneling project and the utilization rates of labour resources. Lau *et al.* (2009) proposed a framework for development of intelligent decision support means to enable effective microtunneling construction planning concentrating on the general site operations planning. Lau *et al.* (2010) implemented the simulation model for the production system and demonstrated the application values of the simulation model for decision support in planning microtunneling construction. The above operations simulation models largely focus on typical site operations, without considering the traffic impact imposed to the road users or the delivery logistics that may be affected during the implementation of TTA plans for the microtunneling site. For effective microtunneling construction planning in congested urban areas, TTA planning plays a pivotal part in achieving smooth, successful operations of microtunneling sites. Owing to the limited road width in the urban area, the traffic impact induces prolonged queuing to road users, potentially leading to public complaints and substantial social cost. The TTA plans are usually prepared by traffic consultants based on available traffic flow information and previous TTA plans in the vicinity. In order to verify the effect of the TTA plans at critical locations, trial runs in the first one or two days before the actual site commencement would be requested by the relevant traffic authorities. However, this practice entails experimentation of the TTA in the real world, possibly causing major traffic disruptions and incurring exorbitant social cost. In view of the public interest, there exist application needs for modeling the traffic-construction interaction operations, as echoed at the 'Research Needs for New Construction using Trenchless Technologies' conference held on 17th June 2003 at the University of Birmingham UK (Chapman *et al.* 2007). On the conference, the whole life costing of trenching and trenchless technology including social cost ranked the highest during the voting on generic issues of planning, design and monitoring. The present research applies discrete simulation modeling to automate the site access layout design and investigate the impact of construction upon the traffic.

2.1 Parameters defining TTA scenario

Fig. 1 shows a typical TTA plan for microtunneling site with one of two lanes in the carriageway closed during the course of construction. Based on the site layout requirement, the existing traffic flow and the restricted speed, the planner defines the vehicle passing speed (V_p) in the system (from site access to site exit), the vehicle approach speed (V_a) (prior to entering the system), the width of pit (W), the length of pit (L_2), and the centre coordinates of the pit (X_c, Y_c).

Three road sections are defined as: 1) the "approach taper" section with length L_1 related to W and V_a according to design guidelines and manuals; 2) the "construction bottleneck" section with the length of pit (L_2); and 3) the "end taper" section whose length L_3 is a function of W in accordance with design guidelines and manuals.

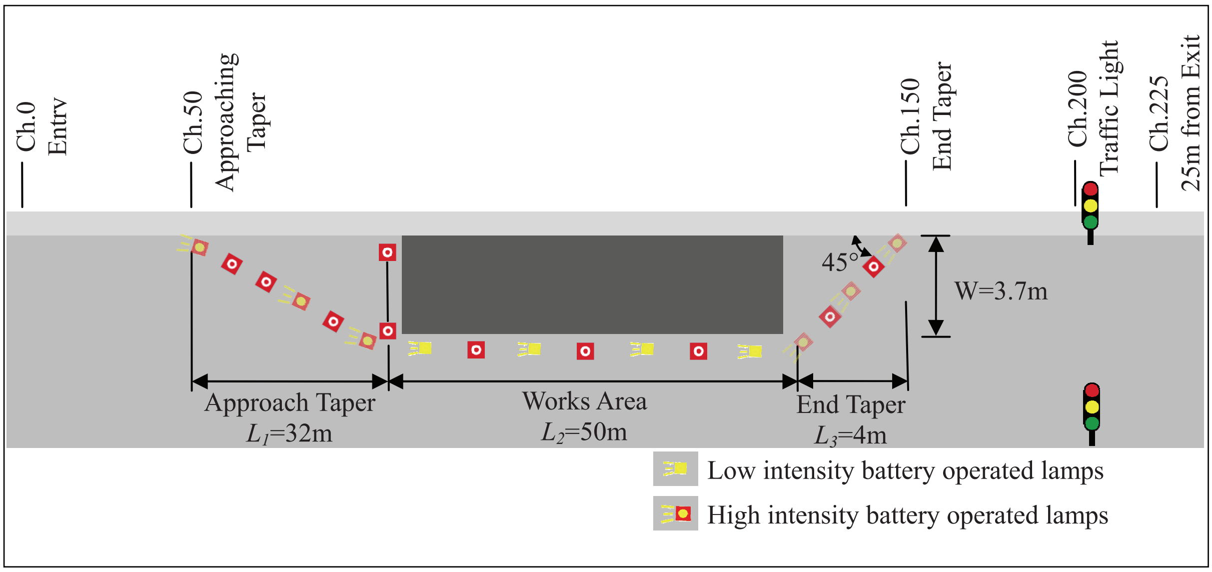

Fig. 1: Basic TTA Layout (Modified from Fig. 5.0 "CoP for the LSG of Road Works" (HyD 2006))

A simulation model is embedded behind the Google Map to model the traffic flow and the site access subject to the interference of ongoing construction activities.

At the site entrance, the inflow of vehicles follows a statistical distribution for inter-arrival time (T_{int}). T_{int} can be fitted to traffic in particular time slots, such as for peak hour traffic versus for non-peak hour traffic.

The traffic carrying capacity for a particular road section (Q_i) is defined as

Q_i = quantity of vehicles per lane * number of lane = L_i/L_v * number of lanes

L_i is the length of a particular lane in meters; L_v is the length of a standard vehicle + gap between vehicles

For the three road sections, we can determine Q_1, Q_2, and Q_3, which will be modeled as finite resources in the simulation model. The logical connection between consecutive road sections is defined as follows: an empty spot in the next road section will trigger the move-in of one vehicle from the previous road section, which releases a spot in the previous road section.

Time for a vehicle to pass each road section (D_i) is defined as

$D_i = L_i/V_p$*60/1000 min

V_p can be a distribution, e.g. UNIF(20,25) km/hr, and can be fitted to each road section given data available.

The site exit is modeled with a traffic light, the green light phase (T_g) and red light phase (T_r) in a cycle are given. The outflow capacity of the site exit is modeled as (Q_g), which is the quantity of vehicles that can exit out of the system during the time period of T_g. Q_g or T_g can be adjusted in simulation modeling to improve the efficiency of the traffic flow system.

Thus, a particular TTA scenario can be uniquely defined by following parameters:

TTA Scenario [$V_a\ T_{int}\ V_p\ L_2\ W\ (X_c,Y_c)\ L_v\ T_g\ Q_g$]

By setting those parameters, the TTA around the jacking pit can be defined. The underlying simulation model will evaluate a specific scenario by analyzing the system performances in terms of total quantity of vehicles passed in a given time period, the statistics on queuing time versus system residence time of a vehicle, the queuing length at site access. .

Given the simulation tool, multiple scenarios will be designed to facilitate the construction planning and traffic planning, addressing following issues:

1. Planning for location and size of the jacking pit
2. Planning site access, including point of ingress and egress, plus any time restrictions.
3. Planning for temporary storage or lay down areas near jacking pit

The preliminary research will develop parametric interfaces to automate the site access layout design by simulation modeling. Those scenario parameters will inform an underlying simulation model to trigger traffic analysis.

3. SIMULATION MODELING APPLICATION

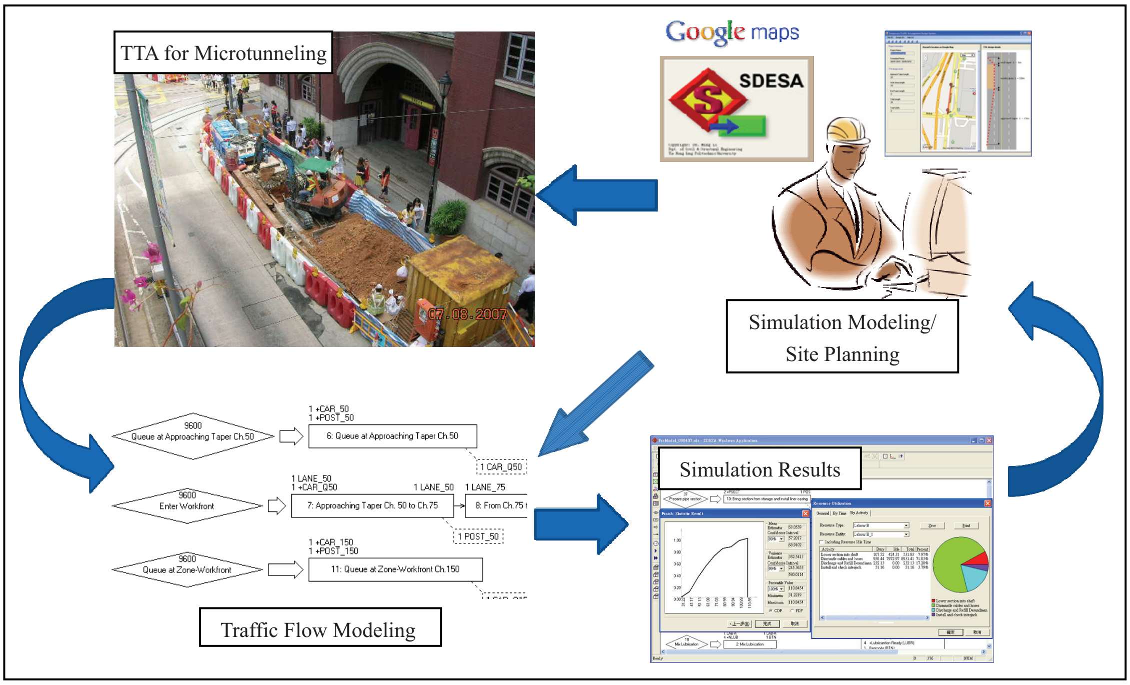

Fig. 2 outlines the framework of the simulation methodology.

At the site planning stage, the Temporary Traffic Arrangement (TTA) is planned based on 1) the required location and size of the jacking pit; 2) site access, including point of ingress and egress, any time restrictions; 3) temporary storage or lay down areas near the jacking pit.

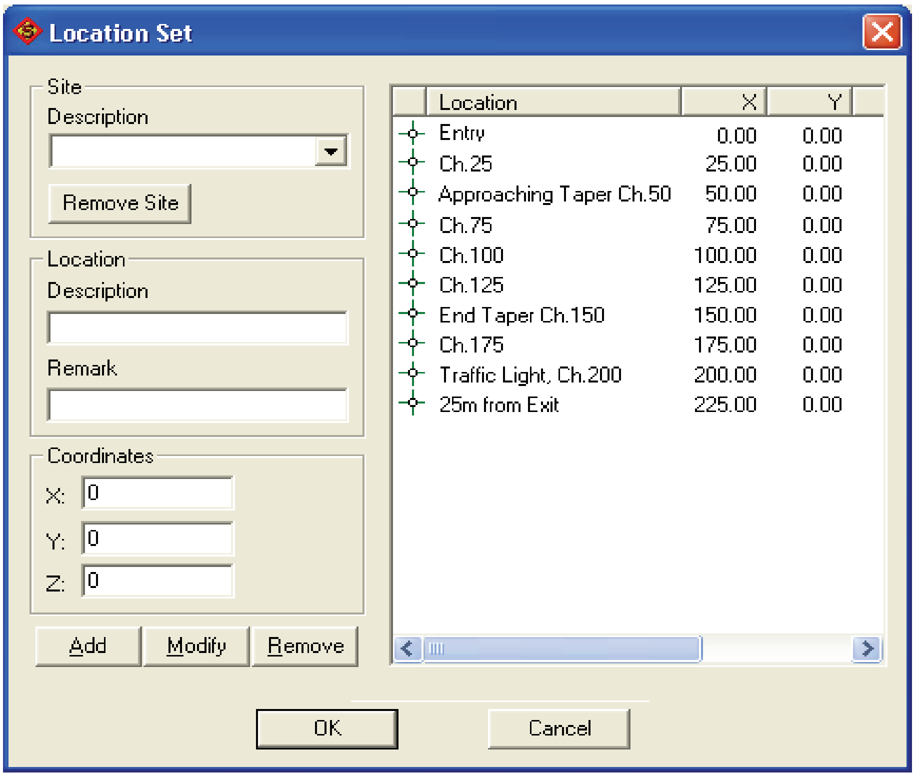

Fig. 3: Location Set for TTA plan of Microtunneling Site

The road concerned between "Entry" and "25m away from exit" as shown in Fig. 1 are divided into 25 metres long sections, from Chainage 0 to Chainage 225. The location set is defined in the model as shown in Fig. 3. All sections consist of two lanes in the baseline case, while one lane will be closed for the section between "Approaching Taper" & "End Taper" (*i.e.* L_1, L_2 and L_3) when implementing the TTA plan in the works area.

Table 1 summarizes the traffic flow details for various TTA sections, providing simulation input models. L_i, the length of a particular lane section is defined as 25 metres along the road; L_v, the length of a standard vehicle + gap between vehicles is specified to be 12.5m. Therefore, the traffic carrying capacity for a particular road section can be determined (Q_i) = L_i/L_v * number of lanes (1 or 2 for cases with and without workfront).

Table 1: Simulation Model Input for Traffic Flow Details at the Concerned TTA Section

Chainage	Length (m)	Speed (km/h)	Number of cars per lane	No. of lane	Total Number of cars
50m from Entry to Approaching Taper					
Ch.0-25	25	24-30	2	2	4
Ch.25-50	25	24-30	2	2	4
Approaching Taper to End Taper					
Ch.50-75	25	24-30	2	2 (1 with TTA)	4 (2 with TTA)
Ch.75-100	25	24-30	2	2 (1 with TTA)	4 (2 with TTA)
Ch.100-125	25	24-30	2	2 (1 with TTA)	4 (2 with TTA)
Ch.125-150	25	24-30	2	2 (1 with TTA)	4 (2 with TTA)
End Taper to Traffic Light					
Ch.150-175	25	24-30	2	2	4
Ch.175-200	25	24-30	2	2	4
Traffic Light to Exit					
Ch.200-225	25	24-30	-	2	-

Limited vehicle positions are defined to model the queues in traffic. Note that only when the previous position is clear the current position would be released. Note the logical connection between consecutive road sections is that an empty spot in the next road section triggers the move-in of one vehicle from the previous road section, which releases a spot in the previous road section.

The incoming traffic flow data for the simulation model in the morning (0600-1200) is summarized in Table 2. The peak hours (0800-1000) and non-peak hours (0600-0800 and 1000-1200) are defined by uniform distributions of inter-arrival time being [1,2] min and [2,4] min respectively. The traffic flows are equivalent to 1200 and 2400 vehicles per hour accordingly.

Table 2: Simulation Model Input of Incoming Traffic Flow

Simulation Time	Peak hour/ Non-peak hour	Inter-arrival Time (s)	Average Inter-arrival Time (s)	Vehicle/hour
0600-0800	Non-peak	UNIF[2,4]	3	1200
0800-1000	Peak	UNIF[1,2]	1.5	2400
1000-1200	Non-peak	UNIF[2,4]	3	1200

For the outgoing traffic flow, the vehicles pass through the work front and stop at a traffic light with the following details: Cycle time is 60 seconds; green light phase (T_g) is 18 seconds; red light phase (T_r) is 42 seconds. Q_g, the quantity of vehicles that can exit during the time period of T_g is 38.

The simulation model is established using SDESA (Lu 2003; Lu *et al.* 2007) as shown in Fig. 4. SDESA is a simplified, activity-based simulation modeling platform for critical path method (CPM) application. Interested readers may refer to those publications for the SDESA algorithm, methodology, and software.

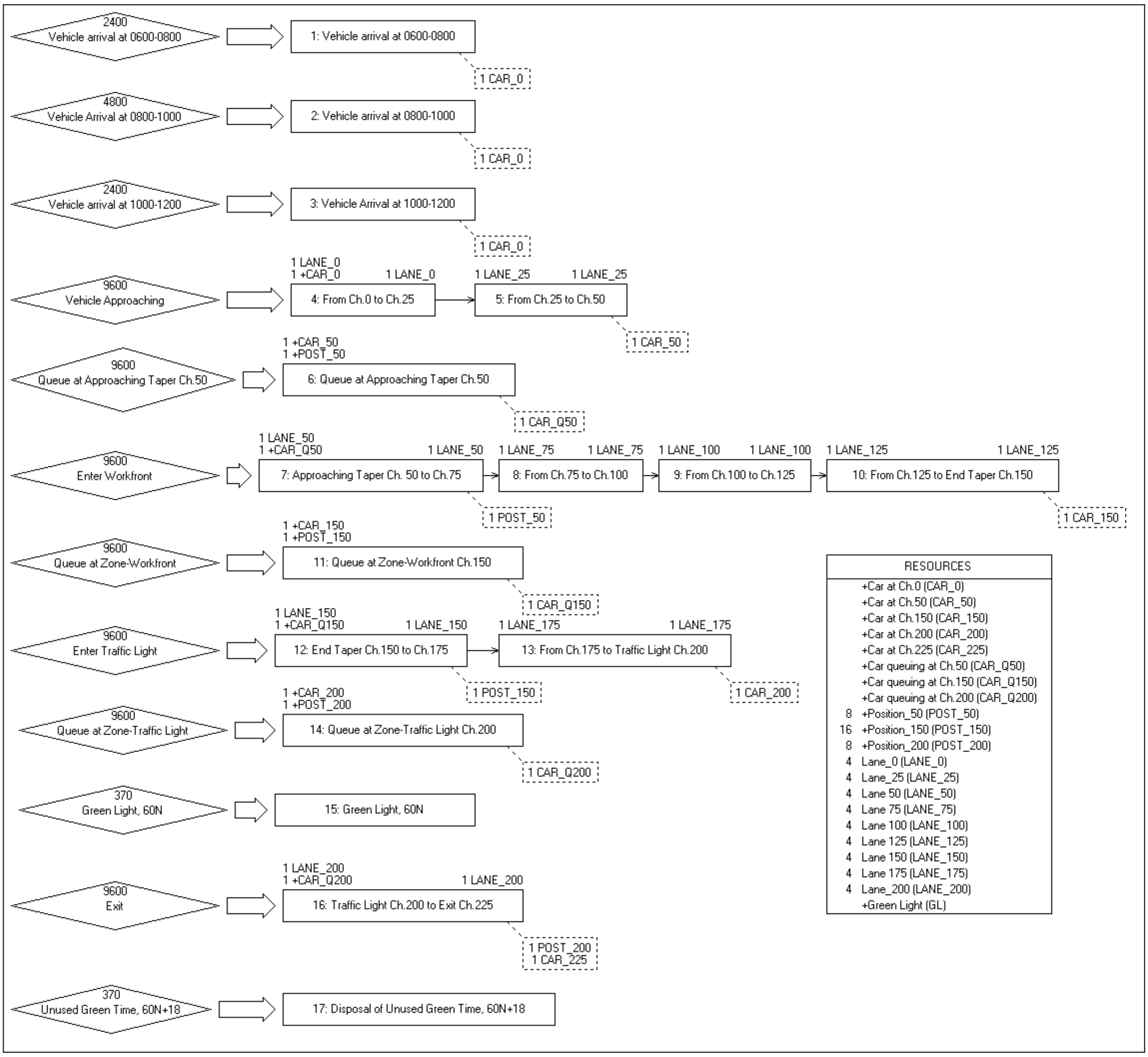

Fig. 4: Traffic Model Using SDESA for TTA of Microtunneling Site

As shown in the figure above, the flow entity diamonds leading a series of activity blocks denote the number of vehicles (vehicle arrival at different timeslots) or the quantity of traffic signals (green light for each minute) to pass through the system. The activity blocks represent activities that consume time and resources in carrying out a flow entity. Reusable resources (number of traffic lanes along the chainage, storage space for vehicles in the lanes) are defined in the initial resource pool to model the traffic spatial constraints. The top left corner of activity blocks shows the resources required to drive an activity. Disposable resources are differentiated from reusable resources by its temporary nature in form of intermediate products or information unit generated from an activity (e.g. "car at different chainages, *CAR_0"* at the right bottom of an activity "*Vehicle arrival")* and requested by another (as shown in the top left corner of the activity block *"(Vehicle Travel) From Ch.0 to Ch.25"* and prefixed with "+").

An activity would commence with all the driving criteria (resources, signals) of an activity block are satisfied. Upon the completion of an activity, the reusable resources (the available space in lanes in this traffic model) at the top and bottom right corner of activity blocks would be released and disposable resources (usually signals to link up different flow entities according to the logical sequences, for example, a vehicle travels across a section and getting into the next section) generated respectively.

The top three flow entities initiate vehicles entering the system at the timeslots 0600-0800, 0800-1000 and 1000-1200 respectively with the pre-defined vehicle inter-arrival time based on the peak and non-peak hour traffic statistics. One Car at Chainage 0 (*CAR_0)* is generated at the right bottom corner of the activities "*Vehicle* *arrival at 0600-0800", "Vehicle arrival at 0600-0800"* and *"Vehicle arrival at 0600-0800"*.

The subsequent flow entity *"Vehicle Approaching"* can then be activated once the signal is passed to the activity *"(Vehicle Travel) From Ch.0 to Ch.25"* which commences when the all resources required are ready including an empty lane *"1 LANE 0"* and one *Car at Chainage 0 "+1 CAR_0"*. The completed activity would further trigger its subsequent activity *"(Vehicle Travel) From Ch.25 to Ch.50"*.

It is worth note that a Start-Finish relationship is defined in the model for the queuing activity. Unlike typical construction processes where the activities are usually linked up by Finish-Start relationship (e.g. form working, concreting and removal of formwork), traffic modeling is on the opposite. The queuing activity starting from the front while the vehicle approaching behind waits until the vehicles in front are clear. As shown in Fig. 4, a *position at Ch. 50 "+ 1 POST_50"* is generated upon the completion of *"Activity 7: Approaching Taper Ch. 50 to Ch.75"*. The signal would in turn initiates *"Activity 6: Queue at Approaching Taper"* since the space in front is ready.

The initial traffic model is defined as a two-lane carriageway as a baseline for traffic impact assessment. The traffic flow information including incoming, passing and outgoing flows is given in the tables above. The model is then modified according to the TTA plan in which one of the two lanes is closed during the course of construction. The traffic statistics of the system before and after TTA implementation can be compared during the peak and non-peak hours. The traffic impact measures including the queue length and the "Added System Residence Time of Each Car" can be obtained from the model output.

Based on the simulation results, the site planning engineer can revise the site configuration, adjust the time for TTA implementation (e.g. 24/7 or 1000-1600 at working day) and schedule loading / unloading of equipment and materials (e.g. only during non-peak hours). The expected queuing time can be also used as a reference for the logistic delivery cycles. For example, given a simulated result of expected delay of [20, 30] minutes during the peak-hours, the site engineer can consider a non-peak hour delivery so as to avoid the delay or arrange for some deliveries at other sites with less traffic congestion in peak hours.

For a multiple-lane carriageway as shown in Fig. 5, the planner can make use of the simulation tool for simulating the closure of two of three lanes during the off-peak hours for loading/ unloading of jacking equipment at a compact site in which there is not enough space for the accommodation of a large crane within the site.

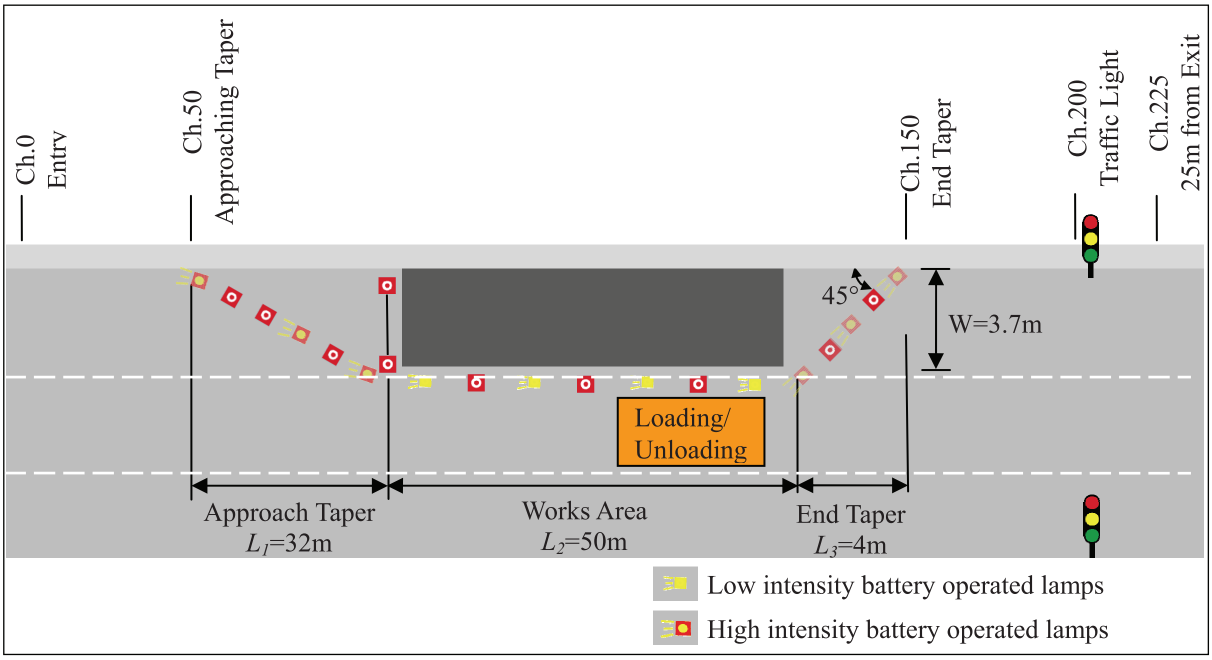

Fig. 5: TTA plan of Temporary Loading / Unloading Beside a Microtunneling Site

4. RESULTS AND DISCUSSIONS

From the simulation results, the baseline case was found to carry the smooth traffic, as indicated by a maximum queuing length of 5 vehicles throughout the whole period. On the other hand, congested traffic was observed with the implementation of TTA plan as shown in Fig. 6, the queue length builds up starting from 08:00 with the invoking of the peak hour traffic flow and reaches a maximum quantity of 255 vehicles per lane at 10:00. The digestion of the whole queue length requires further 30 minutes after the incoming traffic flow changes from peak-hour rate to non-peak hour rate. The effect of construction on traffic, indicated by the "Added System Residence Time of Each Car" statistics is shown in Fig. 7, which measures the additional time for the road user to spend in passing through the system. With the assistance of the simulation tool, the construction planner can review the possibility of extending T_g for increasing the Q_g, or to share the queue length between two directions of traffic flows by adjusting traffic light cycle times at the junction. The "Added System Residence Time of Each Car" would be used as an effective indicator for resource planning and logistics planning on site. For example, given the pipe sections would be delivered to site in the morning, the planner should assign the delivery the day before in order to avoid the peak hours during which the queuing time would significantly increase. He or she may re-schedule the delivery plan at different concurring construction sites to prevent prolonged idling time of critical construction equipment resources, such as TBM, site crews, and trucks.

Another potential application on the simulation results is to forecast the expected driving delay to the road users based on the queue length and the Added System Residence Time of Each Car. For example, threshold values can be defined as "*Amber*" driving delay signal for expected queue length longer than 100 vehicles; the "*Red*" driving delay signal for expected queue length longer than 200 vehicles; and the "*Black*" driving delay signal for expected queue length longer than 300 vehicles. The expected driving delay can be updated on the Google Map such that the road users can decide whether to use the route passing through the TTA plan or choosing alternative driving routes.

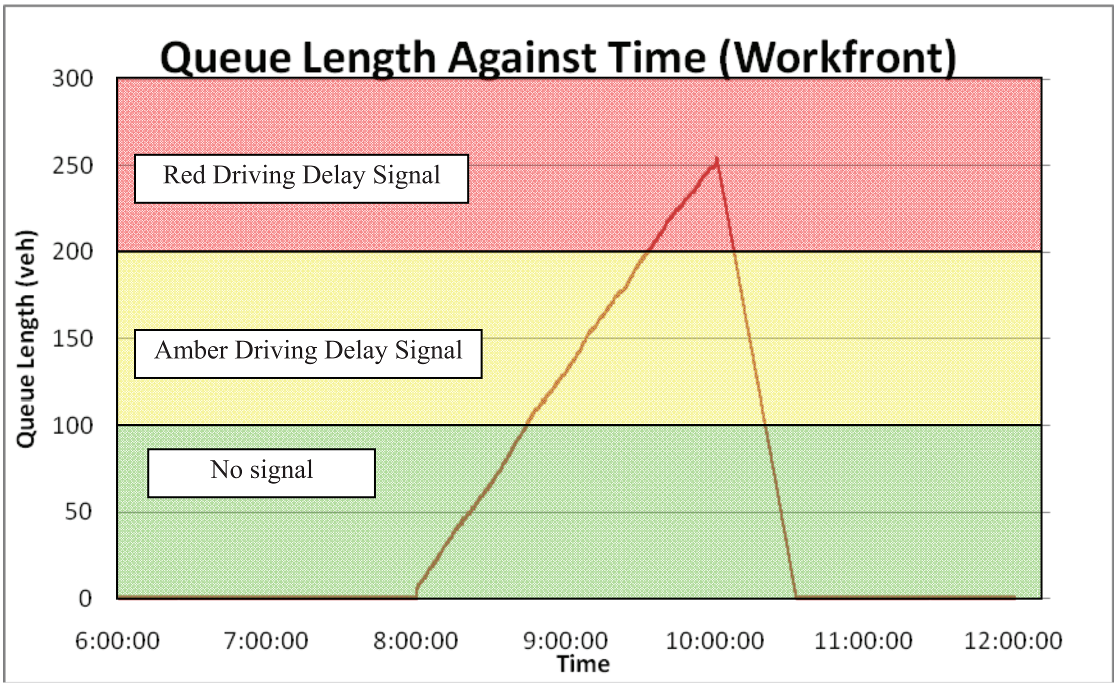

Fig. 6: Queue length against time with TTA plan

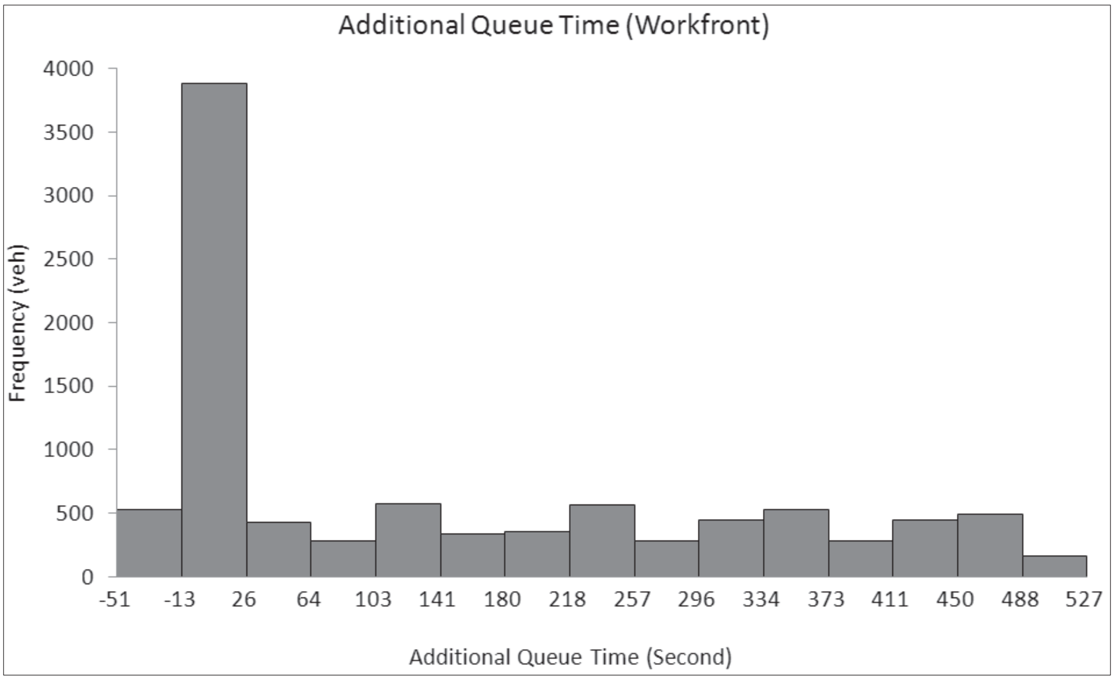

Fig. 7: "Added System Residence Time of Each Car" Generated from Simulation Model

5. CONCLUSIONS

Microtunneling and pipe jacking is commonly used in urban areas for constructing subsurface utility tunnels. A jacking pit is generally required to be excavated in a traffic lane in order to launch a tunnel boring machine (TBM) and install pipe sections. This paper addresses the application needs for modeling the traffic-construction interaction and applies discrete simulation modeling to automate the site access layout design and investigate the impact of construction on the traffic. Relevant parameters are generalized for defining site access and layout design in the context of microtunneling construction in a congested urban setting. Based on those parameters, discrete simulation models are generated to assess the dynamic characteristics for a given scenario of the traffic-construction system being modeled.

With the simulation tool, multiple scenarios can be designed and evaluated to facilitate the construction planning and traffic planning, addressing following issues: (1) Planning for the location and size of jacking pit; (2) Planning site access, including the points of ingress and egress and time restriction; (3) Planning for temporary storage or lay down areas near jacking pit. This is conducive to effective communications and sound decision making among all the stakeholders of the project in planning the temporary traffic arrangement (TTA) for microtunneling in congested urban areas. The simulation condenses the simulation results in terms of traffic flow statistics including "Added System Residence Time of Each Car" into a driving delay warning system (amber/red/black color schemes for certain thresholds of traffic delay).

In order to enhance the user interface in a more straightforward, intuitive fashion, our follow-up research will explore the feasibility of mapping and visualizing the layout of jacking pit on the lane of a particular road along TTA in Google Map, while the simulation results can be displayed by clicking a hyperlink in the Google Map. Fig. 8 shows a conceptual design of the Google Map interface.

6. ACKNOWLEDGMENTS

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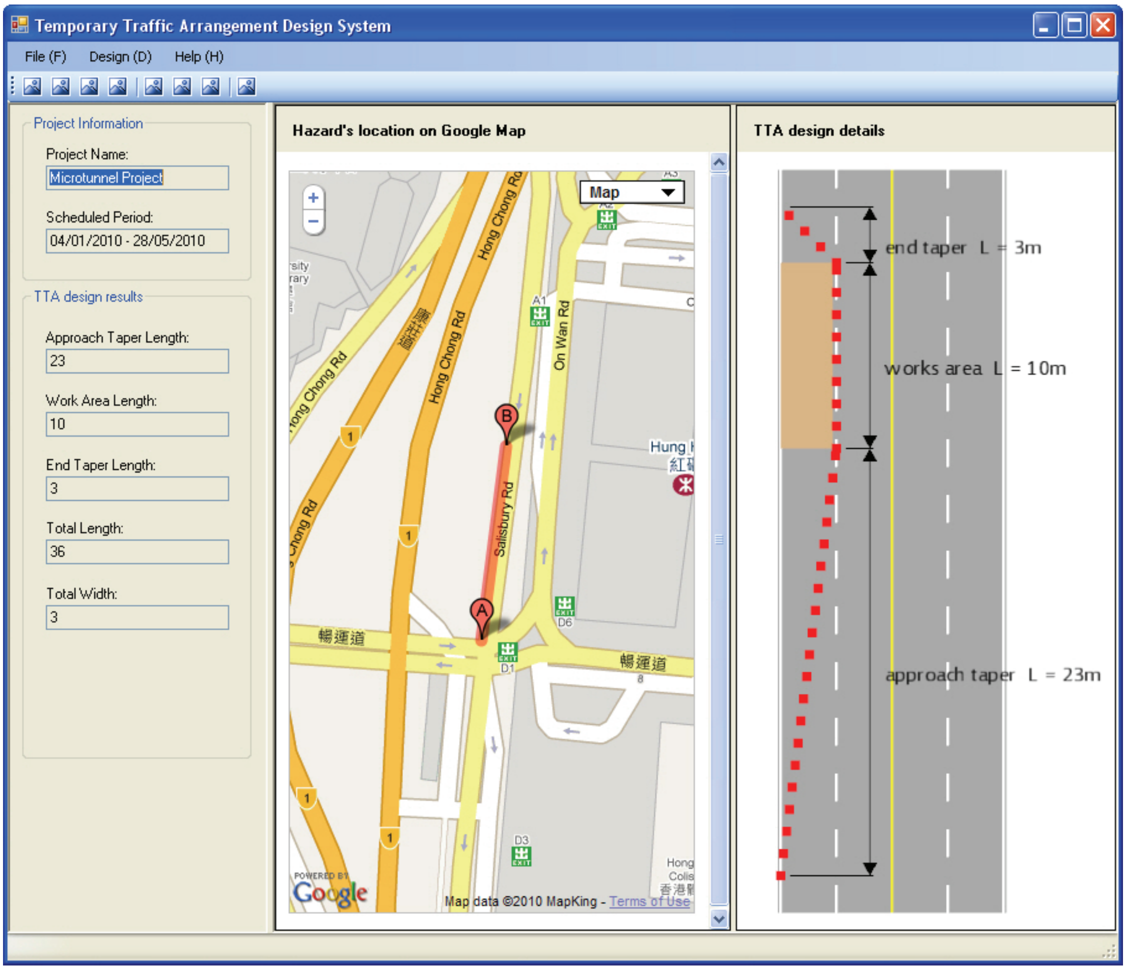

Fig. 8: Google Map interface for simulation-based temporary traffic arrangement design system

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DEVELOPMENT OF AN EARTHWORK SIMULATION SYSYTEM BASED ON BLOCK MODEL

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ABSTRACT: *In the design and construction planning of earthworks for land development or road construction, iterative investigation is usually executed to balance the cut-and-fill volumes and to arrange the conveyance distance of soils. The conventional 2D drawing based method relies on the capability and experience of engineers in judging. Furthermore, it takes a great deal of effort and long time to calculate cut-and-fill volumes for a number of comparative cases iteratively. The objective of this research is to develop an Earthwork Simulation System based on the block model as a low cost and general tool for earthwork planning and cost estimation. Therefore, we used free 3D CAD and general-purpose spreadsheet software packages to implement the system. Another objective is to confirm the feasibility and practicality of the system by applying an actual project. As a result, we confirmed that this system is useful for earthwork simulation.*

KEYWORDS*: block model, earth work, 3D CAD, construction plan, cost estimation*

1. INTRODUCTION

1.1 Back ground

The Earthwork planning is an important consideration in the land formation or road construction. Iterative investigation is usually executed to balance the cut-and-fill volumes and to arrange the hauling distance of soil. The conventional 2D drawing based method relies on the capability and experience of engineers in the earthwork distribution, as three-dimensional judgment of land form is required. There is also a method of three-dimensional deliberations with land formation renderings or models. However, it spends much money and time to make them and has a problem that they cannot be changed easily.

In recently years, various studies about the use of GIS or 3D CAD in the earthwork are performed. Omae performed the study about an information management of earthwork using GIS (2002). Kobayashi performed the study about an outline design system using cubic terrain model as a terrain design with 3D CAD(2009). This is an excellent study to contribute the total design system.

A number of 3D CAD or design applications for earthwork planning are available commercially. They enable three-dimensional representation of terrain to perform an optical study and also support soil volume calculations. However, those applications have not been widely used in practical business. Due to the applications are limited uses and have weak data linkage to other applications.

1.2 Objective

In this study, we studied a process of earthwork and developed an earthwork simulation tool with following objectives.

- The earthwork simulation could be performed as simple as possible.
- The earthwork simulation was evaluated with the estimation such as operation cost and working days.
- The earthworks simulation tool consisted of free 3D CAD and general-purpose spreadsheet software was inexpensive to widely use on site.

2. BLOCK MODEL

2.1 Concept

Block model is a multi-layer terrain model consisting of a number of cube-shaped solids or cuboid-shaped solids on gridded areas. In this study, the cube-shaped solid or cuboid-shaped solid are called “block” and the terrain represented with the blocks is called “block model”.

The advantage of block model is easy operation of 3D CAD, as it is consisted of a number of blocks which are fixed form such as cube shape or cuboid shape. Also, the soil volume can be calculated effectively. As each block has various information such as soil classification, soil volume conversion factor, etc.

2.2 Block model generation

2.2.1 Elevation data

To generate the block model which represents a terrain in three-dimension requires “elevation data” having elevation information at each plane coordinate point. The digital elevation model (DEM) and the digital terrain model (DTM) are provided as wide-ranged elevation data. The aerial survey directly provides elevation data of specific area. It is quite detailed but very expensive. On the other hand, elevation data can be made from a two-dimensional contour map. It takes a deal of effort and time to make the elevation data. However, it is less expensive than making the elevation data by the aerial survey. Making elevation data is not covered in this study. Due to commercially available software have had already the method

The elevation data requires not only information about ground level but also information about stratum boundary. In this study, the elevation data for modeling ground level is called “ground level elevation datum” and for modeling stratum boundary is called “stratum boundary elevation datum”. One ground level elevation datum is accepted to generate block model in principle. A number of stratum boundary elevation data is accepted according to the condition of stratum structure.

2.2.2 Block generation process

The prerequisite for the block model generation are the ground level elevation datum and the stratum boundary elevation data are prepared in advance and the blocks are consisted of homogeneous material.

A block modeling area is arranged in the development area. Fig.1 and Fig.2 show an example of the block modeling area. The modeling base level, as shown in Fig.2, can be arbitrarily placed in the block modeling area. For example, the modeling base level is placed lower than the maximum depth of excavation assumed in earthwork planning. Three –dimensional coordinate is appended to the block modeling area.

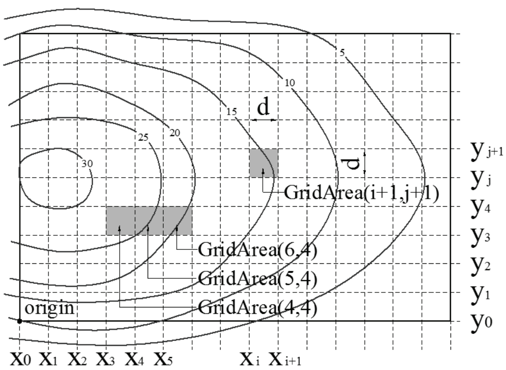


Fig. 1: Conceptual diagram of horizontal block-modeling area

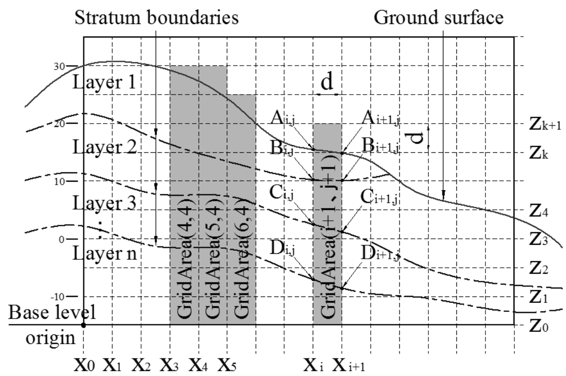
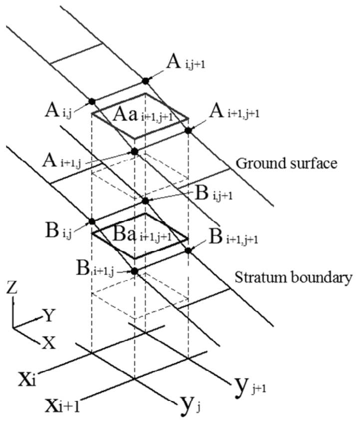


Fig. 2: Conceptual diagram of vertical block-modeling area

A number of areas surrounded by grid lines (grid area) on X-Y plane, as shown in Fig.1, are arranged. Flat elevation surfaces which represents ground surface or stratum boundary are arranged in the grid area. The height of ground surface level is, as shown in Fig.3, the average of elevation A(E1), A(E2), A(E3) and A(E4) which area points at the intersection of the grid area with the ground level elevation datum. The heights of stratum boundaries are also calculated by the method similar to the ground surface level.



$$Aa(i+1, j+1) = \frac{A(E1) + A(E2) + A(E3) + A(E4)}{4}$$

$$Ba(i+1, j+1) = \frac{B(E1) + B(E2) + B(E3) + B(E4)}{4}$$

Fig. 3: The settings of altitude planes

The blocks are generated in each grid area. The block shape basically becomes cubed. If a block is faced the ground surface or the stratum boundary, the block shape becomes cuboid. The height in cuboid-shaped block has to be lower than the height in cube-shaped block.

2.2.3 Attribute information

The soil volume calculation requires information of shape and location of blocks. In addition, soil classification, unit weight, soil volume conversion factor, etc. are useful for it. In this study, these parameters are called "attribute information".

Fig.4 shows an example of the attribute information setting. The information of Shape, location, soil classification and soil volume conversion factor are attached each block as the attribute information. The information of shape means the size of the block (height, width and depth). The information of location means the location of the block which is given the three-dimensional coordinate value of centroid of the block (X,Y and Z). The information of soil classification means name of soil classification (soil, soft rock, hard rock, etc.). The soil volume conversion factor has two factors which are loose factor and compact factor. They represent soil volume change based on soil classification.

Table 1 shows examples of soil volume conversion factor which are extracted from "Estimation Guideline for Civil Engineering and Landscape (URA, 2008)

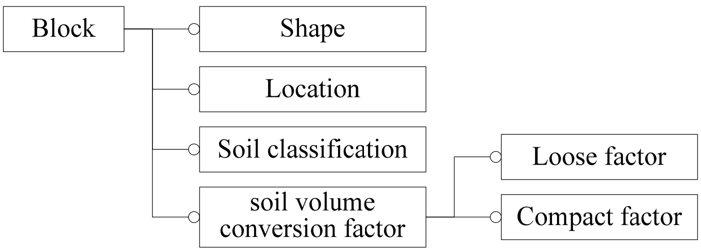


Fig. 4: Attribute information setting

Table 1: Examples of soil volume conversion factor

Material	Loose	Compact
Soil	1.25	0.90
Softrock	1.25	1.05
Hardrock	1.70	1.30

3. EARTHWORK SIMULATION

3.1 Concept

In the earthwork simulation, final shape of terrain and construction process of land formation is determined. The ground consisting a number of blocks can changed natural situation into final shape of land formation step by step. The object of the final shape simulation is mainly to determine the three-dimensional final shape of the terrain and calculate soil volumes and hauling distances of soil. The object of the construction process simulation is to determine the optimize construction process from multiple plans including the hauling route of soil. The results of simulation are evaluated from the standpoint of optical judgment of final shape and estimation such as operation cost and working days. In this study, other structures such as retaining wall or temporary structure, etc. are eliminated from the simulation. And the hauling distance in the block modeling area is only allowed.

3.2 Software applications

One of the objectives was to ease the operation of 3D CAD. Another objective was to use inexpensive software applications for using on site. Therefore, a free 3D CAD and general-purpose spreadsheet application were employed for the earthwork simulation. Google SketchUp (SketchUp) which is Google Inc. provided free software was employed as the 3D CAD. SketchUp has an intuitive user-interface and can be extended its function by a program language Ruby. Microsoft Excel (Excel) was employed as the spreadsheet application for the estimation. Excel is used at a wide variety of business. It can be customized to link data to SketchUp by Visual Basic for Applications (VBA).

3.3 Earthwork simulation process

Fig. 5 shows the conceptual process of the earthwork simulation and the relation with applications.

In phase 1: block model generation, it generates the block model with elevation data and attaches the attribute information to each block. The detail of block model generation was explained in chapter 2.

In phase 2: earthwork simulation, it designs a construction process. And it executes block operations every designed construction steps. The soil volumes depending on the types of work are calculated according to the block operation. The block operation is taken in section 3.4.

In phase 3: estimation, it estimates the operation costs and the working days depending on construction steps based on the quantities of work per hour and the unit costs in advance. The estimation is taken in section 3.5.

In phase 4: summary of estimation and evaluation, it calculates the sum of operation costs and working days as the result of estimation. And the result of the earthworks simulation is evaluated by engineers with the result of estimation

Phase	1	2	3	4
Item	**Block models generation** →	**Earthwork simulation** →	**Estimation** →	**Summary/Evaluation**
	Making / Obtaining of Elevation data	Setting of construction step	Operation cost	
	Block model generation	Block operation	Working days	
		Calculation of soil volume		
Software	Excel / VBA	SketchUp / Ruby	Excel / VBA	Human

Fig 5: Earthwork simulation procedure

3.4 Block operation

3.4.1 Concept

The earthwork in actual construction has many types of work such as excavation, stripping topsoil, etc. However, it is difficult to simulate all types of work at this time. Therefore, this simulation deals with cutting, filling, hauling, surplus soil and borrow material.

Fig.6 shows the process of earthwork simulation which is focused on the block operation. User’s operation in the block operation is to set planning heights and to select the blocks in the earthwork area. These operations are shown as gray box in Fig.6. Whether the block is cut block or fill block, the program determines it by comparing the block top height with the planning height. The hauling soil volume and surplus soil volume are calculated with the soil volume conversion factors in the volume calculation process.

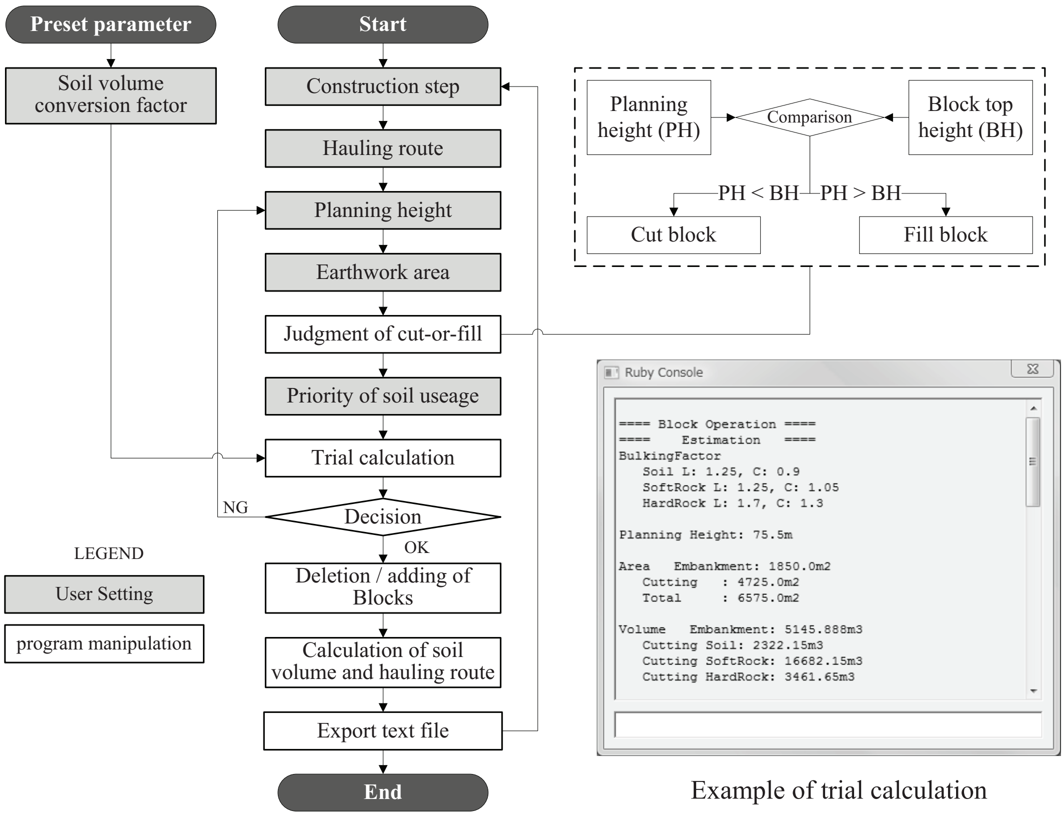


Fig 6: Block operation flow

3.4.2 Determination of cut block of fill block

The program determines whether the block is cut block or fill block by comparing each block top height with the planning height. Fig.7 shows an example of the judgment. The block model consists of soil layer 0.2m thickness and soft rock layer

The block whose top surface locates higher than the planning height are evaluated as cut block. The blocks in the cut blocks which locate between the block top height and the planning height is deleted by the program. And program calculates their volumes at the same time. When the cut brocks have the types of soil, the block volume is calculated depending on the types of soil. When the planning height locates midway in the block, the block is divided into two parts on the planning height. After that, the upper part is deleted by the program.

The block whose top surface locate lower than the planning height are evaluated as fill block The block are added between the block top height and the planning height by the program as filling. And program calculates the volume at the same time. The added block is basically cubed shape but cuboided shape is used as needed.

3.4.3 Soil volume calculation

Soil volumes are calculated each of cut blocks or fill blocks. The sum of soil volumes are calculated depending on the types of soil. The soil volumes are calculated with soil volume conversion factors based on the result of soil volumes calculation. When the cut volume directly uses to fill, the cut blocks have two or more types of soil such as soil, soft rock and hard rock. User can prioritize which type of soil is used first.

Fig.7 shows an example of soil volume calculation. The example block model has two layers. The top layer is soil, other layer is soft rock. The blocks which locate higher than the planning height 22m become cut blocks. Total cut volume is 1200m^3 (soil: 400m^3, soft rock: 800m^3). Possible fill volume is calculated from the cut volume with soil volume conversion factors. It is total 1200m^3 (soil: 360m^3, soft rock: 840m^3). The soil volume conversion factors were used as shown in Table 1.

The blocks which locate lower than the planning height 22m become fill blocks which need to add the blocks. The sum of fill volume is 1000m^3. The possible fill volume which calculated from the cut volume was 1200m^3. The Soil volume is assumed to use first for filling. As a result, 200m^3 volume of surplus soil (soft rock) arises.

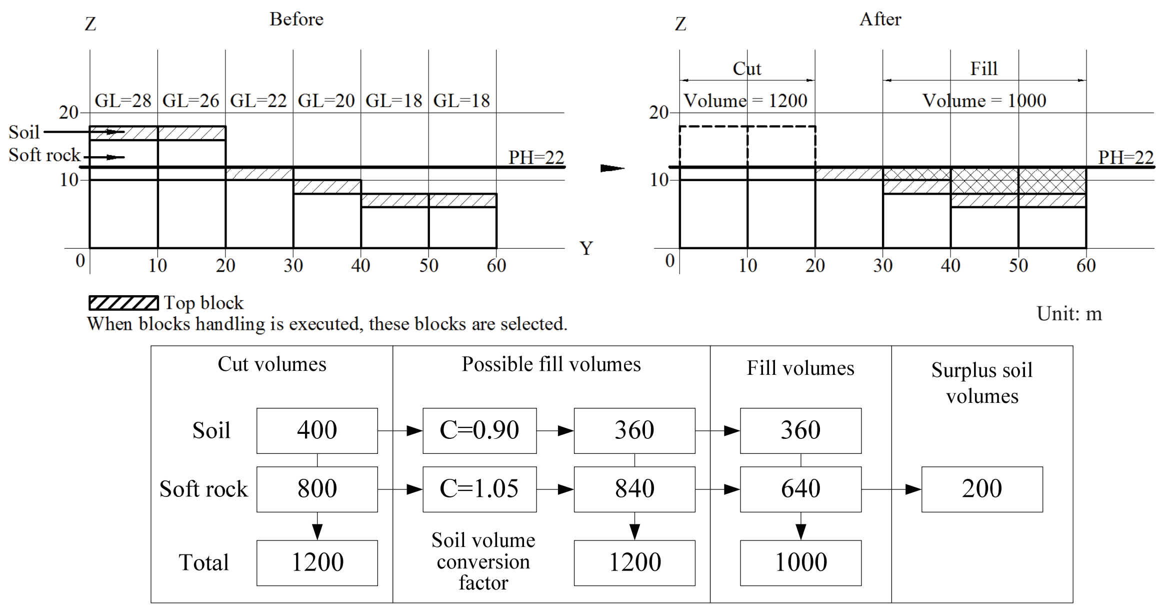


Fig 7: Example of determination of cutting and filling

3.5 Hauling route arrangement

3.5.1 Concept

Hauling route of soil is arranged by a detailed plan depending on construction process or terrain conditions in the site. In particular, the relation between the construction process and hauling route is important in the construction process simulation. The planning of hauling route requires a comprehensive deliberation. However, the detailed deliberation of hauling route is not dispensable in the early stage of earthwork planning. Therefore, in this study, two methods of hauling route setting were employed: the basic method and the advanced method.

3.5.2 Basic method

In case where the distance of hauling route is comparatively short or detailed deliberation is not required; the hauling distance is calculated with basic method. In the basic method, the hauling distance is defined the distance between the centroid of cut blocks and the centroid of fill blocks. Fig.8 shows an example of hauling route arrangement with the basic method. The block was assumed to haul from (a) to (b) in Fig.8. The distance (1) was placed as the hauling distance between centroids of block(a) and block(b).

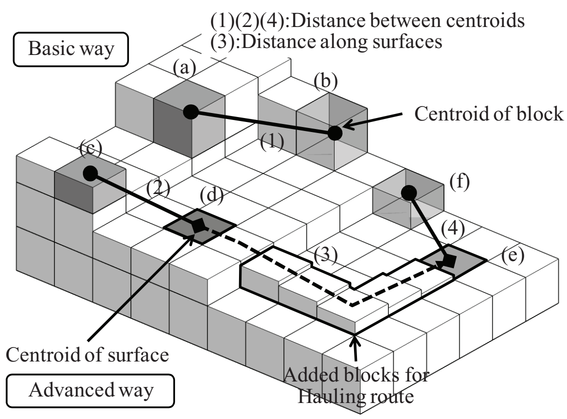


Fig 8: Conceptual diagram of route settings

3.5.3 Advanced method

In case where the distance of hauling route is long or detailed deliberation is required; the hauling distance is calculated with advanced method. Firstly, a number of blocks on hauling route are picked continuously. The first picked block becomes the starting point and the final picked block becomes the end point. In case where the hauling route has a gradient, the program judges how gradient on natural ground is in the limit gradient. If the gradient of natural ground is exceeded the limit gradient, the program determines to delete or add blocks in the hauling route and executes deleting or adding blocks automatically. The volumes of cut blocks and fill blocks are calculated at the same time. The distance of hauling route in the advance method consists of the sum of three distances. The first distance is the liner distance between centroids of cut block and the start point of hauling route. The second distance is the distance of hauling route itself. The third distance is the liner distance between the end point of hauling route and the centroid of fill blocks.

Fig.8 shows an example of hauling route arrangement with the advanced method. The block was assumed to haul from (c) to (f) in Fig.8 The hauling route was arranged from (d) to (f). This hauling route had the vertical interval which was exceeded the limit gradient between (d) and (c). The program added the blocks to fit for the limit gradient.

4. Estimation

4.1 Selection of an estimation standard

"Estimation Guideline for Civil Engineering and Landscape (URA, 2008)" is employed as the estimation standard. "Estimation standard for civil works (CRI, 2009a)" is currently employed on many constructions in Japan. Thus, it is preferable to employ the CRI's standard in the earthwork simulation. However, the standard does not deal with the cycle-time. On the other hand, the guideline deals with the cycle-time. As a result, we employed the URA's guideline for the earth simulation.

4.2 Estimation method

Estimation has three steps. Necessary quantities of work per hour and unit prices are prepared before starting the simulation (step 1). Soil volumes and hauling distance depending on the types of soil are retrieved from the result of earthwork simulation (step 2). Operation cost and working days are calculated with the values which are obtained from step 1 and step 2. Table 2 shows the types of construction equipment, quantities of work per hour and unit price.

The quantity of work is calculated with the type of construction equipment, depending on the type of soil, based on the estimation standard. The construction equipments in Table 2 are assumed for large-scale earthwork. However, for the small-scale earthwork, the construction equipments are allowed to change into the match specifications.

Expenses for unit cost are as follows. Labor cost is based on "Specified Labor Rate for Public Works (MLIT, 2008)". Equipment rent is based on "Table for Operation Loss Prevention Equipment Cost (JCMA, 2008)". Material cost is based on "Price of Construction, Materials and Wedges (CIR, 2009b)".

Table 2: List of Construction machineries, payloads and unit prices

Work	Material	Machine type	Specification	QOW m^3/hr	Unit price Yen/m^3
Excavation	Soil	Crawler excavator	Bucket capacity 1.5 - 2.1m^3	159	103
	Soft rock	Bulldozer equipped with ripper	32 t class	324	52
	Hard rock	Hidraulic breaker	1,300kg class	41	2,169
Loading	Soil	Crawler excavator	Bucket capacity 1.5 - 2.1m^3	including in excavation	
	Soft rock			147	111
	Hard rock			53	356
Hauling	In common	Dump track	46 t class	dipend on distance	
Compacting	Soil	Bulldozer	20 t class	230	47
	Soft rock			230	47
	Hard rock			169	74
Placing	Soil	Bulldozer	20 t class	443	24
	Soft rock			379	28
	Hard rock			307	40

QOW: Quantity of works

5. PRACTICAL EXAMPLE

5.1 Block model generation

An example of the earthwork simulation is assumed a land formation for hills along reservoir in Fig.9. Fig.9 shows the excerpt terrain map of the land formation. The land formation was a part of large-scale land formation having total 140 million m^3 in soil volume. In the earthwork simulation, the development area was divided into seven areas. The land formation was executed to the planning height of each area. The construction equipments for estimation were used in large scale which is same type of whole construction.

Block model was generated using elevation data from two-dimensional contour map as shown Fig.9. In this example, the blocks basically have cubed shape 5m on a side. And the cuboided shaped blocks were located on ground surface or stratum boundaries as needed. We didn’t have information about stratum structure. Thus three strata were assumed as follows: the top stratum was soil having 0.5m thickness, second stratum was soft rock having 5m thickness and bottom stratum was hard rock having approximately 15m thickness. The block model generation was executed by Ruby made program with the extended function of SketchUp. In addition, a report says the error in the block model was within from 0.15 % to 1.95 % as compared a surface model with a block model having 5m intervals in grids of same terrain (Yabuki, 2009). The attribute information was attached to each block as explained in 1.4.4.

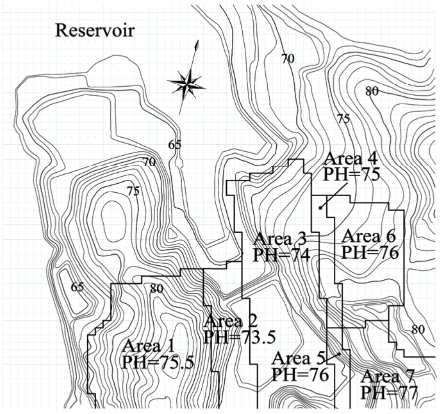


Fig 9: Development plan

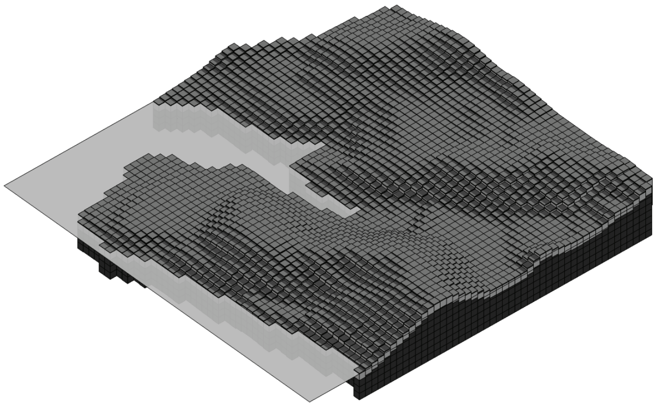


Fig 10: Block model

5.2 Earthwork simulation

The earthwork simulation was executed according to the process as shown in Fig.5 and Fig.6. Firstly, in every area, the trial calculations of soil volume on the planning height was executed according to the process of Fig.6 As a result, cut volume and fill volume were not balanced inside each area. It was necessary to balance the cut-and-fill volume. Therefore, the nine construction steps ware assumed to balance the cut-and-fill volume in each steps. Fig.11 shows the final shape of land formation. The block operations were executed according to the construction steps.

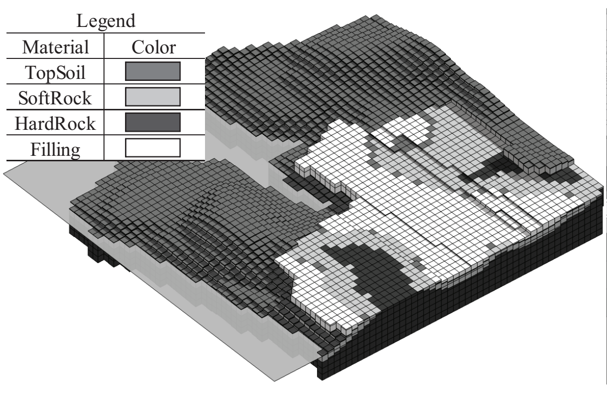


Fig 11: Final shape

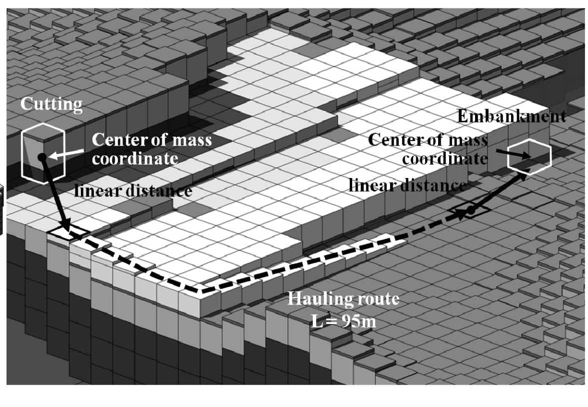


Fig 12: Example of hauling route setting

The hauling distances were mainly calculated with the basic method. Due to the maximum distance between cut area and fill area was maximum 80m.

If to arrange the hauling route in every step was needed more detailed deliberation. For reference, an example of the hauling route with the advanced method is shown Fig.11. In Fig.11, the hauling route was assumed to haul blocks from cut area in the area 1 to fill area in the area 3.

5.3 Estimation

In the estimation, the operation costs and working days were estimated based on soil volumes as a result of the earthwork simulation. The operation costs were estimated for cutting, filling, hauling and surplus soil. The working days were estimated for cutting and filling. The quantities of work per hour and unit prices were used the values as shown in Table 2. The working days were estimated as net 6 hours a day

Table 3 shows an example about estimation about cutting. Table 3 was formatted with Excel. Each values ware calculated in Excel with the text file which was exported form SketchUp.

Table 3: Result of estimation of cutting

Step	Material	Volume (a)	Unit Price (Yen/m^3)					Operation Cost (a)x(b)	Working Days
			Excavation			Loading	Total (b)		
		m^3	Excarvator*	Ripper	Breaker	Excavator		(Yen)	
1	soil	346.419	103				103	35,681	0.25
	softrock	1,241.637		52		111	163	202,387	0.90
	hardrock	0.000			2,169	356	2,525	0	0.00
2	soil	82.863	103				103	8,535	0.06
	softrock	232.369		52		111	163	37,876	0.17
	hardrock	0.000			2,169	356	2,525	0	0.00

Excavation cost of soil is including loading cost.

5.4 Summary of estimation and Evaluation

Table 4 and Table 5 show the sum of estimation. The Sum of operation cost was approximately 30 million yen (direct cost), and the sum of working day was gross 117 days. The final shape showed that slopes or retaining walls were needed to place surrounding the development area due to the formation level was higher than the natural ground level.

Table 4: Summary of operation cost

Number of steps	Material	Cutting		Filling		Hauling		Total (Yen)
		Volume (m^3)	Cost (Yen)	Volume (m^3)	Cost (Yen)	Volume (m^3)	Cost (Yen)	
9	soil	6,286.621	647,522	5,200.796	369,257	6,279.917	1,393,054	2,409,832
	softrock	35,508.130	5,787,825	34,979.074	2,623,431	29,856.911	7,145,140	15,556,395
	hardrock	4,107.095	10,370,415	3,700.826	421,894	1,776.514	1,058,802	11,851,111
Total		45,901.846	16,805,762	43,880.696	3,414,581	37,913.341	9,596,996	29,817,339

Table 5: Summary of working days

Number of steps	Material	Cutting		Filling		Days
		Volume (m^3)	Cost (Yen)	Volume (m^3)	Cost (Yen)	
9	soil	6,286.621	7	5,200.796	5	12
	softrock	35,508.130	40	34,979.074	40	80
	hardrock	4,107.095	13	3,700.826	12	25
Total		45,901.846	60	43,880.696	57	117

5.5 Result

We confirmed as follows from the practical example. The earthwork simulation was executed as is originally envisioned. The block operation was simply executed with selection of the blocks. This method could be executed iterative investigation to balance the cut-and-fill volume in thee-dimensions.

6. CONCLUSION

We confirmed following points from this study.

- The earthwork simulation was showed that it could be executed with free 3D CAD and general-purpose spreadsheet application.
- The process of block model generation was shown from the elevation data of ground surface or stratum boundary.
- The process of earthwork was shown with 3D CAD in the practical examination.
- This simulation method was shown to execute in chronological order.
- This simulation method was shown to interface the operation costs.

The block operation can be executed with the minimal operation in such a way that user clicked the object blocks. This method enables inexperienced users to easily execute the earthwork simulation with 3D CAD. This method can save the cost of software by using free 3D CAD. In this study, the block model is generated as the natural ground. For executing more detailed simulation, the accuracy of simulation is improved by the block size changes smaller. The hauling route arrangement has two ways. User can choose the basic method or the advanced method according to the accuracy of simulation. This method can also apply to the simulation about road or river construction having long distance. In the estimation process, that accepts various values depending on client or site condition due to using general-propose spreadsheet application. Highly accurate estimation and earthwork distribution are executed by the use of soil volume conversion factors.

The future tasks are to develop the automatic generation of slope and automatic calculation of formation height based on earthwork distribution in site.

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INVESTIGATION OF THE NOH STAGE SPACE BASED ON THE PLOT *"JO-HA-KYU"* USING VR

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ABSTRACT: In this study, we formed and verified the hypothesis that Noh's "jo ha kyu" should have a structure resembling that of nested boxes and that it should be structurally correlated with the distinctive character of a Noh stage. For analyses of "jo ha kyu," we chose the sound of a small hand drum, interjection, and dancing. Based on the analysis results, we verified that the Noh stage is divided to resemble nested boxes. Furthermore, to clarify the superiority of the fact that the stage shape is square and that it is distinctive in that it has four pillars, we verified them using VRML representation. After producing the CG images of the Noh stage including the ken-sho and the Kabuki stage, we compared the Noh's dancing trajectories, as identified by CG images, between both stages. Consequently, we confirmed that the square floor is fit for the Noh stage space and that all the four pillars function as important landmarks for the main actor wearing a mask.

***KEYWORDS**: Japanese Noh play, Noh plot "Jo-ha-kyu", Noh music, Noh masked dance, VRML image, 3DCG animation, Noh stage.*

1. INTRODUCTION

Noh is a Japanese traditional masked dance drama or opera with history dating back to the fourteenth century. The stage or theater where Noh is performed is called "*Noh butai*". *Butai* means a stage in Japanese. *Noh butai* space comprises a stage, *hashigakari* (a passage-like extension of the stage, connecting the stage and the back stage), *kagami-no-ma* (back stage), and *ken-sho* (audience seats) as shown in Figure 1 (a) (b). These components are collectively called "Noh butai." On the other hand, although the Kabuki stage space, which originated from the *Noh butai*, also consists of a stage and *hanamichi* (a long walk-like extension of the stage that runs through audience to the back of the theater), the theater space including a stage and audience seats is not called "*butai*". As is true of western stages. Thus, calling the theater space collectively including a stage and audience seats "*butai*" might be one of *Noh*'s distinctive characteristics.

The authors believe that there are three characteristics of *Noh butai* as the following. First, it has particular kind of spaces, i.e., *kagami-no-ma* and *hashigakari*. Second, the *hon-butai*, a central stage and main acting area, is a foursquare and wooden floor. Third, the central stage has a roof that is supported with four pillars at the four corners, even though it is indoors. In addition, we imply that audience seats attached to the stage also have a significant meaning. Zeami Motokiyo (1363-1443), a great author and director as well as a Noh player, insisted in his book on the importance that players and the audience should make Noh together. In this study, we specifically examine *"jo ha kyu"* (respectively meaning Introductory part, Development, and Conclusion) as dramatic constituents of Noh to elucidate the three points described above about *Noh butai* and the meaning of the space which constitutes it. *"Jo ha kyu,"* as *Noh*'s grammar is called, applies to everything in *Noh* from the organization for the *Noh* performance of a day, to *mai* (dancing), to *utai* (Noh chants), to *hayashi* (musical accompaniment), and to the stage space. (Nogami et al., 2009; Konparu et al.,1980) Noh organizes its dancing and music by a unit of three factors of *"jo ha kyu." Noh*'s stage is also zoned into a *jo* zone, a *ha* zone, and a *kyu* zone. (Kinoshita et al.,1890). Consequently, Noh's dancing, music and stage are mutually related in a structural sense through the unit of *"jo ha kyu"*. In this study, we made a structural analysis of *"jo ha kyu"* aimed at discussing the characteristics of *Noh*'s stage space, based on the data. In this paper, we made the three-dimensional CG models of Kasuga Shrine's *Noh* stage and *ken-sho* built in 1861 and Old Kompira Oshibai's (Kanamaru Theater's) *Kabuki* stage (the oldest play house existing in Japan) built in 1835 and verified them by VR. About an archive of Japanese traditional performing arts, which is an intangible cultural treasure such as the Noh. We are able to restore a document and not only the save of the photography record but also performance, and it is thought that the VR technology contributes to record, saving it. As a report for the information processing society, Kazunari Kojima et al. (Kojima et al., 2003) produced Noh actors' radical animation, by using their motion capture data, as an attempt of expression techniques. They have been also exploring the use of the SMIL (Synchronized Multimedia Integration Language) technology to integrate the digitized resources into an interactive viewing system as a next generation of digital archive. VR contributes to the area of reconstruction of cultural heritage so that this example shows it. Although this study is ongoing, we introduce our research method in this paper and the knowledge obtained to date.

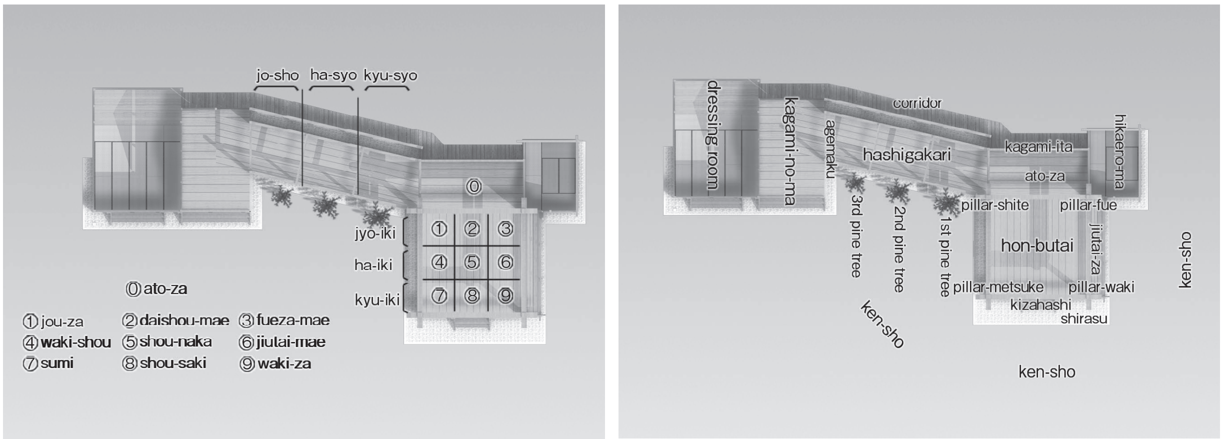

Fig.1: Floor plan of Noh stage (a) floor plan of a whole Noh stage (b) spatial construction of the main stage

2. HYPOTHESES OF THIS RESEARCH

2.1 Hypothesis 1: *Kagami-no-ma*, *hasigakari*, main stage, and dancing

The main stage consists of *kokonoma*, which is three kyo-ma mats square (5909 mm square). As shown in Figure 1, four pillars, set up at four corners of the stage, support the roof. *Noh* has the order of *jo, ha*, and *kyu*; the *kokonoma* is also zoned into a *jo* zone, a *ha* zone, and a *kyu* zone from the back with *kagami-ita*. Essentially, a dance is danced in the zones. In fact, *"jo ha kyu"* has internally another *"jo ha kyu"* In other words, *jo* is subordinated into *jo* of *jo*, *ha* of *jo*, and *kyu* of *jo*; *ha, jo* of *ha, ha* of *ha*, and *kyu* of *ha*; *kyu, jo* of *kyu*, *ha* of *kyu*, and *kyu* of *kyu*. It has a kind of hierarchical structure resembling that of nested boxes. In terms of the *jo, ha,* and *kyu* of the first hierarchy, where to dance is prescribed as stated above. However, in terms of that of the second hierarchy, there is no study discussing where to dance is to be performed. In this paper, we propose the hypothesis that *the jo, ha,* and *kyu* of the second hierarchy should be further divided into a *jo* zone, a *ha* zone, and a *kyu* zone from the back with *kagami-ita* within each one *kyo-ma* mat square, which is one of ninth of *kokonoma*. In other words, we assume that a *jo* zone and a *ha* zone should be divided as in a nesting structure because the stage is divided into a *jo* zone, a *ha* zone, and a *kyu* zone from back to front.

2.2 Hypothesis 2: *Kagami-no-ma, hasigakari*, main stage, dancing, and sound

Among *"jo ha kyu"* called *Noh*'s grammar, *jo* (*jo* of *jo, ha* of *jo, kyu* of *jo*) and *ha* (*jo* of *ha, ha* of *ha*, and *kyu* of *ha*) are identifiable in a temporal axis because they are described in the literature. However, no description exist of *"jo ha kyu"* of "*kyu.*" Does *"jo ha kyu"* of "*kyu*" exist? In this study, we propose a hypothesis that they exist. Furthermore, the *"jo ha kyu"* of "*kyu*" should be divided into three portions, in order from back. If they exist, when combined with our hypothesis 1, they can indicate that there is a hierarchical structure of *"jo ha kyu"* similar to that of nested boxes.

2.3 Hypothesis 3: Main stage

Unlike other stages, the *Noh* stage is a regular square, not a rectangle or a trapezoid. Four pillars are set up at the four corners of the stage, supporting the roof, which is unique. In this study, we made a hypothesis that a *Noh* stage is a regular square because of the following reasons: The stage is divided into three parts of *jo, ha*, and *kyu* from the back to the front. Therefore, if it were a rectangle or a trapezoid, the movement from the back to the front of the stage would not be so recognizable. Consequently, it is unsuitable for *jo, ha*, and *kyu* of *Noh*. Unlike Kabuki or Western stages with the audience arrayed in one direction, *Noh* is seen by the audience on three sides. Long ago, there used to be an audience behind the stage. *Noh* lacks direction in performance; its stage is therefore a regular square, resembling a boxing or wrestling ring. A *Noh* actor, when wearing a mask, has a narrow outlook and would therefore not be sure of his position when on a wide stage. In contrast, on the narrow and square stage, an actor can easily determine locations at any time. Moreover, the four pillars at the four corners function as markers, further simplifying the task.

3. REVIEW OF PREVIOUS STUDIES

3.1 Previous studies about *Noh* stages

In terms of *Noh* stages, Fumio Ohgishi and Katsuyuki Sato (Ohgishi et al., 2007) studied about the formation process of design theory related to the structure of *Noh* stages and the main buildings of Shinto shrines existing in the Kinki region, including Nara prefecture, and on Sado Island. Toshiyuki Okutomi (Okutomi et al., 2007) discussed the concept of nested-type *Noh* theaters through Kongo *Noh* theaters and Hosho-kai *Noh* theaters. As a report for the information processing society, Kohei Furukawa et al. (Frukawa et al., 2006) produced a walk-through animation scene observed from a Noh actors' eye position during the play. They used their motion capture data, as an attempt at determining and recording expression techniques. As studies of theater history, there are "the Study of the History of Japan's Theaters" by Atsuo Suda and "the History of Theaters in Japan" by Keiji Sudo, each of whom attempted to trace the origin of *Noh* stages, and "Noh Stages," written by Gakudo Yamazaki as *Noh* treatise, which is a traditional study of *Noh* stage space. However, none discussed the meaning of the unique mode of *Noh* theaters as performing spaces from digital information of *Noh*'s musicality and dancing, particularly addressing the *"jo ha kyu",* which is "the grammar to express *Noh*."

3.2 About *"jo ha kyu"* of Noh

The idea of *"jo ha kyu"* in *Noh*, originated in the term to express three parts of *Bugaku* (traditional Japanese court music accompanied by dancing), which was introduced with *Gagaku* (ceremonial court music of Japan) from China to Japan during the Nara period (around the eighth century). The idea had spread to various performance art (from music organization of *okagura* or *shomyo* to theorization of *renga* or *shugiku*) during the Heian period (12th to 13th centuries). During the Muromachi period (especially in the 15th century), applying the principle of *"jo ha kyu"* to everything, from utterance of a sound, to beat with a foot, a whole structure of a piece of music including dancing and *Noh* chant, to the organization of *shidai* (program) of *Noh* performed in a day or days, Zeami had brought *Noh* to completion (Nogami et al., 2009). The main stage, called "*butai*," except for *waki-za* and *ato-za*, each of which is a performing space, is divided into nine parts, of which every three parts are named the *jo* zone, *ha* zone, and *kyu* zone in order from the back ---the line between the *shite* pillar and *fue* pillar --- to the front. Similarly, *hasigakari* is zoned into *jo-sho*, *ha-sho*, and *kyu-sho* in order from the *Kagami-no-ma* to the *butai*. The spatially zoned parts are important in performing positional relationship expressions (Kinoshita et al., 1890). *Noh* consists of three factors of the *Noh* chant, musical accompaniment, and dancing and has a nested-box-like structure, in which each factor is repeated by the unit of *"jo ha kyu."* The space of the *Noh* stage also follows the same rule of *"jo ha kyu."*

4. METHODOLOGY OF THIS STUDY

4.1 Validation approach of hypothesis 1

We chose "*Hagoromo*" as our target *Noh* play for the following two reasons. First, it belongs to the genre of *Kazura-mono Noh*, whose rank is "*ha* of *ha*." Second, "*jo-no-mai* (dancing of *jo*)" is incorporated in the play. Noh's plays are classified into five kinds according to the rule of *Goban-date-ho* (that a set of five plays should be played on a *Noh stage*). Hagoromo belongs to *Kazura-mono* (or *on-na*, in which the main actor acts the part of a woman), which is also called *Sanban-me-mono* (a genre to be played third among five plays). It is played in the midst of the program of five plays. That is why it is considered as the most important as well as the core of the program.

Meanwhile, in terms of the dancing, the *Jo-no-mai* is supreme (Nogami et al., 2009. book2).

Using video image (Hagoromo et al.,1988), we traced the motion trajectories of the main actor and the secondary actor, identified their *jo* (*jo* of *jo*, *ha* of *jo*, and *kyu* of *jo*), *ha* (*jo* of *ha*, *ha* of *ha*, *kyu* of *ha*), and *kyu*, and separated them by color. However, putting the main actor's and secondly actor's motion trajectories, separated by color, on the plat in which the *kokonoma* stage was divided into nine parts and in turn every part was divided into nine parts, we verified whether our hypothesis was verified or not.

4.2 Validation approach of hypothesis 2

Regarding way to identify *jo, ha*, and *kyu* in a play of *Noh,* some scholars of Noh wrote articles, describe the only way to identify *jo, ha*, and *kyu* of "*jo*" and "*ha*". (Nogami et al.,2009 book2). However, no description identifies them as "*kyu*." Therefore, we presumed that we should be able to identify them by particularly addressing "sound." We used the video image of "Hagoromo," which is used in 4-1, as the sound source.

The sound components of *Noh* are apparently categorized into the following five parts: (1) Tempo, (2) Volume, (3) Pitch, it is apparently invariable in *jo, ha and kyu.* (4) Dynamics, (5) The number of musical instruments (*fue* or flute, *Ohtsuzumi* or big hand drum, *kotsuzumi* or small hand drum, and *taiko* or drum); only the sound of a *taiko* starts at the level of "*kyu*".

First, to conduct a data analysis of the relation between hand drum and interjection, we extracted the sound of a hand drum and interjection from the CD (Kanze et al.,1988). We made line charts by plotting the extracted data on the temporal axis (every 10 seconds, one minute, and three minutes) of *jo ha* and *kyu..* To verify the validity of the method, we confirmed whether *jo, ha*, and *kyu* of "*jo*" and "*ha*" can be articulated. If they were confirmed, then we attempted to identify the *jo, ha, kyu* of "*kyu*". Next, by overlapping the *jo*, *ha,* and *kyu* of "*kyu*" and the position of the main actor of each time spot, we confirmed that the *kyu* zone should be divided into three parts: *jo*, *ha*, and *kyu* in order from the back to the front.

4.3 Validation approach of hypothesis 3

We made three-dimentional(3D) CG models of both a *Noh* stage including *Ken-sho* (the spectators' seats or stands surrounding the stage on three sides) and a normal, rectangular stage for validation by VR. We chose the *Noh* stage of Tanba Sasayama Kasuga Shrine. The *Noh* stage was dedicated by Tadayoshi Aoyama, the third lord of Sasayama clan, and built in 1861 (the first year of the Tenbun era). It is a one-storied wooden building with a half-hipped and tiled roof. It has *hasigakari* (passage), *kagami-no-ma*, and *gakuya* (backstage). According to its pedigree copy, it was built in imitation of the Noh stage's style in the keep of Edo Castle. There remains an architectural historical material of the *Noh* stage, with signature of "the box of a set of architectural drawings of the *Noh* stage dedicated to Kasuga shrine" written in 1816. In addition, there is a layout drawing of the spectators' seats when the *Noh* program was seen in the shrine, "the stage and the spectators' seats for *Noh* performance," in which the "Yotsuasi-do" located on the south of the front shrine is shown to be the seats for "*o-ometsuke-ijo*" (over the inspector general), suggesting that persons of exalted rank including Tadayoshi Aoyama as lord, watched *Noh* plays there. It also indicates to us that the seats for "*machi-kata*" (townsmen) *and* "go-kata" (clansmen and their families) were set up. In this study, we produced 3DCG of the *Noh* stage of Kasuga Shrine on the basis of "the ground plan of Sasayama Kasuga Shrine's *Noh* stage on a scale of 1 to 100" owned by the Sasayama City Board of Education, along with the architectural drawings described sabove. The photographs taken on the spot were used for texture-mapping data to represent the texture of the Noh stage. It is true of the data that they represent an image of pine and bamboo painted on the *kagami-ita*. First, with the image from the viewpoint of the main actor, the motion trajectories of the main actor dancing on the *Noh* stage and then on a normal, rectangular stage were followed to confirm the advantage of the former regular square stage. Next, we compared the image as viewed by a spectator at the ken-sho, the spectators' seats surrounding the *Noh* stage from three sides, and the image seen at the normal, rectangular stage's seats to confirm the advantage of the former.

5. PRELIMINARY RESULTS AND DISCUSSION

5.1 Regarding hypothesis 1

First, we plotted the positions of "dancing" of the main actor and the secondary actor from the video image as base data onto the *Noh* stage represented by CG. All motions of the actors are called "dancing." Next, we identified the trajectories of the dancing of the main actor and the secondary actor as jo (*jo* of *jo*, *ha* of *jo*, and *kyu* of *jo*) and ha (*jo* of *ha*, *ha* of *ha*, and *kyu* of *ha*) and then divided them by color. Finally, we produced a ground plan in which the stage of *kokonoma* stage is divided into nine parts and, and then each part, into nine parts. Then we overlaid the dancing trajectories of the main and secondary actors on it to verify whether our hypothesis is correct or not.

5.2 Regarding hypothesis 2

5.2.1 Data analysis of *"Jo ha kyu"* of hand drum and interjection

The instrumental performance of musical accompaniment consists of percussion instruments of three kinds such as a small hand drum, a big hand drum, and a drum as well as a fife called *nokan*. To visualize *jo, ha,* and *kyu*, we chose a small hand drum for use in this study for the following reasons. First, a *nokan* has a bamboo tube called "*nodo*" inside itself to produce a sound called "*hisigi*" in the high register. It is difficult to identify *jo, ha,* and *kyu* by the sound belonging to in high register. In addition, the *nokan* is not played as frequently as the small hand drum and the big hand drum. As for the drum, it always starts from the level of "*kyu* of *ha*" in the latter half of a play, so it is inappropriate for analysis. Through comparison of the quantities of the beat through a play between a small hand drum and a big hand drum, a small hand drum with more numerous beats was considered to be the most appropriate for attempts to visualize *jo, ha,* and *kyu*. Meanwhile, the percussion performance of musical accompaniment is accompanied by "*kake-goe*" (interjection). The musical accompaniment of *Noh* has no conductor. Therefore, the "*kage-goe*" is significant and particularly important for the chant of the main actor and *ji-utai* (Noh chorus). It facilitates their understanding and mutual communication. (Asami et al.,1993). To extract data of *"jo ha kyu"* from a small hand drum, we counted beats (a strong beat and a weak beat are checked respectively by ○ and ×) and interjection (categorized into 11 kinds) through the whole CD (1:10'51").

5.2.2 Data of a small hand (kotsuzumi) drum and interjection (kake-goe)

We produced the data table of a small hand drum and interjection taken every minute. The numbers of hand drum beat and 11 kinds of interjection are shown along the vertical scale; time is shown along the above horizontal base line. Figure 2 shows a graph of the total number of small hand drum beats and interjection per minute. The horizontal base line represents time (minute) and the vertical represents the number. The markers on the time axis represent from 0, through *jo* zone and *ha* zone (*ha* of *jo*, *ha* of *ha*, and *kyu* of *ha*) to *kyu* zone. In the *jo* zone (0 to 13 min), the number of beats at the beginning was 18, the maximum number was 54, and the number upon termination was 27; the difference between maximum and minimum was 36. In the zone of *ha* of *ha*, in which *jo-no-mai* (dancing of jo) starts, the initial number was 17, the maximum number, 37, and the number upon termination, 28; the difference between maximum and minimum was 20. In *kyu* zone (67-71 min), in which the lyrics are chanted with a single syllable per beat according to the rhythm of "*oh-nori*" the initial number was 44, the maximum was 60, and the termination number, 7. The difference between the maximum and minimum, was 53. The figures suggest the following characteristics of *jo, ha,* and *kyu*: the expression of the *jo* zone is rather rough and has a rather quick tempo; the *ha* zone involves sensitive twists and turns, adds even some relaxation, and has a slow tempo; the *kyu* zone is quickest and urgent, with the quickest tempo. For comparison, we took a 10-s sample at 3-min intervals.

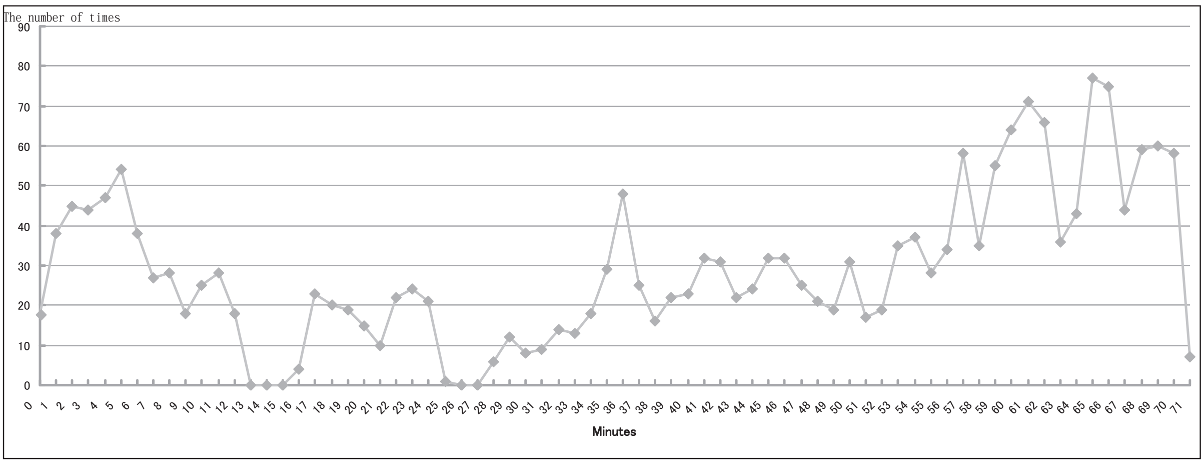

Fig.2: Total number of a small hand drum and interjection every minute

5.3 Regarding hypothesis 3

5.3.1 Noh stage and Kabuki stage comparison by VR

We produced three-dimensional CG models of Kasuga Shrine's *Noh* stage and *ken-sho* built in 1861 and Old Kompira Oshibai's (Kanamaru Theater's) Kabuki stage (the oldest play house existing in Japan) built in 1835. Then we verified them using VR. For the human body model of the main actor (*shite*), to make it easy to distinguish the front surface and the back surface, we colored the former red and the latter blue. In contrast, with the secondary actor (*waki*), we colored the front surface yellow and the back surface navy blue. We took human motion data from both the main actor and the secondary actor. Although all motions of the main actor and the secondary actor are called "dancing," not “motion," for convenience, we are now describing it as "motion." The VRML image of the main actor (*shite*) on the *Noh* stage was illustrated (Figure 3).

The factors of "dancing" of the main actor include many conventional movements in Noh plays, such as "*uchi-komi*," "*hiraki*," “*sayu*," "age-oghi," and "*tome-hyoshi*." Here, we extracted only the position and direction of the physical motions of the main and secondary actors in the play of "Hagoromo" on the basis of video images; we omitted the close conventional movements. We assigned the 3DCG human body models on the Kasuga Shrine *Noh* stage represented by 3DCG and put the data of the dancing trajectories of the main and secondary actors. The actors slide their feet (the walking style is called "*hakobi*" in *Noh*) on the stage. Therefore, we made the human body models move in parallel, not walking, to represent the waking path of motion. The method used to produce the animation is identical to the described in 5-2-1. The dancing trajectory is depicted in 4-1. Audio data of a Noh chant were linked with the 3D human body models of the main and secondary actors.

1) Position: the positions of the actors on the stage are represented as "the positions of 3D human body models" on the "3D Kasuga Shrine *Noh* stage."

2) Direction: the directions of the actors on the stage are represented as "the directions of 3D human body models" on the 3D Kasuga Shrine *Noh* stage.

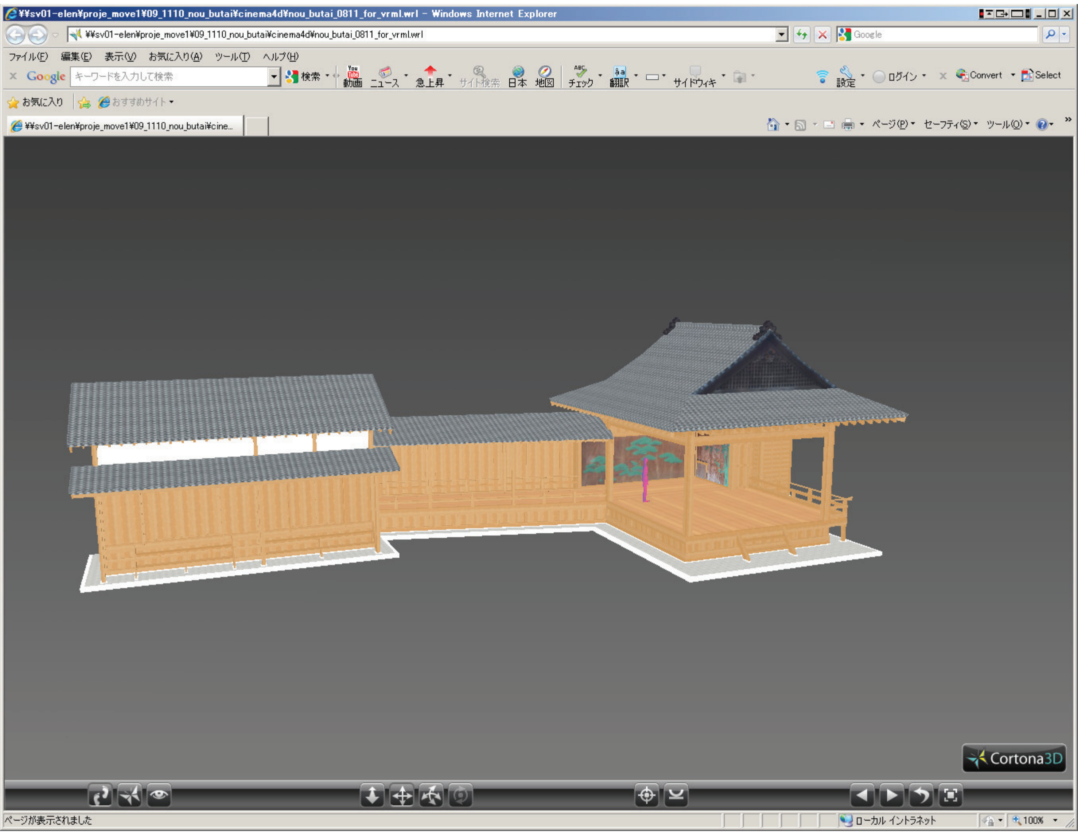

Fig. 3: Shite on the Kasuga Shrine Noh stage (VRML)

5.3.2 Field of vision of the main actor wearing *Noh* mask

The video cameras were set in places of the eyes of the main actor wearing a mask and the secondary actor. The main actor wears a mask, we restricted the field of vision of the main actor as shown in Figure 4.

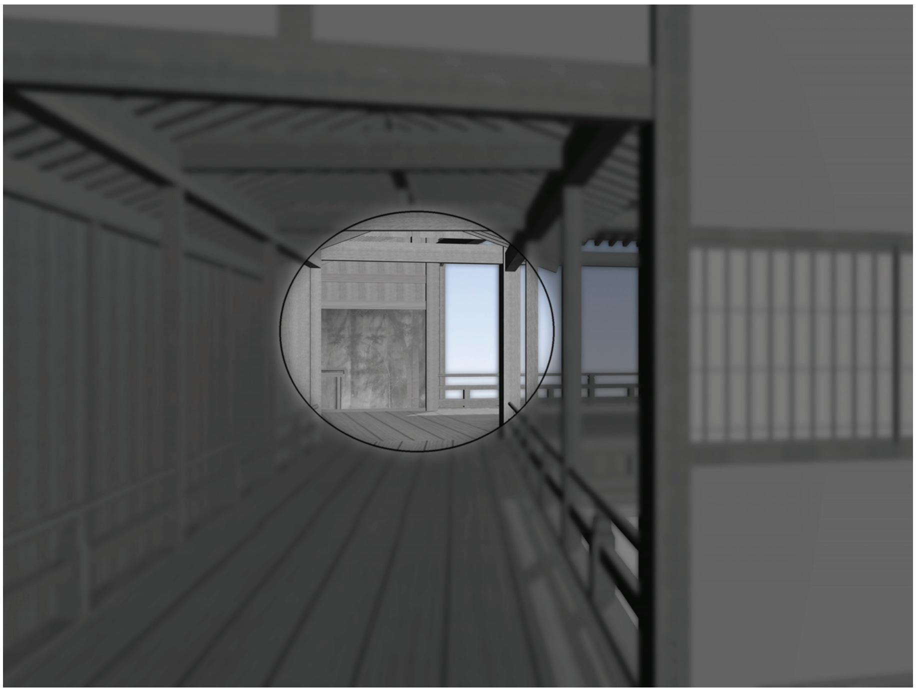

Fig. 4: Field of vision of the main actor when wearing a mask.

The video image with the restricted field of vision of the main actor wearing a mask (*omote*) moves along his dancing trajectory on the *Noh* stage. The one with the normal field of vision of the secondary actor wearing no mask (*hita-men*) also moves along his dancing trajectory. We also verified how the actors were "seen" from the *ken-sho* perspective (the spectators' seats surrounding the stage from three sides) when the *Noh* performance was conducted within the pale of Kasuga Shrine. On the ground plan of the spectators' seat described above, setting up the three perspectives (from the three sites of seats for honor, for townsmen, and for village men), we generated dynamic picture images from each viewpoint. The position of each viewpoint: the "Yotsu-ashi-do," which seems to have been temporarily built, does not exist now. Because the seat of the resident monk of the lord's family temple was set up on the front shrine on the north of the *Noh* stage, we considered that the height of the seats for honor on the “Yotsu-ashi-do" should be the same as that of the seats for honor. The seated height was estimated as 80cm. (FL=2040+800)

The respective heights of the seats for "*machi-kata*" (townsmen) was estimated as the seated height of a sheet of rush mat spread on the ground. (GL+800) The position of the viewpoint of *ken-sho* was illustrated (Figure 5).
(1) "Yotsu-ashi-do," the seats for honor including the lord of the clan
(2) "Machi-kata"
(3) "Sato-kata"

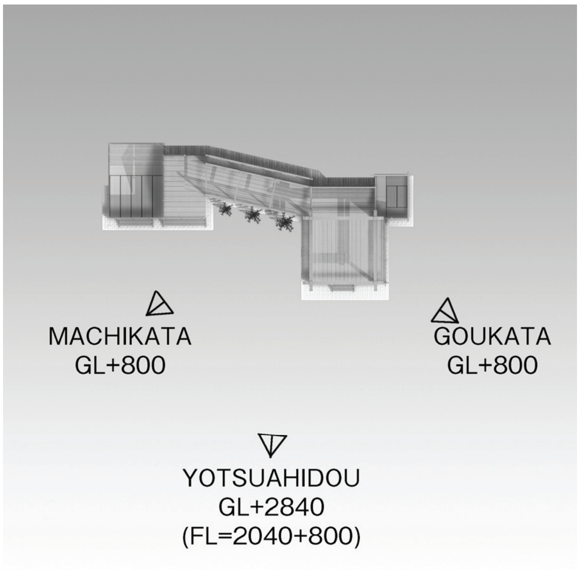

Fig. 5: Position of the viewpoints of "ken-sho"

Video images clearly show the restricted field of vision of the main actor wearing a mask goes along the dancing trajectory on the Kabuki stage. In addition, the video image with the normal field of vision of the secondary actor moves along the dancing trajectory. Setting the viewpoints from the spectators' seats on the box seat covered with a *tatami* mat at the center (between the flower way and the temporary flower way) on the first floor, we generated the dynamic picture images.

6. CONCLUSION

Through our continued exploration of hypothesis 1 and 2, we obtained the following knowledge to elucidate hypothesis 3. A *Noh* stage jetties into *the kens-sho*. The audience surrounds the actors on the stage, likely fostering a sense of unity between them. Although the scene on a *Kabuki* stage, which is shallow, is flatly seen, a *Noh* stage seen from three sides can have a stereoscopic composition of performance. Regarding the performance on a regular square stage, results show that the motions of moving forward or backward and walking around the stage are important. In *Noh*, it is said that stepping forward is associated with the expression of emotion such as high spirits and great joy and that walking around widely on the stage often represents the emotions of reminiscence and doubt (Yokomizo et al.,1987). In contrast, the actors cannot move broadly or boldly forward or backward because of the restrictions imposed by the structure on a *Kabuki* stage. This exploration also verified that the rectangle and shallow stage are unfit for *Noh* plays, in which the story is conveyed by physical motions, not by speech, as in *Kabuki*. Furthermore, a *Noh* stage has four pillars at the four corners in the main stage, with the roof even if it was set up in a building. The pillars are called "*shite-bashira*," "*metsuke-bashira*," "*waki-basihra* (or *daijin-bashira*)," and "*fue-bashira*" in order from the *hashi-gakari*. For the main actor wearing a mask and with an extremely restricted field of vision, all four pillars, not only the pillar called *metsuke-bashira*, function as important landmarks. Although two pillars exist at the left of stage and the right of stage on a *Kabuki* stage, the pillars are embedded into the wall. In *Kabuki*, the space between the two pillars is the main stage. In the earlier era of *Kabuki*, there used to be a roof over the stage and pillars to support it, called *daijin-bashira* (Japan Arts et al., web). We were able to verify that it is difficult for a main actor wearing a mask to dance on a rectangular stage without pillars as landmarks. From above, it is shown that the *Noh* stage with the square floor is the most appropriate for use as the performance space of *Noh* plays. The stage shape, the actors' positions, and the performance content of a play are closely related. To clarify the correlation among them might contribute to deepening the architectural understanding of a *Noh* stage.

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DEVELOPMENT OF "GEOSPATIAL DISASTER PREVENTION INFORMATION MASH-UP SERVICE"

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ABSTRACT: *Geospatial information such as satellite images and GPS became more and more important as social structure has become diversified and complicated. Those information are vital especially in disaster situations. Although public service companies are required to act promptly when a disaster occurs, they collect and analyze necessary information separately; a lot of valuable information is stored separately and is not shared efficiently. Our goal of this study is to eliminate waste of time and energy in collecting information and to support efficient recovery work. We have devised "Geospatial Disaster prevention information Mash-up Service (GDMS)", in which each organizations can share information. We focused on two platforms; one is an organizational platform to operate this service on a commercial basis and the other is a systematic platform to store information. As an organizational platform, we plan to set-up "GDMS Consociation"; a workshop including public service companies, academic experts and contents providers. As a systematic platform, we adopted Google Earth, 3D GIS provided by Google Inc. The system consists of four parts; 1) GDMS Application, 2) GDMS Server, 3) KML Server and 4) Google Earth Enterprise Server. We have decided basic direction, system requirements and operational framework, and developed a prototype system which contains some basic data we listed up by hearing from a local government and public service companies. The system also contains high-definition satellite images and 3D terrain models covering almost all areas of Japan. We plan to conduct a demonstration experiment in Shizuoka this year. This project is commissioned by Ministry of Education, Culture, Sports, Science and Technology.*

KEYWORDS*: 3D GIS, disaster prevention, disaster information, recovery support*

1. INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

Scheme for handling large-scale disasters is defined in Basic Act on Disaster Control Measures. According to the act, local governments, public institutions, and public service companies in the disaster-stricken region are responsible for taking actions. Such bodies outside the region also devise effective support schemes and take measures based on agreements or from a humanitarian standpoint. The act stipulates that when a disaster happens, the disaster headquarter will be set up in the government and every related organization in the area should share information through the headquarter. However, the actual situations in the past indicate that each organization gathered information separately and took measures individually.

Our goal of this study is to eliminate waste of time and energy in collecting information and to support efficient use of information by mashing-up those which each organization can gather or already has. This study would enable smooth disclosure of information regarding disaster situations and progress in restoration works, and we hope it brings a sense of relief to society. This project is commissioned by Ministry of Education, Culture, Sports, Science and Technology.

1.2 WHAT MASH-UP IS

According to Wikipedia, “mashup” is “a Web page or application that uses and combines data, presentation or functionality from two or more sources to create new services. The term implies easy, fast integration, frequently using open APIs and data sources to produce enriched results that were not necessarily the original reason for producing the raw source data.”

An example of mashup is to integrate CRM applications on the Web with open API services such as GoogleMap.

In this study, we redefine “mash-up” as “gathering various information or services scattered on the Web or in-house systems of each company, and integrating those information by putting them regardlessly on one platform to achieve better result than just piling them up.”

1.3 FOCUS OF THIS STUDY

We focused on two platforms. One is an organizational platform to operate this service on a commercial basis and the other is a systematic platform to store information. As an organizational platform, we plan to set-up “GDMS Consociation (tentative name)”. As a systematic platform, we adopted Google Earth, 3D GIS provided by Google Inc. In this paper, we call disaster countermeasures service that utilizes these two platforms as GDMS (Geospatial Disaster prevention information Mash-up Service.)

1.4 CHARACTERISTICS COMPARED WITH EXISTING SERVICES

Similar approaches have been made by public organizations. In 2003, Central Disaster Management Council set up an Expert Panel on Sharing Disaster Information, which made a suggestion toward setting up "Common Platform for Sharing Disaster Information among Government Offices." From 2004 to 2006, an innovative study on information platform for disaster mitigation was funded by Ministry of Education, Culture, Sports, Science and Technology. Scope of this study included information concerning local governments as well as that of private companies. Based on this study, Agency for Promoting Disaster Mitigation and Damage Reduction aims to set up a platform for practical use.

Also the Association for Promotion of Public Local Information and Communication has been trying to set up a platform to integrate governmental information for ordinary times.

Each approach would be socially effective if it comes into practical use. However, as these are led by public sectors, advantages for private companies are not quite clear yet. It seems that there are some difficulties for private companies to join the scheme.

On the other hand, as GDMS is a private-sector-led system, its characteristics are that it is quite practical. To be more specific, it enables companies to make profits or to improve business efficiency if they join this scheme.

2. GENERAL OUTLINES OF GDMS

2.1 BASIC CONCEPT

Basic concepts of GDMS are 1) independence 2) self-sustaining expansion 3) practicality and feasibility 4) private leading.

1) Independence: GDMS should be beneficial for participant companies’ primary business and every relevant participant should cooperate voluntarily.

2) Self-sustaining expansion: Anyone who joins in this scheme can mash-up everything. This is based on the shared sense that what is helpful for someone is also helpful for others. As we do not venture to seek a perfect system from the starting point, we plan to put feasible functions into practice at the beginning. In addition, we plan to create a basis where those involved can offer data voluntarily.

3) Practicality and feasibility: Our top priority is to make this service useful at business. This will encourage companies to participate positively, which will lead to improving practicality and feasibility. We will secure feasibility by setting up a structure where every participant can establish give-and-take relationship.

4) Private leading: Core members of GDMS Consociation will be companies that provide infrastructure, which will facilitate to meet demands of companies in the same field.

There are some assumptions concerning major users of information, collectable information, and service operation.

We assume that major users of this service at the first stage will be public service companies such as railway companies, electric power companies, gas companies, telecommunications companies and so on. These companies are responsible for recovery of life-support services in case of natural disaster. We assume that when their information are mashed-up, it will be practical for local governments, companies, voluntary organizations, and citizens.

As for collectable information, we plan o collect data required for disaster drills, for post-disaster emergency recovery and for full-scale recovery. In addition, we plan to mash-up data possessed by local governments which is related to disaster prevention. We also look forward to mash-up satellite images and aerial photos which are commercially available, and other useful data provided by private companies.

GDMS Consociation, which will be composed of public service companies, academic experts and contents providers, will take an initiative role in operational management.

2.2 CONSTITUTION OF GDMS

Those who will be involved in GDMS are public service companies, which are responsible for recovery work, service providers (contents venders and software-sellers), local governments, government agencies and government institutions (Fig. 1). Core members of GDMS among these organizations will be public service companies.

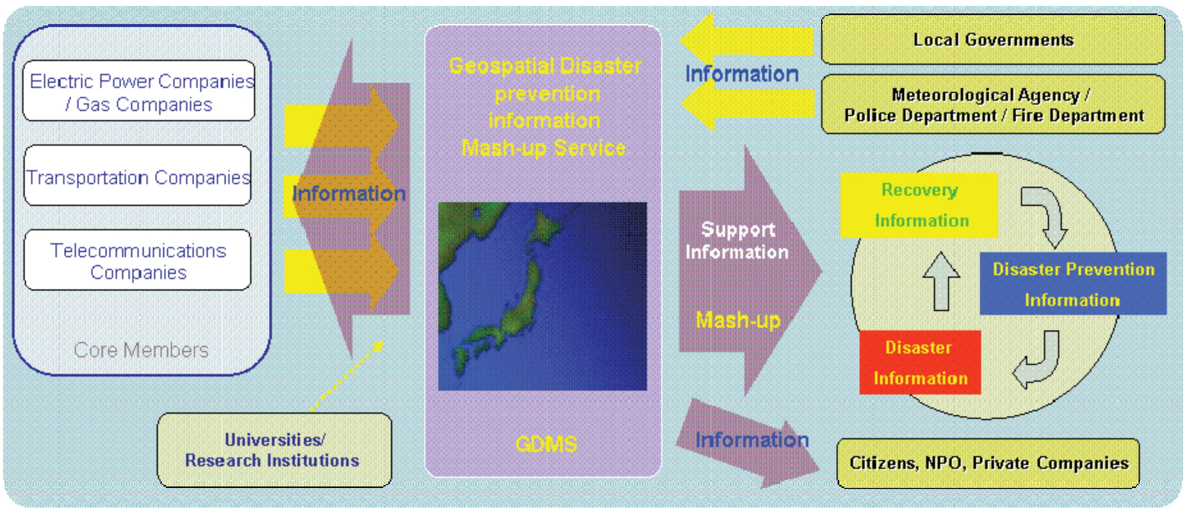

Fig. 1: Constitution of GDMS

Core members will provide disaster information which they used to collect and store individually upon GDMS, the common platform. On the other hand, they will be able to collect information through GDMS. This structure simply has the advantage that those companies will be able to share data with other companies, which will contribute to cost reduction in data gathering and its management. It will streamline recovery efforts.

Service providers will be able to sell information or software to public service companies. Government institutions can open information to citizens. We anticipate that universities and research institutes will also provide information or software. These information and software will be provided through GDMS platform.

Users of mashed-up information on GDMS will be the core members of GDMS, government institutions, and general publics. GDMS will be opened for anyone who would like to utilize the data upon its platform.

It will be convenient if this plan is put to practical use, as the data could be distributed to everyone who needs them. What is important for suppliers of data or services is that there is someone who pays for their data or services, or that it is more convenient for them to supply their services through GDMS compared to their conventional methods. From users' standpoint, the key to fulfill GDMS is that the data or services on GDMS are worth the cost.

The paid and free services would be controlled separately on GDMS. We will collect fee when users require paid services. However, we consider that it is essential for GDMS that free services are valuable enough.

2.3 SIGNIFICANCE OF GDMS

Public service companies will be able to obtain necessary information promptly on GDMS. They will be able to streamline their recovery work; in other words, they will be able to focus on what is most important. Moreover, it would be rather inexpensive to gather information through GDMS than to gather it on their own.

Advantage for contents and software providers will be that their data or services will be more valuable by mashed-up, and that their data or services will spread even faster in society. Even if they provide their services at a lower price, it will benefit them on their business activity as they could possibly acquire more customers.

Government institutions will be able to acquire more channels to release information. It will be an efficient method to educate citizens about disaster prevention.

For citizens, GDMS will be helpful not only because it will increase their method to collect information, but also it will help them to obtain all necessary information at once. Universities and research institutes will be able to make use of GDMS to apply their research outcome to practical business.

To sum up, GDMS will be profitable to every organization or people concerned, and it will be beneficial socially and commercially if we could manage it properly.

2.4 QUALITY AND IMMEDIACY OF INFORMATION

When we discuss information gathering and sharing system, we must note that generally there are problems about quality and immediacy of information. However, it does not seem to fit in case of GDMS. Quality of information should be guaranteed as each organization would mash-up information they use in their ordinary activities. In other words, useless information will be cleared out in each organization. As for the immediacy, it should not be a problem, as organizations offering information are on the front line to cope with disaster. Market mechanism will also ensure immediacy. Paid services cannot attract customers if they are outdated, that is, it would be pointless if contents providers mash-up services without immediacy.

3. GEOSPATIAL DISASTER PREVENTION INFORMATION MASH-UP SYSTEM (GDMS STSTEM)

3.1 SYSTEM CONFIGURATION

GDMS system is consists of 4 components (Fig. 2).

1) Application for client computers to mash-up disaster information (GDMS Application);

2) Server which delivers data uploaded by GDMS Application (GDMS Server);

3) Server which compiles information (KML or KMZ files) from associated service providers or companies and delivers these files to GDMS Application (KML Server);

4) Google Earth Enterprise Server which delivers satellite images as base maps.

1), 2) and 3) are the subject of this study.

3.2 OUTLINE OF GDMS APPLICATION AND SERVER

GDMS Application is an add-on function for Google Earth, which transfers data and program commands

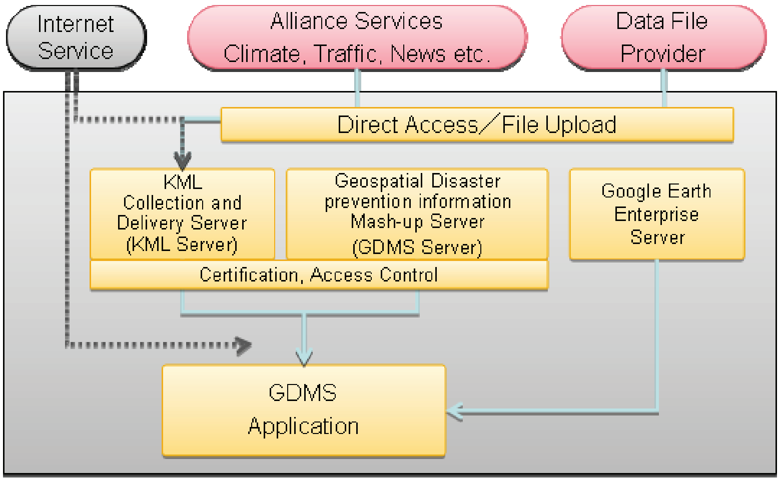

Fig. 2: GDMS System configuration diagram

interactively between external applications and Google Earth. Its basic functions are to display data updated every minute, to search necessary information, to store data in chronological order, to analyze some information by superimposing images, and to input disaster damages. This application should be user-friendly to spread GDMS.

3-3. OUTLINE OF KML FILE COLLECTION AND DELIVERY SERVER

KML file collection and delivery server is the site where KML files are uploaded or downloaded, and it collects updated KML files and adds them to the database automatically. It imports files transferred by FTP, checks designated URL periodically, and updates the database in KML Server when it finds updated files. This function prevents unnecessary duplication of information uploaded by providers.

This server also has basic database management functions such as search, view, update, and delete. In addition, it has access control function to allow access to mashed-up data according to its level of secrecy. Secrecy levels are set according to type of files, users, and time (pre-disaster or post-disaster).Crucial point of system construction is to develop search ability, as this server will store a wide range of information.

Quality of data in GDMS is relatively reliable as the information providers are limited to governments and enterprises. However, as the volume of information increases, it will cause various resolutions, scales, and accuracy of data such as “not sure”, “not so sure”, or “sure”. Requirement for promoting GDMS is to enable users to find necessary information with ease.

4. UTILIZATION OF GDMS

4.1 INFORMATION CLASSIFICATION ACCORDING TO PHASES

We had workshop discussions to define information which would be necessary in case of disaster. We adopted simulation approach. Participants included public service companies and academic experts.

The information is categorized in three phases:

1) The first phase to grasp outline of the damage in the area (Phase 1);

2) The second phase to grasp the detail of the damage in the area (Phase 2);

3) The third phase to grasp information to assist recovery work (Phase 3).

In addition, there should be another phase to prepare in advance for Phase 1, 2 and 3.

In the pre-disaster phase, we plan to prepare basic information such as satellite images, statistics (population distribution, etc.), spatial information (condition of urban areas and roads), and hazard information (active fault zone and ground condition, etc.) (Fig. 3.)

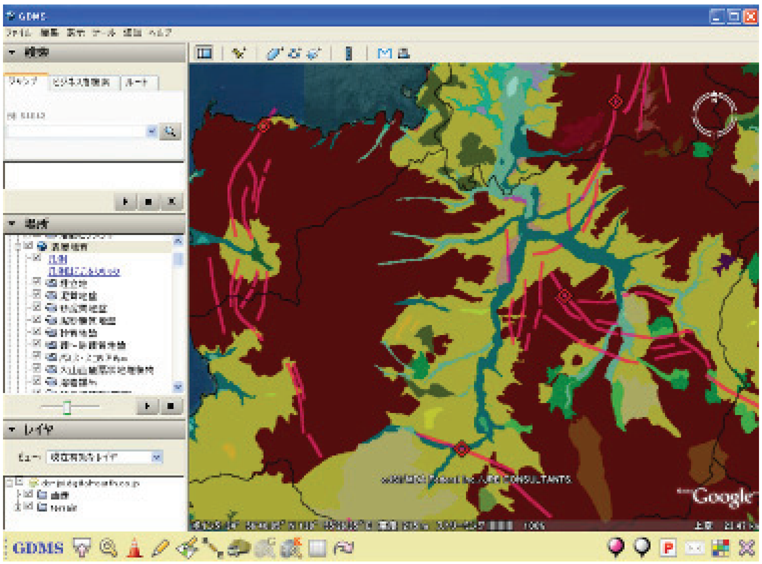

Fig. 3: Subsurface geological map and Active fault zone

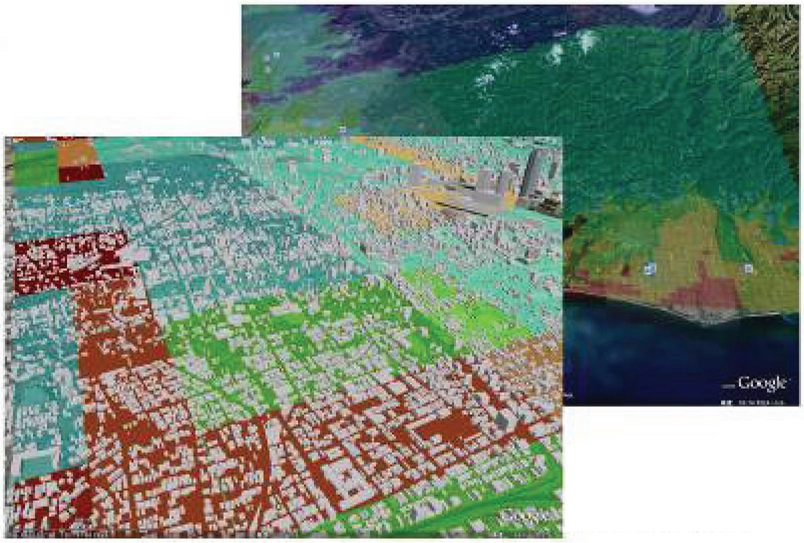

Fig. 4: Estimation of seismic shaking

In phase 1, the Meteorological Agency announces the seismic center and intensity of an earthquake. We will convert the information and mash-up them onto GDMS. We will also show damages estimated by damage-model (Fig. 4.)

In phase 2, we will provide photos shot in the area or shot by aerial photographs, and field survey results such as traffic conditions (Fig. 5.)

In phase 3, users will be able to collect and share necessary information to draw up a maneuver for recovery work. Assumed information is newest field survey results, conditions around the area, traffic report, and weather information (Fig. 6.)

We anticipate that other useful data will be accumulated on GDMS as it develops in the future.

4.2 BASIC SATELLITE IMAGES

GDMS utilizes satellite images as base maps. What we mean by satellite images are archived images in the past and also images shot after a disaster. It is preferable if archived satellite images were shot recently before a disaster. However, it would be adequate enough to decide shooting period from a viewpoint of cost-effectiveness.

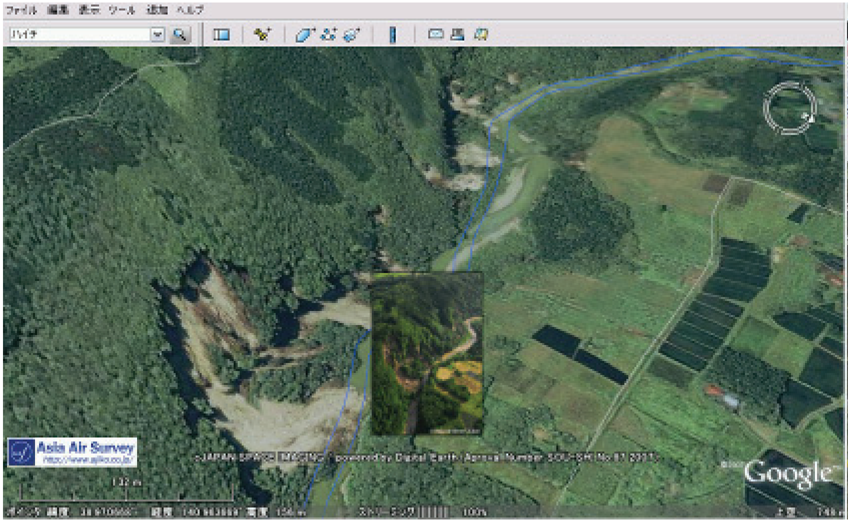

Fig. 5: Aerial photo after an earthquake and satellite image before the earthquake

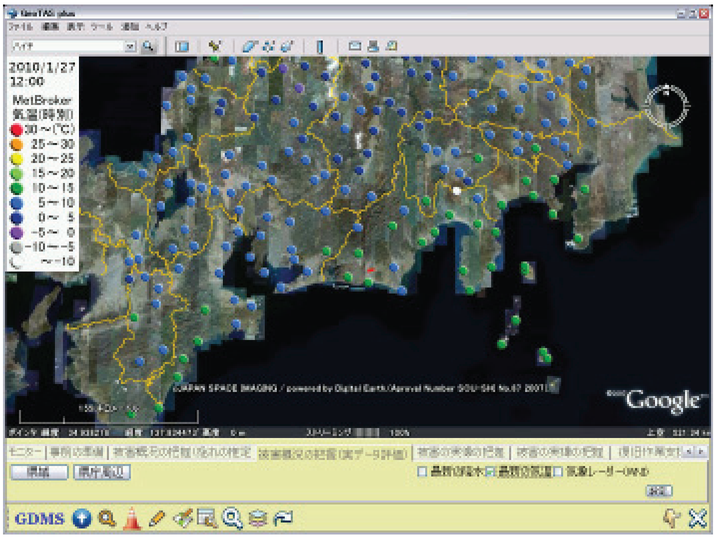

Fig. 6: Weather information in a disaster-stricken region

On the other hand, we must acquire post-disaster images, as those are important to presume the situation by comparison to pre-disaster images.

We have investigated three types of satellite images; IKONOS (optical sensor), GeoEye-1(optical sensor) and Cosmo-SkyMed (synthetic aperture radar; SAR). Time period of revisit is 2.9 days for IKONOS and 3.2 days for Geo-Eye-1. On the condition that the weather is clear and we can operate two satellites at once, we will be able to acquire images in a devastated area within 2 days at the latest. SAR irradiates objects with microwave radar, and reveals undulation and construction of objects by analyzing its reflected wave. SAR can shoot images even in the night or on a cloudy day; it does not depend on the weather.

If we are to run optical sensor satellites alone, it depends on the satellites' orbits how long it takes for us to acquire satellite images. It also depends on time period of revisit and weather. We should take SARs into account to insure promptness against weather condition, such as Japanese ALOS or Italian Cosmo-Sky MED. Also, we need to prepare for delays regarding the time period of revisit by running more than one satellites.

It is not effective to shoot images regardless of damages levels. We should clarify standards for emergency shooting. We have been discussing that we should limit emergency shooting to the situation when an earthquake measured more than an sixth level (by Japanese scale) occurs.

4.3 COLLECTING BASIC DATA

We have listed up necessary data from interviews with local governments and public service companies. Our business targets are railway companies, gas companies, electric power companies, water and sewerage departments, telecom companies, and local governments. Information is categorized by the phases mentioned above. We classified demands according to business categories and information categories.

Raw data can not always be displayed on the system. Our technology development enabled us to convert such data into KML format. We have developed the system so it can import early warning data for earthquakes provided by the Meteorological Agency and high-sensitivity seismograph data from National Research Institute for Earth Science and Disaster Prevention (Fig. 7, Fig. 8.)

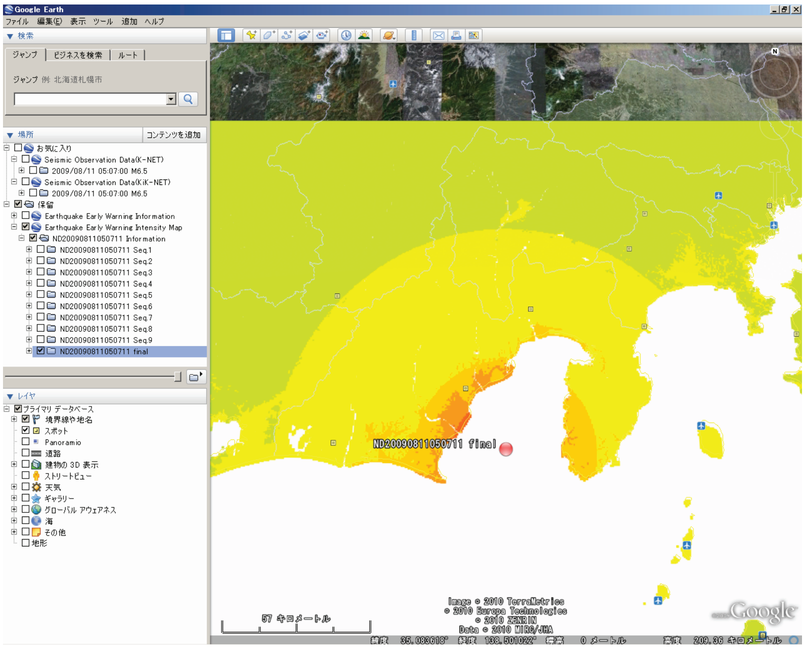

Fig. 7: Seismic intensity converted into KML format

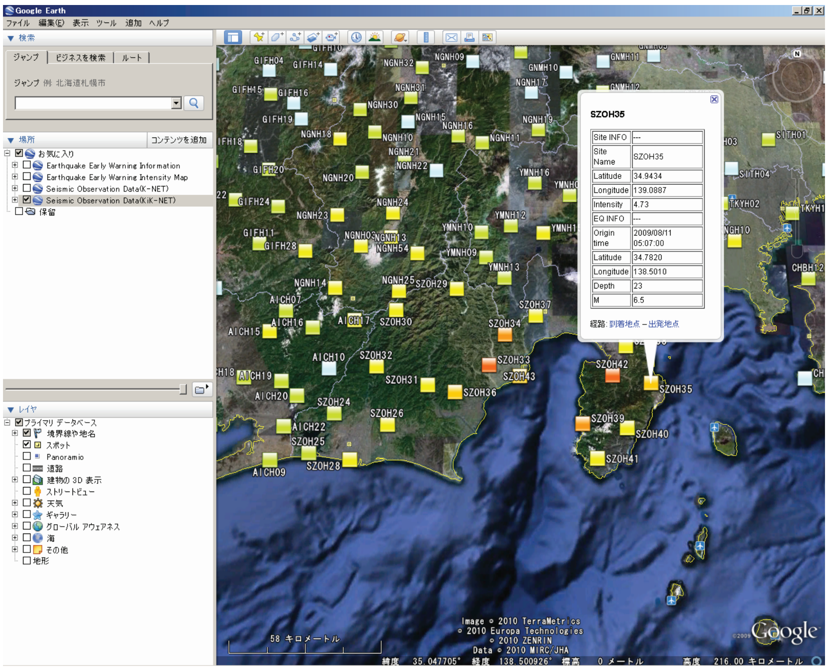

Fig. 8: Information from K-NET converted into KML format

Although we have collected necessary data, we acknowledge that we need to verify consistency between the data list and the requirements of users. We plan to interview with users again, and to update the data list based on the result of the previous interview. At the same time, we plan to estimate the costs required to meet the demands and define minimum contents which we should prepare at the startup of service operation.

5. CONCLUSION AND FUTURE WORK

There are many challenges and difficulties left. We must draw up rules for mash-up operation and prepare manuals. There are some technical difficulties to be solved, for example, how to treat geocoding of road data. Moreover, there is still room for improvement of the system to make it more user-friendly. The largest challenge is whether this service makes good business sense. This depends on the cost which companies would allow to invest for efficiency of disaster prevention and recovery act. We expect that it will be clarified in the feasibility survey.

We conducted prototype testing of the system in FY 2009. We plan to conduct demonstration experiments within this financial year, in corporation with Shizuoka Prefecture. This experiment will clarify the gap between our supply and demands of local government or public service companies. It will also clarify effectiveness of information sharing between government and citizens.

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DEVELOPMENT OF AN INTERACTIVE VISUALIZATION SYSTEM USING VR TECHNOLOGY FOR FLOW SIMULATION

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ABSTRACT: *This paper presents an interactive visualization system using virtual reality technology for three dimensional flow simulation based on unstructured grid. The present system is available to the visualization of scalar and vector fields, and is developed by VR programming (Open GL and CAVE library). User can select a visualization method by operating the controller in VR space. The improvement of the computational time and the accuracy of visualization are investigated. The present system is applied to several numerical examples and is shown to be a useful visualization tool to investigate the three-dimensional flow problems with complicated geometry.*

KEYWORDS*: Flow visualization, virtual reality, CAVE, VFIVE*

1. INTRODUCTION

Three-dimensional numerical simulation is becoming more popular to evaluate the flow problems in accordance with the development of hard and software of computers. Especially, the numerical simulation based on unstructured mesh is useful for the flow simulation with complicated spatial domain such as wind flow in urban area, since the unstructured grid can easily treat the complicated geometry of land and buildings (Takada et al., 2008). The flow visualization is very important to understand the three-dimensional flow phenomena. Recently, the visualization using virtual reality technology such as CAVE system (Cruz-Neira et al. 1993, Kuhlen et al. ,2004) using Immersive Projection Technology (IPT) (Ogi, 1999) is becoming more popular in order to understand the flow phenomena more accurately. Kageyama et al. developed an interactive visualization system VFIVE (Vector Field Interactive Visualization Environment) (Kageyama, et al., 2000, Ohno, and Kageyama, 2007, Kashiyama et al., 2009) for CAVE system. User can understand the complicated flow phenomena in three dimensional domain by using the VFIVE. However, as the system is available for the structured grid only, it is difficult to apply the system to the visualization of flow simulation based on unstructured grid.

This paper presents an interactive visualization system for three dimensional flow simulation based on unstructured grid for the CAVE system. The concept of the present system is similar to the VFIVE and the VR programming (Open GL and CAVE library) is employed for the development of the system. The VR space is realized by the IPT (Immersive Projection Technology). The CAVE Library is employed to develop the interface available in the VR space and OpenGL is employed to render CG image. User can select a visualization method by operating a controller in the VR space. The visualization based on unstructured grid is time consuming comparing with that based on structured grid. The improvement of the computational time and the accuracy of visualization are investigated. The present system is applied to several numerical examples and is shown to be a useful tool to investigate the three-dimensional flow problems with complicated geometry.

2. VR ENVIRONMENTS

The visualization system using VR system is developed for the post-processing of the three dimensional flow simulation. Fig. 1 shows the exterior view of the VR system "HoloStage" based on IPT. Fig.2 shows the layout of VR projectors and screen; three large and flat screens and three high-performance projectors corresponding to the screen. The front and side screens are transmissive ones and the bottom screen is reflective one. The present system consists of a PC cluster (1 master-PC and 4 slave-PC), 3 projectors, VR display (3 large screens) and a position (head) tracking system (see Fig. 3). The master PC manages the action of whole system, the slave PC performs the position tracking of user's glasses and controller, and the slaves PCs 1-3 perform the computation for visualization and displays the visualized results by CG image for each screen. The stereoscopic image from the arbitrary viewpoint of observer is displayed in VR space (CAVE room) by the position tracking system. The details of the VR system are described in the reference (Takada and Kashiyama, 2008).

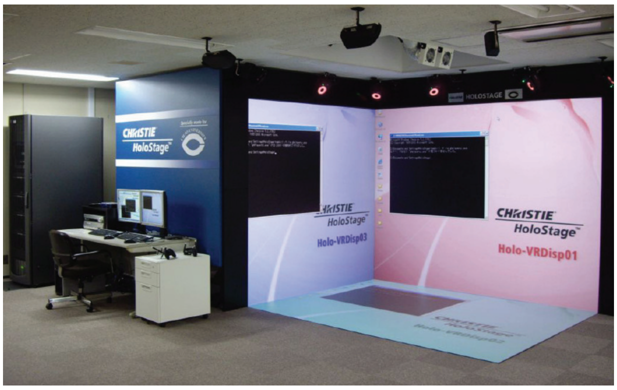


FIG.1: VR system "HoloStage"

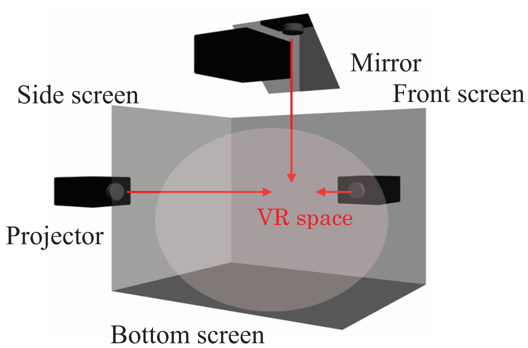


FIG.2: VR projector and display system

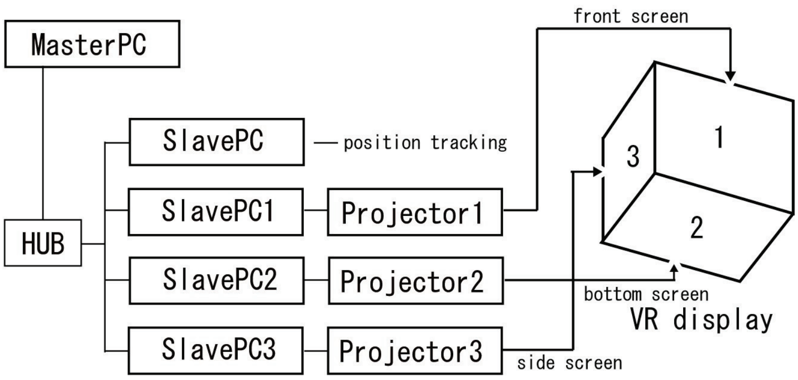


FIG.3: Hardware configuration

3. AN INTERACTIVE VISUALIZATION SYSTEM USING VR TECHNOLOGY

The process of the visualization of the present system is shown in Fig.4. The present system performs two thread, display thread and calculation thread, independently. The calculation thread performs the calculation for visualization and the display thread performs the creation of CG image for each screen. The sharing of data is performed on the shared memory and the results of calculation thread are refereed from the display thread by the CAVE Library. The details of visualization process in the calculation thread are shown in the following section.

3.1 Input data

The input data of the present visualization system is as follows; unstructured mesh data based on linear tetrahedron element, the data for computational results for vector data (velocity) and scalar data (pressure and density (in case of compressible flow)) at nodes of the tetrahedron element. In case of unsteady simulation, the data for computational results are prepared for every time step.

3.2 Search of observer position

The VR system (Holostage) has a VICON tracking system which is the optics type motion tracking system. This visualization system searches the position of the observer by the tracking system. The tracker device VICON (see Fig.5 (a)) tracks the position of markers fitted to the liquid crystal shutter glasses (Fig.5 (b)) and the controller (Fig.5(c)) used by observer, the white small ball in Fig. 5 (b) and (c) denote the marker. The six VICONs are provided in the 3D VR space surrounded by the three screens.

3.3 Selection of visualization method

The present system provides the following visualization methods in the VR space; isosurface, contour lines, color slice, particle tracing, field line and so on. The major visualization methods of present system are listed in Table 1. The observer can select the visualization method from the menu displayed in the VR space by using a controller (see Fig. 6).

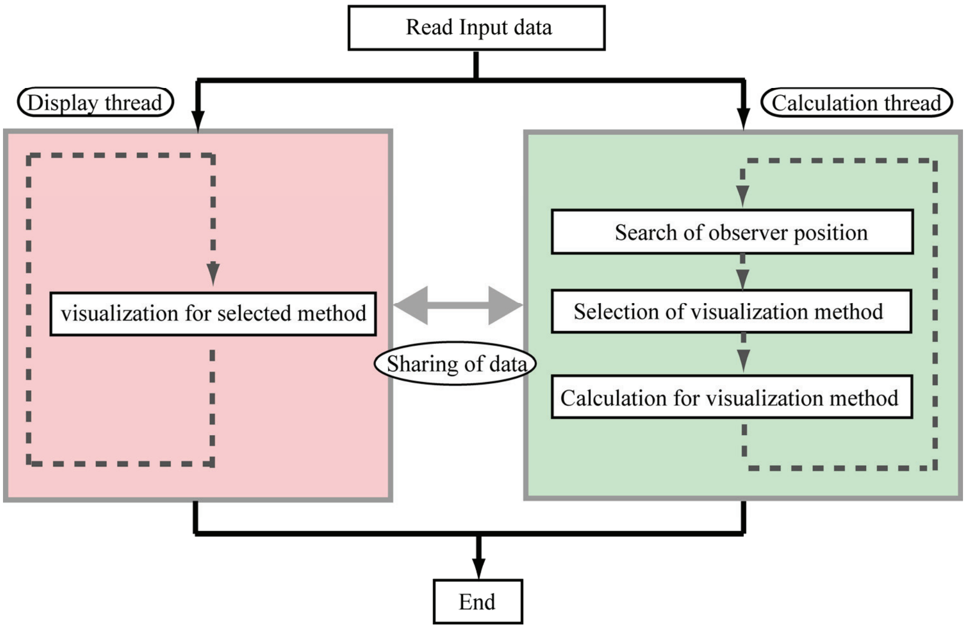
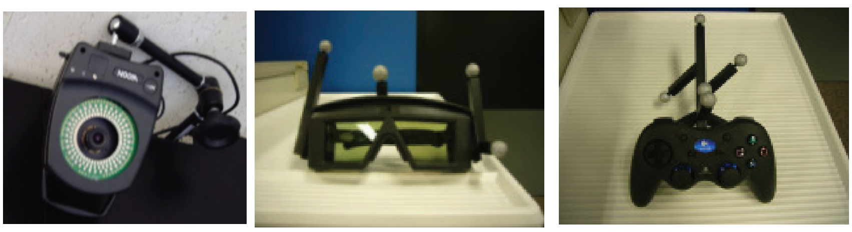


FIG.4: The process of the visualization



(a) (b) (c)

FIG5: VICON tracker(a), liquid crystal shutter glasses(b) and controller(c)

TAB. 1: Major visualization methods of present system

For Vector data	For Scalar data
Field Lines	*Isosurface*
Particle Tracer	*Local Slicer*
Local Arrows	*Ortho Slicer*
Hotaru	*Volume Rendering*
Snow	*Prove*
Line Advector	
Prove	

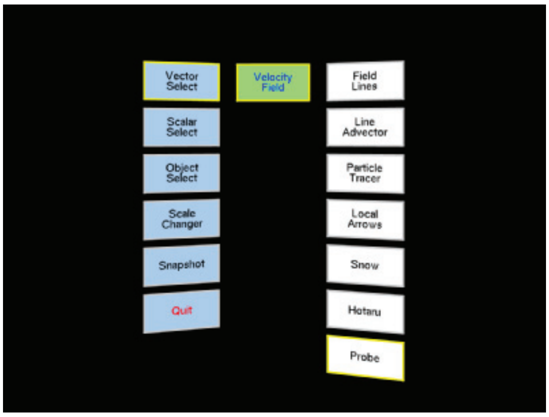


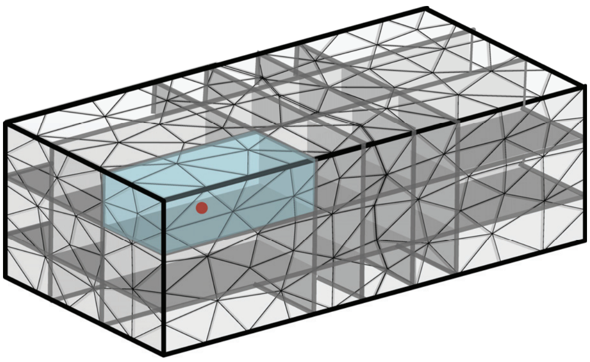
FIG.6: Menu of visualization method in VR space (for velocity field)

3.4 Calculation for visualization method

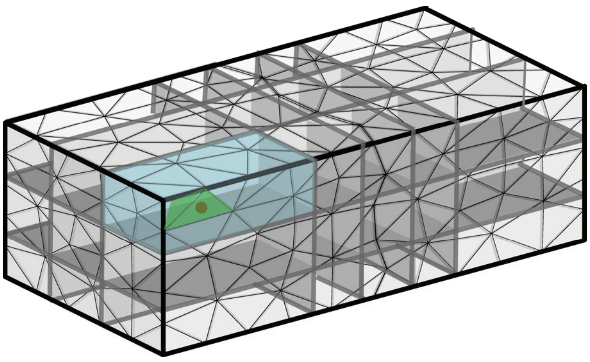
For the visualization using unstructured grid, it is very important to find vector and scalar quantities at the designated point quickly. To do this, it is necessary to find the element where the point is included quickly. Once the element is searched, the vector and scalar values at the point can be calculated by the nodal values of the element by the appropriate interpolation method. The following algorism is employed to accelerate the computational time..

3.4.1 Search of the domain that include designated point

First, the search of the sub-domain that includes the designated point is performed by the bucket method. The domain decomposition based on the structured domain is employed for the computational whole domain as shown in Fig. 7 (a). The sub-domain is created to realize that the number of element nodes in each sub-domain is almost constant. The small sub-domain is employed for the region where the density of mesh is high. Next, the domain which include the designated point (red point if Fig.7 (a)) is searched easily and rapidly by using the rectangular coordinate values of the designated point as shown in Fig. 7 (b).



(a) Domain decomposition and search of the domain



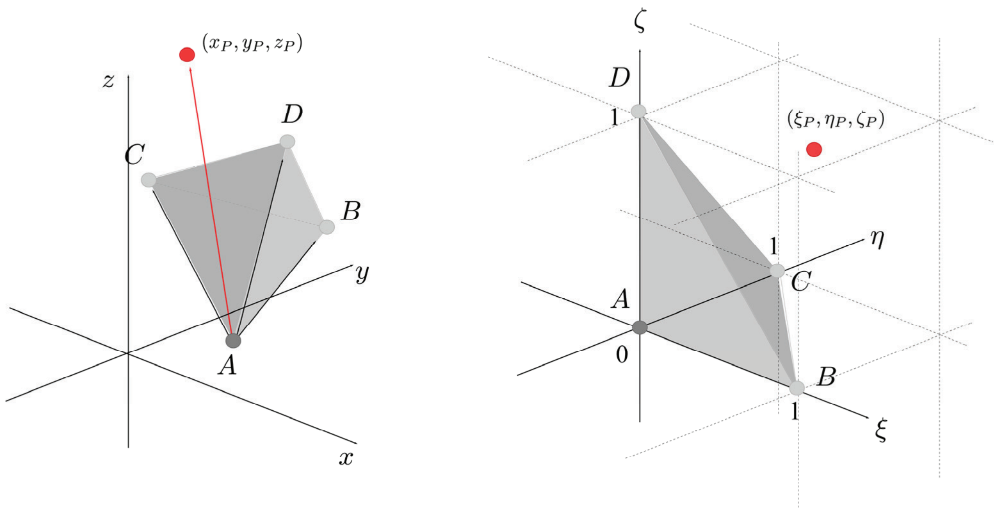
(b) Search of the finite element

FIG.7: Search of the finite element which include the designated point

3.4.2 Search of the element that include designated point

Next, the search of the element where the designated point is included Fig. 8 (a) shows the relation between the element and the designated point in the physical coordinate system. In order to investigate the judgment that the element includes the designated point or not, the mapping method using a generalized coordinate system is employed as shown in Fig. 8 (b). If the coordinate of the designated point in the generalized coordinate system (ξ_P, η_P, ζ_P) is satisfied the following condition, the element includes the designated point.

$$(0 \le \xi_P \le 1) \cap (0 \le \eta_P \le 1) \cap (0 \le \zeta_P \le 1) \cap (\xi_P + \eta_P + \zeta_P \le 1) \tag{1}$$



(a) Physical coordinate *(b) Generalized coordinate*

FIG.8: Search of the element using the generalized coordinate

3.4.3 Interpolation of the vector and scalar values at the designated point

Once, the element that includes the designated point is searched, the vector value and scalar value at the designated point is interpolated by the value of the element node in the generalized coordinate system as follows (see Fig.9).

$$q(\xi_P,\eta_P,\zeta_P)=q_A+(\frac{q_B-q_A}{\Delta\xi})(\xi_P-\xi_A)+(\frac{q_C-q_A}{\Delta\eta})(\eta_P-\eta_A)+(\frac{q_D-q_A}{\Delta\zeta})(\zeta_P-\zeta_A) \quad (2)$$

where, q_A, q_B, q_C, q_D denote the vector and scalar value at the element node.

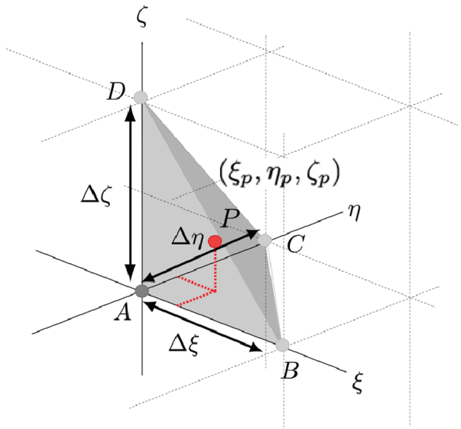


FIG.9: Interpolation of vector and scalar values

4. ACCURACY AND SPEED

In order to investigate the effectiveness of the present visualization system, the present system is compared with the VFIVE in the aspects of computational accuracy and speed.

4.1 Comparison of the calculation accuracy

The present method is applied to the visualization for the columnar rotating flow problem that tilted 45 degrees on y-axis as shown in Fig.10. The coarse mesh is employed as a 5×5×5 structured grid. Fig11 shows the situation that the observer uses the visualization method "Particle Tracer". Fig. 11 shows the streamline during four-rotation. The 1-st order Euler method and the 6-th order Runge-Kutta method are employed for the integration scheme for the computation of streamline ("Particle Tracer"). From Fig. 12, it can be seen that the results obtained by the present system using 6-th order Runge-Kutta method is very good agreement with the VFIVE. In case of the results by the Euler method, the streamline gets out of the right line gradually.

4.2 Comparison of the computational speed

The comparison of the computational speed for visualization is performed using the example for the wind flow simulation. Fig.13 shows the simulation area for wind flow analysis, Nihonbashi, Tokyo. The box area denoted the visualization area and the total number of nodes and elements in this visualization space are 98,387 and 469,055 respectively.

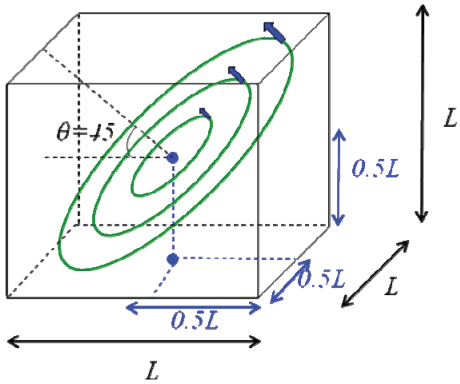


FIG.10: Numerical test example

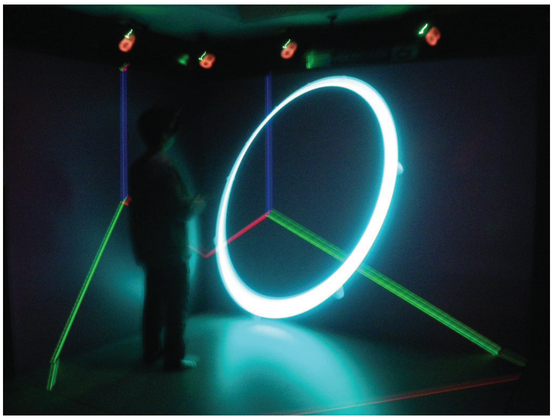


FIG.11: Comparison of stream lines in VR space

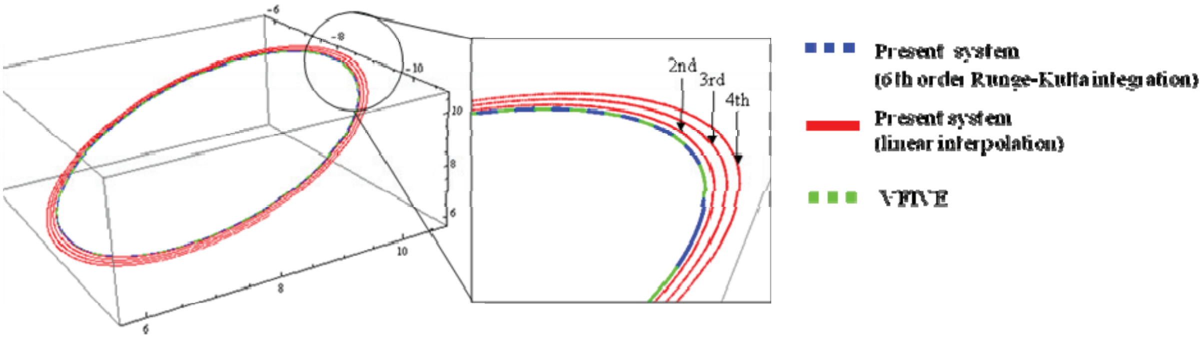


FIG.12: Comparison of stream line

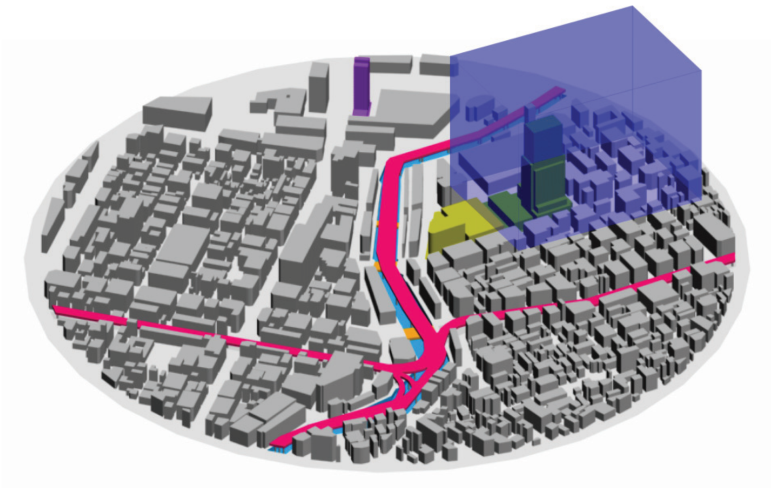


FIG.13: Visualization example for wind flow simulation

In this example, the optimal number of subdomain for domain decomposition is investigated in the element search based on the bucket method. Fig. 14 shows the average computational time versus the number of subdomain to find the position of the 5,000 particles that are randomly distributed for the computational domain, in the visualization method “Hotaru”. From this figure, it can be seen that the computation time decrease in accordance with the number of domain decomposition and become constant in the cases more than 30×30×30 subdomain.

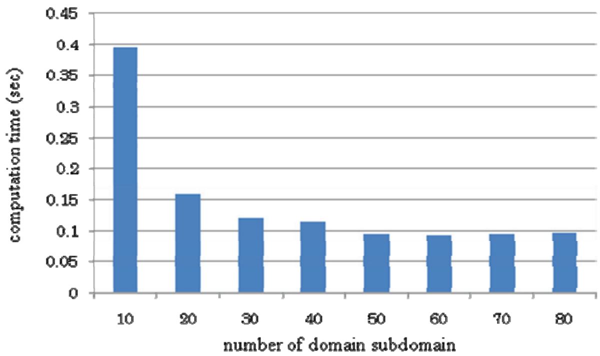


FIG.14: Comparison of mean computational time versus the number of domain decomposition

Fig. 15 shows the computational time of "Hotaru" at every time step. From this figure, it can be seen that the computational speed of the present system is slower than the VFIVE, but it is enough fast for visualization when the method based on a generalized coordinate system is employed for the method of element search.

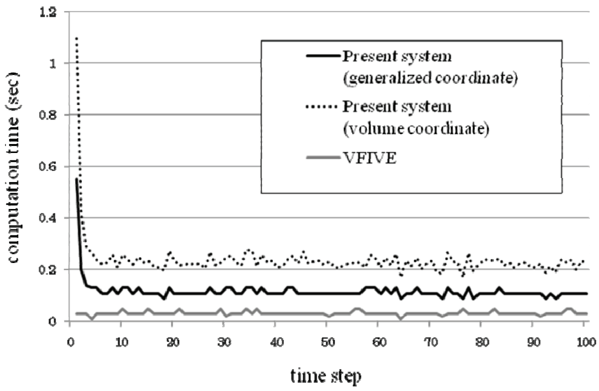


FIG.15: Comparison of the computation time of "Hotaru" at every time step

5. APPLICATION EXAMPLE

The various visualization methods are employed for the wind flow simulation of Nihonbashi area, Tokyo. Fig. 16 shows the scene that the observer uses the visualization method "Particle Tracer" and "Local Arrows" which shows streamlines and velocity vector, to check the three dimensional vortex occurred behind the building. Fig. 17 shows the scene that the observer uses the visualization method "Volume Rendering" to check the three dimensional pressure distributions. Other visualization methods are also usefully applied to understand the complicated flow structure. Fig. 18 shows the scene that the observer uses the visualization method "Probe" which shows the vector and scalar value at the point specified in VR space. It can be seen that the present visualization system based on unstructured grid is very useful for the three-dimensional flow problems with complicated geometry.

FIG.16: Visualization by "Field Line" and "Local Arrows"

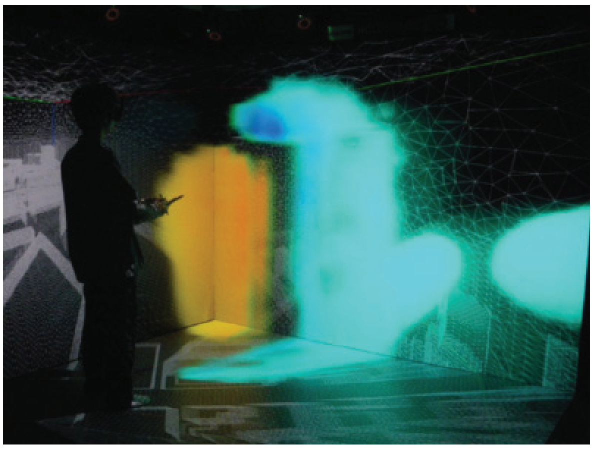


FIG.17: Visualization by "Volume Rendering"

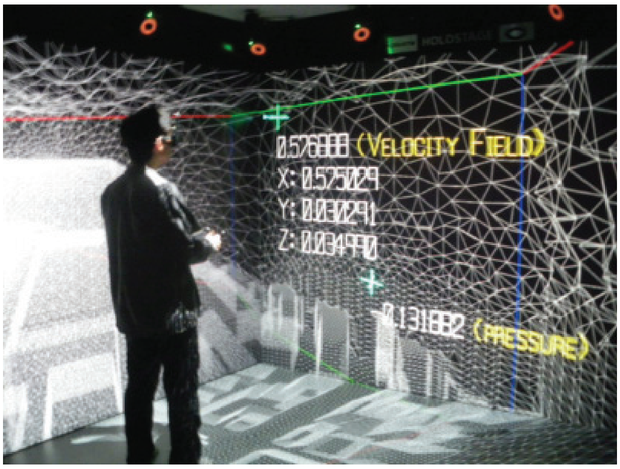


FIG.18: Visualization by "Proves"

6. CONCLUSIONS

An interactive visualization system based on VR technology has been presented for flow simulation based on unstructured grid in this paper. User can select the visualization method from the menu displayed on the screen in the VR space and can display the visualized results from the arbitrary view point. In order to accelerate the computational time for visualization, the element search method based on the bucket method using generalized coordinate has been developed. The 6-th order Runge-Kutta method has been employed for the integration scheme for the computation of streamline ("Field Line", "Particle Tracer" and "Line Advector") to improve the numerical accuracy. The computational accuracy and speed have been compared with that by VFIVE. The present system has been applied to the wind flow simulation in urban area with complicated geometry for an application example.

From the results obtained in this paper, it can be concluded that the present system provides a useful visualization tool to investigate the three-dimensional flow problems with complicated geometry.

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ACCESSIBILITY EVALUATION SYSTEM FOR SITE LAYOUT PLANNING

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ABSTRACT: *Construction site layout planning is concerned with the existence, positioning, and timing of the temporary facilities that are used when throughout a construction project. Previous researchers have developed many approaches for dealing with this complicated problem. However, little research has been conducted on the problem of transport accessibility, which can significantly influence the operational efficiency of transportation and safety of the working environment. Therefore, we aimed to develop computational methods to visualize and simulate the transportation details at job sites. In this research, we developed an accessibility evaluation system comprising of four modules: (1) transportation module, (2) site importing module, (3) accessibility evaluation module, and (4) visualization module. The computational system was implemented using Microsoft XNA (a game platform) and Nvidia PhysX (a game engine). The realistic visualization simulations made possible using this approach can provide solid references to engineers to enhance the quality of layout planning. Using the system we developed, engineers can identify potential accessibility problems and unsafe situations early in the design and planning stages.*

KEYWORDS*: accessibility, site layout, trailer truck, physics-based simulation, game engine.*

1. INTRODUCTION AND BACKGROUND

Construction site layout planning is an important issue which can greatly influence the scheduling and cost of the construction project. Such planning is primarily concerned with the positioning, existence and timing of the temporary facilities that are used throughout the construction project (Mawdesley et al., 2002). The site layout planning problem can be dissected into the following sub-problems: (1) identifying the shape and size of the facilities to be laid out; (2) identifying the constraints between facilities; and (3) determining the relative positions of these facilities (Zouein et al., 2002). As accessibility between various facilities can become problematic, the positioning of the different facilities correctly, with consideration of both cost and safety, is very important.

The problem of accessibility in construction site is a very significant issue as it can directly affect the planning of the entire site layout. However, this aspect has been mostly ignored in the research on site layout. During the planning stage of construction, the location of facilities will be largely determined by considerations such as distance to materials, the transportation time, or transportation cost. Important considerations such as safety and accessibility are often ignored. However, we contend that the factors related to the transportation path should not be confined to distance and cost, but also safety and accessibility. If the transportation path is difficult to pass due to numerous obstacles or convoluted routes, even though the distance is shorter, the efficiency of the operation can be adversely affected. Although this may seem to be an intuitively important issue in construction site layout planning, accessibility problems still happen frequently on construction sites.

In practice, engineers deal with the accessibility problem daily. Daily meetings are held to discuss transportation paths and the location of the heavy equipment and temporary facilities to ensure that all the various processes are not in conflict. Conflicts are usually caused by the incorrect assessment of the space occupied by the equipment and facilities. All these aspects are associated with accessibility in the construction site.

Therefore, in this research, we aimed to develop a computational method to deal with this problem We developed a system composed of four modules: (1) transportation, (2) site importing, (3) accessibility evaluation, and (4) visualization. Using this system we can easily simulate transportation processes in the construction site and test the safety and accessibility of the site plan. The system can also be used to visualize the test results. Engineers can therefore easily identify the unsafe parts of the site and mitigate potential accessibility problems.

2. RELATED WORKS

Site layout planning has been studied over many years. We organized the research according to three different criteria: (1) genetic algorithm analysis; (2) space analysis; and (3) environment safety consideration. Under the first criterion, Zouein et al. (2002) tried to resolve the transportation cost problem in construction site layout planning by using genetic algorithm analysis. Mawdesley et al. (2002) used genetic algorithm to reduce the cost of a transportation paths, Lam et al. (2009) combined the genetic algorithm and Max-min ant system (MMAS) to provide a computing method for reducing cost and transportation time. Using this kind of method to simplify the construction sites led to a reduction in the computational effort. After the simplification process, the site would be taken apart into rectangular objects. Therefore, the model could not truly represent the original site. This approach assumes that all facilities can be presented in box shapes, and then computes the distance between facilities for calculating the cost of transportation. Even though the genetic algorithm could provide the "best" result, there remain some limitations to this method.

The second criterion concerns the use of the space analysis method for site layout planning. Sadeghpour et al. (2006) utilized computer-aided tools to analyze the appropriate location of the facilities, and used simplified 2D visualization tools for analyzing their geometric relationships. The computer-aided tools approach has some similarity with what has been implemented for this research, in terms of developing a site representation. However, the major difference is that the tools they provide are in 2D, such that there could be some defects that are not represented or identified. El-Rayes et al. (2009) developed a dynamical site layout planning model for determining the best disposition in the construction site. They used the approximate dynamic programming modeling to analyze complex and multi-dimensional dynamic problems. However, there are limitations in these methods. For example, they modeled the construction site using only two-dimensional rectangles, approximated travel paths as the shortest distance between site facilities, and assumed that the site storage requirements were predetermined and static (El-Rayes et al., 2009).

In the third criterion, researchers did not only focus on the cost or transportation time. They studied other topics of site layout planning, such as the safety problem (Sanad et al., 2008). However, the safety problem is orientated differently, with the research concentrating on the environment around the construction site, such as noise pollution affecting the nearby hospital, suggesting that high noise-generating facilities should not set up next to hospitals.

Most previous studies focused on the transportation cost of site layout planning. Use of the mathematic model or algorithm for computing the least distance between facilities ignores important safety issues and accessibility problems. Although the computing method can generate the plan with paths of least distance or lowest transport cost the proposed paths might be difficult for operations in practice.

Therefore, this research aimed to provide a tool for easily testing the safety of paths to indicate the potential problems of the site layout plans.

3. RESEARCH GOALS

In this research, we developed an accessibility evaluation system for site layout planning. The system can facilitate the achievement of the following goals:

1. The proposed system can provide the simulation of transportation in an interactive virtual environment. Therefore the system can help users to identify the safety and accessibility problems under various situations and construction site layout.

2. The proposed system can support a visualized output of evaluation result to help users understand the unsafe areas of a site layout, and therefore to work out a better, lower cost, and safer plan.

3. The proposed system can enable users to import the map of the construction site and easily build up the virtual environment of the construction site for accessibility evaluation.

4. ACCESSIBILITY EVALUATION SYSTEM

We developed an accessibility evaluation system which consists of four modules. The transportation module simulates the dynamic motion of a tractor-trailer by using multi-body dynamics, a method commonly used for game physics. The site importing module enables users to generate the construction site environment precisely and efficiently from a 2D blueprint or image file of a construction site. The safety evaluation module is used to evaluate the accessibility by adding a multi-layer collision boundary to the transport unit, which detects collisions between the boundary of each layer and obstacles at the site. A formula was then developed for assessing the accessibility of each divided area at the site. The visualization module is used to render the virtual construction site, and also to simulate the transportation activities (i.e. detailed motions of the trailer) at the construction site.

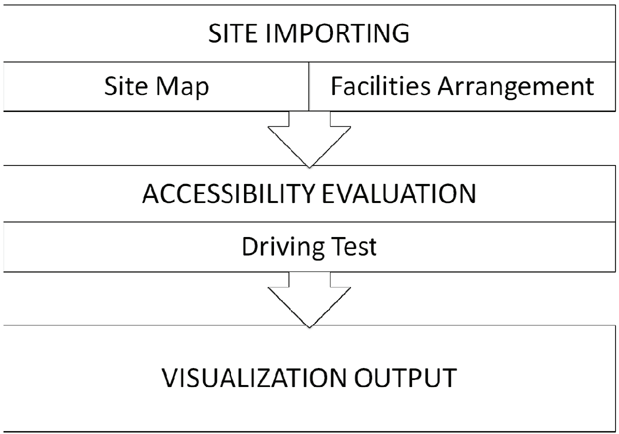

FIG. 1: System framework and information flow.

5. TRANSPORTATION MODULE

The transportation module aims to provide engineers with a real-time interactive system for operating the tractor-trailer in a virtual environment so that problems in the transport process can be discovered efficiently. We used a tractor-trailer, a commonly used transport vehicle in construction, as the transport unit. A tractor-trailer is composed of multiple rigid bodies and connections. Mathematical equations can be used to represent the relationships between the connections of rigid bodies, which are controlled by physical rules. We utilized the concept of multi-body dynamics, which are commonly used in simulating and modeling dynamic motions of articulated mechanisms or equipment (Hung and Kang, 2009). We also provide a mathematical model to compare with the developed model for verifying its feasibility.

5.1 Tractor-trailer model using multi-body dynamics

Multi-body dynamics is mainly used for computing physical feedback between multiple bodies in mutual contact with each other or connected to each other by joints (Erleben et al., 2005). The simulation of multi-body dynamics is generally composed of rigid body dynamics and constraints. By solving the equations of motion (which are used to describe the dynamical behavior of multi-body dynamics), the simulation can calculate the behaviors of a multi-body during each time integration (Hung and Kang, 2009).

The rigid body in the tractor-trailer is called the *actor* in this paper (for example, these steer the wheels of a car). The *joint* describes the motion in a pair of rigid bodies of the entire multi-body. The basic joint used in this paper is the *revolute joint*, which attach two actors by a hinge structure. It only has one degree of freedom of rotation, and removes other degree of freedom, so that the two actors can only rotate in one specific axis (Hung and Kang, 2009).

A tractor-trailer can be separated into two main parts: the tractor and trailer. The trailer connects a fill-up tank. To build up the tractor-trailer model, we need to analyze where the wheels, tractor, trailer and fill-up tank are, and connect them correctly. In this paper, the tractor-trailer is simulated as an eight-wheel truck, with four wheels on the tractor, and four wheels on the trailer. The construction of the tractor and trailer is similar; the wheels are connected to the steers by revolute joints, and the steers are connected to the main body of the truck by revolute joints. The only difference between the tractor and trailer is that the trailer is connected to the fill-up tank by another revolute joint. Fig. 1 shows the developed model represented by the symbols as defined in the previous research (Hung and Kang, 2009).

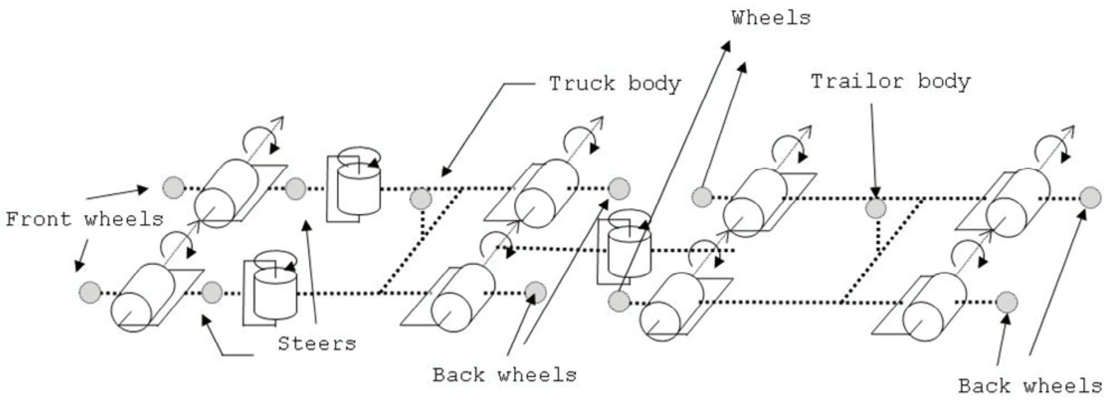

FIG. 2: The tractor-trailer model using multi-body dynamics.

5.2 Tractor-trailer mathematics model

The mathematical model of the tractor-trailer is constructed based on a previous study by Rouchon et al. (1993), and the following are the equations of the tractor-trailer model:

$$\dot{x}_0 = \cos(\theta_0)\, u_1 \tag{1}$$

$$\dot{y}_0 = \sin(\theta_0)\, u_1 \tag{2}$$

$$\dot{\varphi} = u_2 \tag{3}$$

$$\dot{\theta}_0 = \frac{1}{d_0}\tan(\varphi)\, u_1\ , \text{ for } i = 1, \dots\dots, n \tag{4}$$

$$\dot{\theta}_i = \frac{1}{d_i}\left(\prod_{j=1}^{i-1}\cos(\theta_{j-1} - \theta_j)\right)\sin(\theta_{i-1} - \theta_i)\, u_1 \tag{5}$$

In these equations, $(x_0, y_0, \varphi, \theta_0, \dots\dots, \theta_n) \in R2 \times (S1)_{n+2}$ is fixed. u_1, u_2 is the velocity control factor, and d represents the distance between trailers (Rouchon et al., 1993). Fig. 2 shows the representation of these variables. By these equations, we can derive the mathematical relationship between the tractor and trailer, and simulate the motions of the tractor-trailer. We used this approach to simulate the construction tractor-trailer for comparison with our developed model.

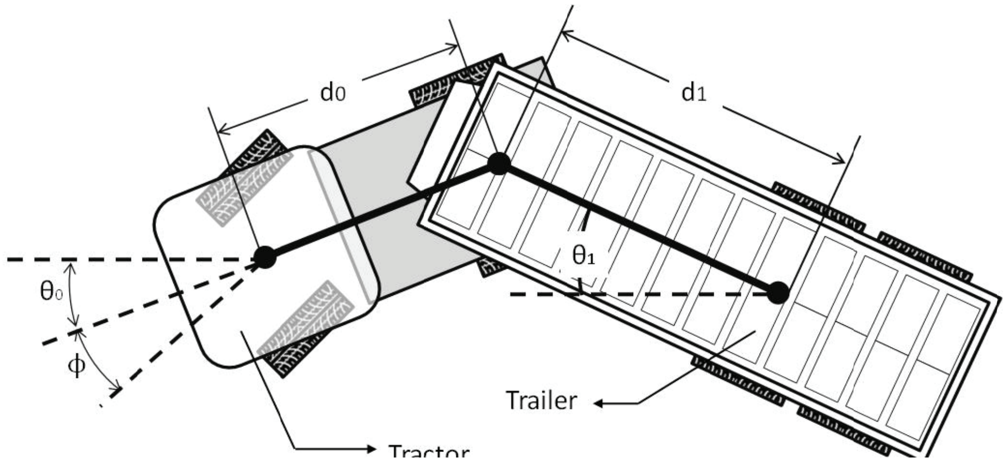

FIG. 3: Mathematical tractor-trailer model

5.3 Comparison between two models

The result of the mathematics model simulation is used for comparing with, and verifying the model developed in this research. We set the degree of turning and velocity to the same value in the two models during the simulation, so that the trajectory of the tractor-trailer would be a circle. We then checked the difference of two models under different degrees of turning and velocity.

5.3.1 Motion trajectory

In the Fig. 3, the velocity and turning degrees are set to the same value for the two models. One turning degree is set at 6°, and another at 12°. We discovered that the lower the turning degree, the greater the motion trajectory radius, with the difference and error between the two models becoming greater; the higher the turning degrees, the lower the motion trajectory, and the smaller the error between the two models.

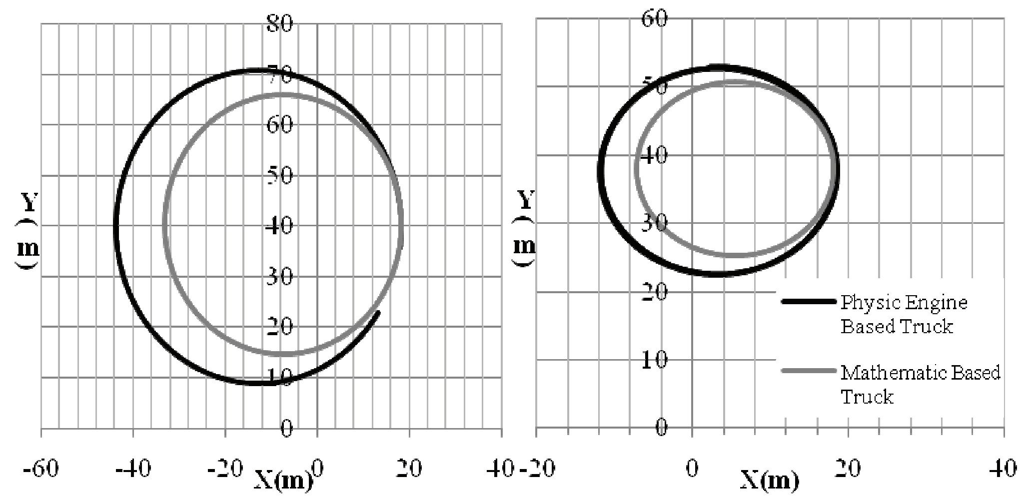

FIG. 4: The motion trajectory coordinates of two models: (a) in 6 degrees of turning and (b) 12 degrees of turning

5.3.2 Motion trajectory with time

In this section, we describe the addition of the time factor. The comparison result is shown in Fig. 4 and demonstrates that the error accumulates when the time increases. The possible reasons of error are discussed in the following section.

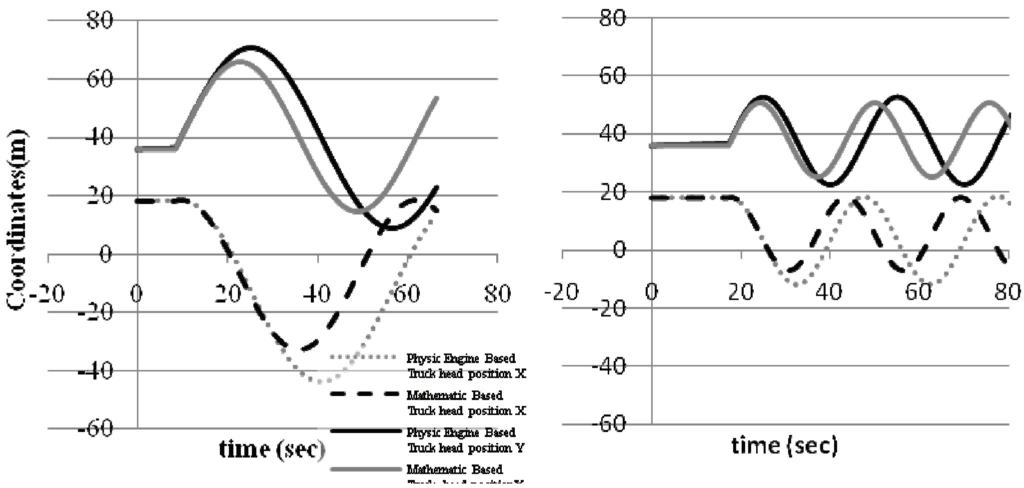

FIG. 5: The motion trajectory coordinates with time for two models: (a) in 6 degrees of turning and (b) 12 degrees of turning

5.3.3 Error discussion

The mathematics model equation is constructed in a very simplified manner. It ignores the friction between the wheels and the ground. However, the physics engine would enhance the detailed behavior between the tractor-trailer and the environment we constructed in the virtual world. Hence, there would be some differences between the two models. However, given that the extent of error is acceptable, we can conclude that the physics model is acting similarly to the mathematics model, and possibly even more accurately.

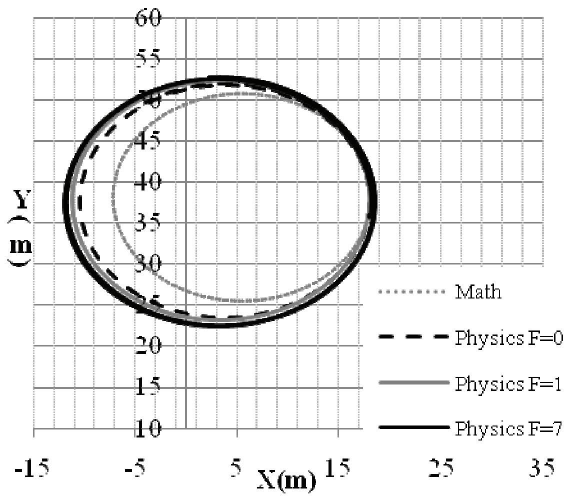

FIG. 6: The difference of motion trajectory with different friction setting of the physics model. F represents the friction coefficient setting between wheels and the ground.

6. SITE IMPORTING MODULE

To begin the evaluation, we have to generate the virtual environment of the construction site, which must be precise in terms of dimensions and include all possible obstacles along the transportation routes so that the safety test will be realistic. Since the facilities at the site are changeable during construction, the procedure of site environment generation must also be efficient and automatic. This can then allow engineers to test several layout plans in a fast manner.

To achieve this goal, we developed a site importing module which uses the 2D image of the site plan as the input data for generating the virtual construction site, including the functionality of collision checking. Users should manually modify the plan image to a specific scale and then highlight every obstacle with a specific color which will be recognized by the system. The system will render an obstacle in a default size at each highlighted location. Fig. 6 shows an example of modifying a 2D site plan. In this case, the site's dimension is about 400 meters in width and 300 meters in height. We set the resolution so that 1 pixel represented a square meter, such that the 2D plan would be converted to 400 pixels in width and 300 pixels in height, being a rather small scale for the modification process. During the modification process, only necessary boundaries are kept, while others are deleted. In the case of Fig. 6(b), there are permanent facilities such as the factory and office, an existing road, and walls or fences of the entire site.

Currently, the site importing module uses 2D images of the site plan as the input data, which does not have the height information. Therefore, the construction site is generated as a flat plane. This problem can be resolved if the site map includes height information, which will then enable the generation of the terrain geometry for 3D simulation.

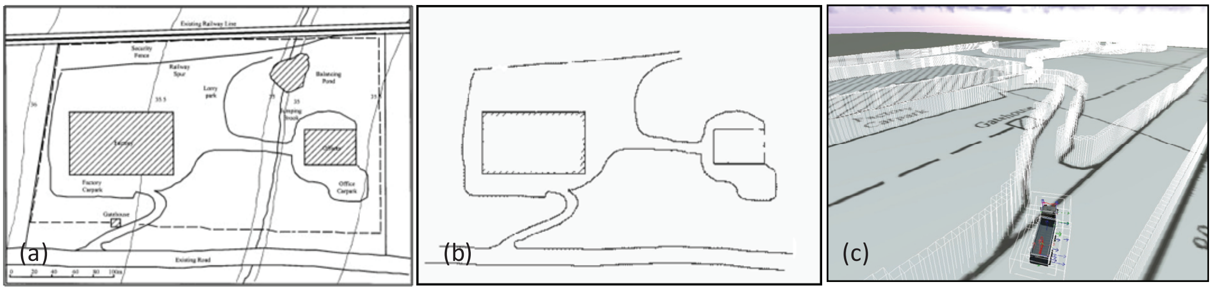

FIG. 7: Import necessary obstacles by modifying a 2D plan: (a) original site image; (b) processed image; and (c) virtual construction site environment built by the processed image.

7. ACCESSIBILITY EVALUATION MODULE

After the virtual construction environment is built, the accessibility evaluation can be commenced in the accessibility evaluation module. In this module, we assess the safety level of the transportation route numerically. We developed an index called *Safety Factor* (SF) to evaluate the site layout by integrating 3 different safety parameters. Detailed concepts relating to each safety parameter will be discussed in the following sections.

Safe driving range: We evaluated the safety range of driving path of transportation by adding a multi-layer collision boundary, called *Safety Bound*, to the transport unit, which detects any collision between the boundary of each layer and obstacles on the site. An illustration of Safety Bound is shown in Fig. 7(a).

Narrow level of route: If a route is narrow, there shall be obstacles near enough to the transport unit on both sides, namely the left and right side. By separating the multi-layer collision boundary into two parts, we can evaluate the level of narrowness of the route. An illustration of modified collision boundary is shown in Fig. 7(b).

Curvature of route: If a route is tortuous, more driving skills are required than driving on a straight one. Therefore we take the curvature of the route into consideration. *Instant curvature* of each segment of route will be evaluated while the transport unit is on the move.

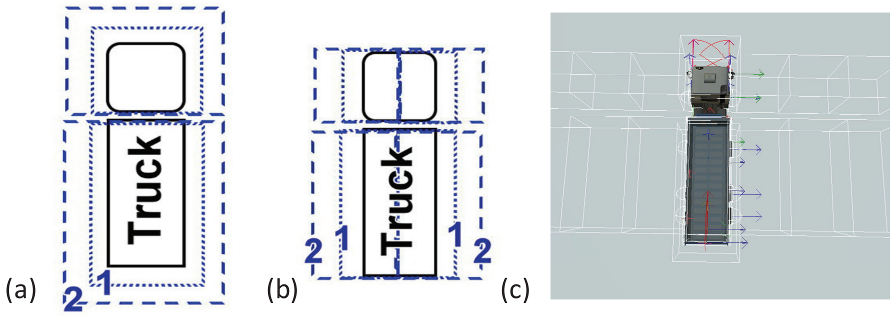

FIG. 8: The multi-layer collision boundary: (a) the safety bound; (b) the modified safety bound for narrow route; and (c) the safety bound and modified safety bound visualized in the virtual environment

The safety factor: To execute a route safety test, the user needs to drive the tractor-trailer through a desired route, and can repeat this several times in order to test several possible driving conditions. After that, each unit obstacle gains a safety score s_i), which implements three safety parameters by a formula we developed as shown in Equation 1, including curvature score c_i, narrow level n_i, and safety range score l_i. The symbol α is a magnifying factor for C. In this case, we have used 10 for C, because the value of curvature lies mostly in between $10^{-2}$and 10^{-1} and will be too small to bring out its significance. Firstly, there are three layers of safety bound, representing safety range score 3, 2 or 1, from inside to outside. Whenever an obstacle runs into safety bound, it will gain a safety range score according to the level it touches, and the maximum value will be kept. Otherwise, the *L* value will be zero. In other words, this obstacle will not make any contribution to the Safety Factor. The narrow level is recorded in the same manner and we classified it into four levels. Finally, the curvature score *C,* which is computed every instance during the test, will also be recorded whenever an obstacle contacts the safety bound.

To turn safety scores into practical usage for safety evaluation, users can select a certain resolution for summing up safety scores in an area. For example, if the chosen resolution is $10\text{m} \times 10\text{m}$, each divided area will gain a SF by summing up every safety score available within its 100m^2 scope as shown in Equation 2.

$$s_i = (\alpha \times c_i + 1) \times n_i \times l_i \tag{1}$$

$$SF = \sum_i s_i \tag{2}$$

8. VISUALIZATION MODULE

The *visualization module* was designed for visualizing the evaluation results. This module is to provide a direct and brief method for engineers to quickly check through the evaluation result based on visualization rather than interpretation of numerical data. After the evaluation, SF will be presented by the height of a rectangular column overlain for each divided area, as shown in Fig. 8 (a). Engineers can thus have a broad understanding of the result at a quick glance. In addition, the complete operated trajectory of the tractor-trailer will be stored and can be rendered again if required, as shown in Fig. 8 (b).

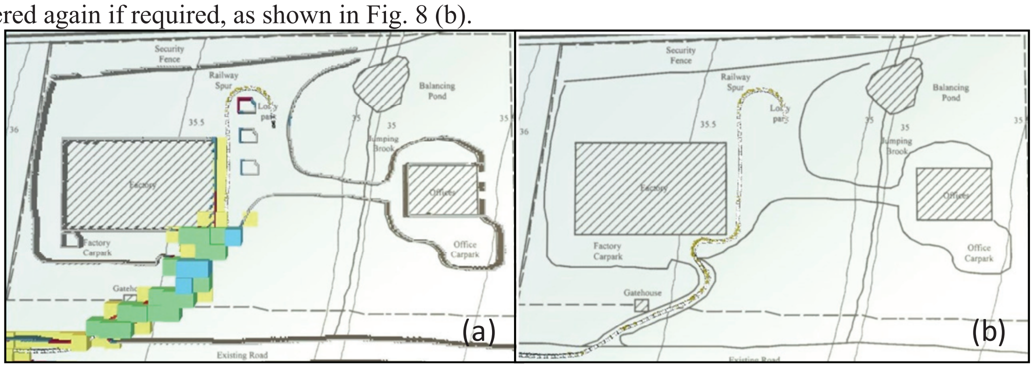

FIG. 9: Visualization of safety test result: (a) SF columns and (b) trajectory of the tractor-trailer

9. IMPLEMENTATION

We used a previous research's (Hunag and Kang, 2009) simulation engine, which combines two primary libraries: Microsoft XNA as the 3D graphic engine, and NVIDIA PhysX as the physics engine. A graphic engine, or a rendering engine, generates consecutive images from 3D models. A physics engine provides an approximate simulation of certain physical systems and the function of collision detection. NVIDIA PhysX primarily uses *position based dynamics* to simplify and approximate multi-body dynamics. Microsoft XNA supports the use of the XBox360 gamepad, which we take as an approach to increase interactive control of the virtual transport unit.

10. EXAMPLE CASE

A previous site planning study by Mawdesley et al. (2002) was based on a detailed real-life site example. This research leveraged on and utilized the data as an example case to test our system, as shown in Fig. 6 (a). There are permanent facilities in the construction site, such as factory, lorry park, and office. The goal of site planning is to determine the locations of temporary facilities, which includes reinforcement store, temporary office and batching plant. We modified the construction site plan, adding possible locations of temporary facilities according to its research result, as shown in Fig. 9(a) and 9(b). An evaluation was then executed to evaluate the feasibility of the proposed research result. The visualized result is shown in Fig. 9(c), which clearly indicates the low-safety locations which have higher risks of accidental damage.

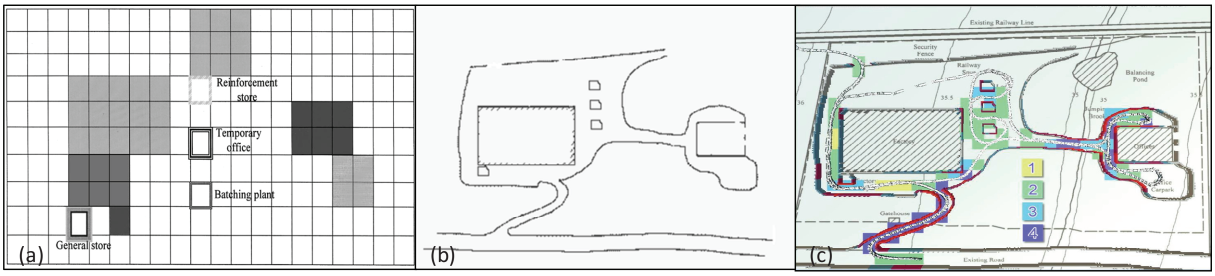

FIG. 10: Example case of evaluation process: (a) site plan map; (b) modified 2D image; and (c) visualized evaluating result

Fig. 10 shows the snapshots of the evaluation process using the developed system: (a) shows the tractor-trailer as it prepares to enter the site through the entrance; (b) is the *physics mode*, which visualizes the physically effective elements in the virtual environment; (c) is the combined view of the physics mode and normal mode. In this mode, we can clearly see that the obstacle changes its color when it comes into contact with different levels of the safety bound; (d) shows the visualization of the curvature score using yellow columns. The scores are relatively large in a sharp turn; (e) shows a wide area which will cause a zero narrow level; (f) is a return trip of the tested route; (g) is a top view of visualization result, whereby the color and height of the columns indicate the value of Safety Factor in each location; (h) is the *curvature mode* which shows curvature score columns; and (i) is *trajectory mode* which enables visualization of the trajectory of the tractor-trailer during the entire test.

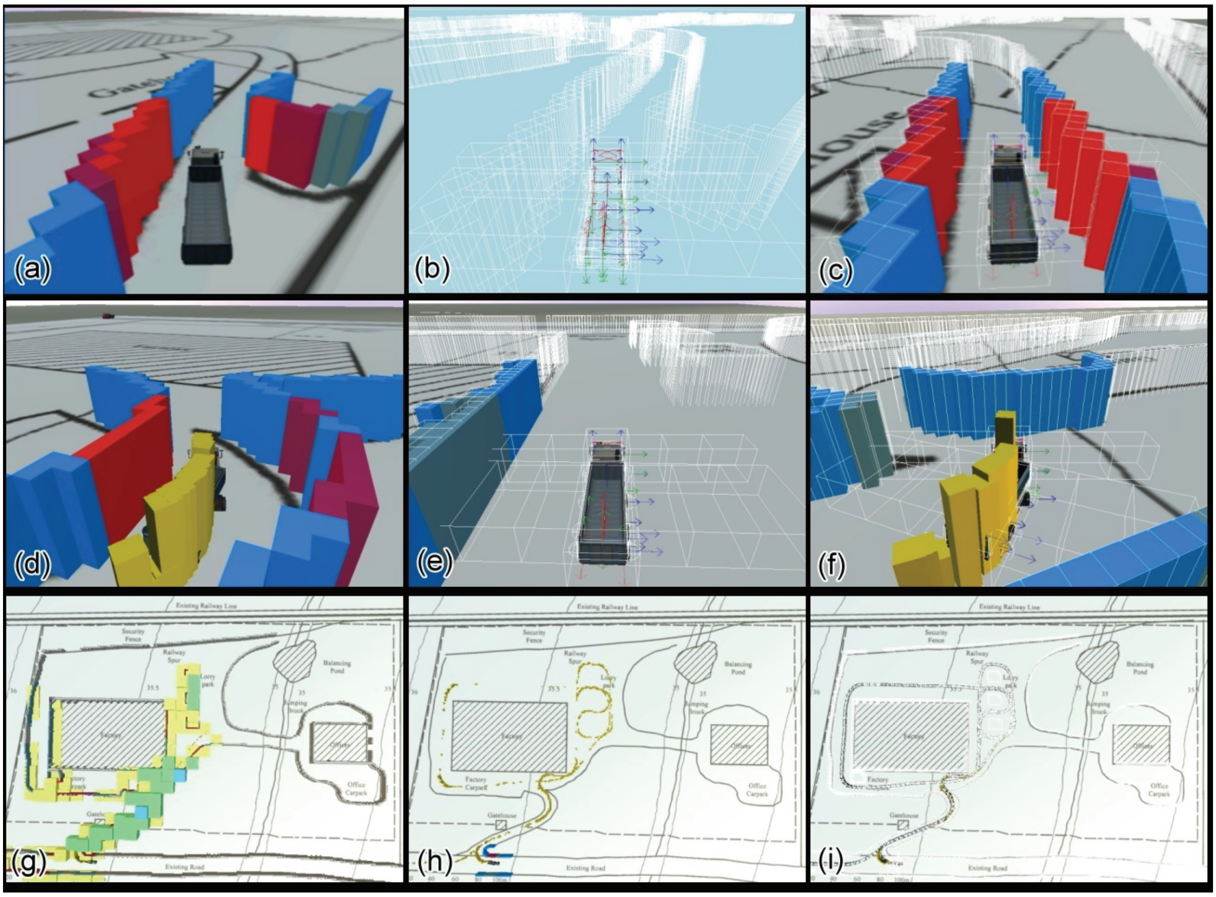

FIG. 11: Snapshots of the evaluation process in the developed system

11. CONCLUSION

This research demonstrated an innovative approach to solve the problems in traditional site planning procedure. We developed a 3D simulation platform for verifying the feasibility of site planning proposals. In this system, a physics engine is used to represent every motion and reaction of objects in the environment in order to approximate real world condition. In enabling work on different planning cases efficiently, a site importing module was designed. The visualization module features the advantages of virtual reality, providing engineers an easy way to check evaluation results and improve current site planning proposals. With proper site planning, construction projects will become safer, more efficient and cost-effective. The proposed method demonstrated in this research is suitable for achieving this goal.

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Research for Utilization of Spatial Information on WWW for Disaster Prevention by Mobile Phone

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ABSTRACT: *In Japan, there are many natural disasters, such as earthquake, typhoon, flood, and tsunami. In such a situation, in order to prevent the damage of disaster, various approaches are taken. As these result, it is recognized that the latest in-formation about disaster prevention are taken by citizens themselves is important recently. We paid attention to the information on WWW as a source of disaster prevention information. The disaster prevention information on homepages by public institution is not enough. On the other hand, huge information is updated by real time in the blog and bulletin board on WWW, and there is spatial information which has position information. In this research, the information about disaster prevention is extracted out of the space information by natural language processing, and proposed prototype system realizes that citizens receive the information easily. The system informs a user about a safe place or a dangerous place through a mobile phone. Furthermore, in consideration of a user with little information literacy like a child or elderly people, the technique for giving disaster prevention information only with vibration and the sound of a mobile phone is also examined.*

KEYWORDS*: Disaster Prevention, World Wide Web, Natural Language Processing*

1. INTRODUCTION

In Japan, there are many natural disasters, such as earthquake, typhoon, flood, and tsunami. Recently, serious damage has occurred by local heavy rain. In such a situation, in order to prevent the damage of disaster, various approaches are taken by technology.

As a problem of the present condition of disaster prevention, the limit of the provision in administration levels, such as a country and cities, towns and villages, is pointed out. For example, when a local heavy rain occurred, the situation of encountering damage is also generated during refuge by the directions from administration. As these result, it is recognized that the latest information about disaster prevention are taken by citizens themselves is important recently (DPRI 2001).

Therefore, we paid attention to the information on WWW as a source of disaster prevention information. The disaster prevention information provided from citizens on homepages by public institution is not enough. On the other hand, huge information is updated by real time in the blog and bulletin board on WWW, and there is spatial information which has position information. In this research, the information about disaster prevention is extracted out of the space information by natural language processing, and proposed prototype system realizes that citizens receive the information easily.

This paper describes two systems. One is a system which extracts the spatial information about disaster prevention from the information on WWW automatically. Another is a system for offering disaster prevention information by mobile phone.

2. SYSTEM FOR EXTRACTING SPATIAL INFORMATION ON WWW

2.1 Outline of the system

Services for providing spatial information like GPS (Global Positioning System) or GIS (Geographic Information System) are increasing recently. These services are easily used by a personal computer or a mobile phone. Technology, such as car navigation and pedestrian navigation, has already spread to the world. Thus, spatial information is indispensable to our life.

All things on the world where we live hold some space information including coordinates information. Therefore, using spatial information is very important for disaster prevention.

In this research, we paid attention to the information on WWW as a source of disaster prevention information. By searching web pages on WWW and using the spatial information included in the web page, it becomes possible to associate disaster prevention information on a map.

In this system, automatic search of WWW and the natural language processing realize acquisition extraction of disaster prevention information, and plot to the map of the information. Figure 1 shows the outline of the system.

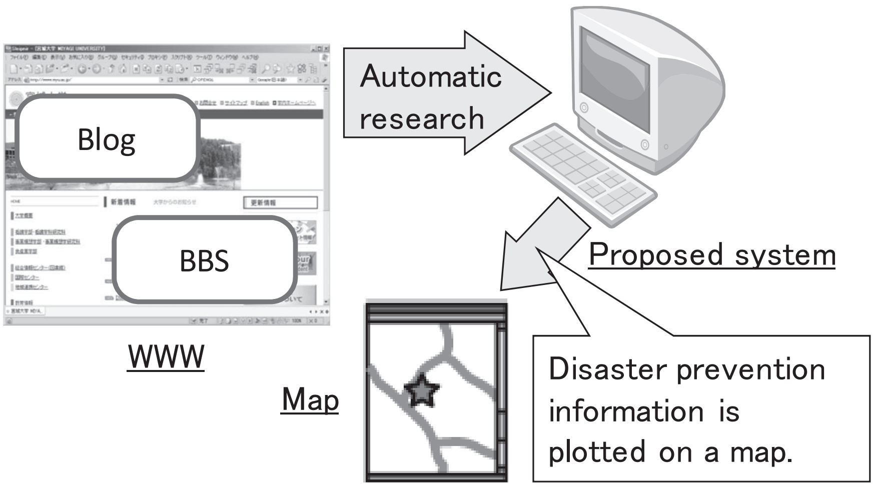

Fig. 1: Outline of the system

2.2 Details of the System

This system realizes automatic extraction of disaster prevention information by searching the WWW. This system consists of 6 processes: 1) Searching the WWW; 2) Analyzing HTML; 3) Extracting spatial information; 4) Extracting disaster prevention information; 5) Acquiring coordinates; and 6) Outputting spatial information. Details of each function will be explained below.

2.2.1 Searching WWW

In this process, search will be performed on the WWW, and web pages will be collected by tracing link information on the web pages. Process flow is as shown in Figure.2. Files in HTML form are acquired, but EXE files and PDF files are ignored for the following reasons:

- There is a low possibility of such files having address information
- Analysis requires a long time
- Much of the information is not analyzable

HTML files whose URL is a relative path are not acquired, because following links that are relative addresses can lead to repeated searches within the same site. The flow for automatic collection is as follows:

(1) Get a URL from a database

(2) Connect to the web page of the URL

(3) Acquire the file of the connected web page

(4) Extract link information from the acquired web page file

(5) Save the link information in a database

(6) Repeat the process from step (1)

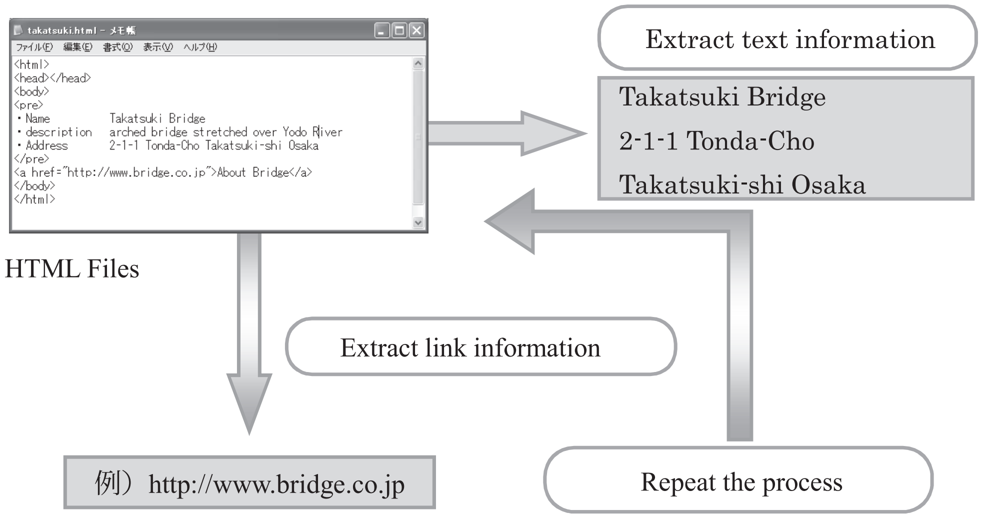

Fig. 2: Flow for Searching WWW

In this process, we must determine the web page to be used as a reference point. Selecting the reference point page affects the results of information gathering, so it is very important. In our research, we use the following criteria for selecting the web page to be used as a reference point.

- The page should have abundant link information
- The links of interest should be absolute paths
- There should be spatial information
- The page is in Japanese

2.2.2 Analyzing HTML

The web page gathered in the last process is analyzed with HTML document parsing software. In the analysis, URLs are acquired from link tags in the page. Furthermore, text data, except for tag information and image information, is acquired. The URLs and text data are saved in a database.

2.2.3 Extracting Spatial Information

In this process, address information is extracted from text data acquired in the last process. The extraction of spatial information is realized by morphological analysis. In our research, the Java "Sen" morphological analysis system is used. When morphological analysis determines “area” as the part of speech in the processed text, then spatial information is extracted.

However, morphological analysis may extract this spatial information in an imperfect form. For example, incomplete address information such as "Osaka" or "Takatsuki-shi" cannot be converted to exact coordinate information, so they cannot be used by this system. Rather, perfect address information is required, such as "2-1-1 Ryozenji-cho, Takatsuki-shi, OSAKA.” Such perfect address information can then be processed using pattern rules to locate the parts of speech in a text line. However, there is limitation in extraction of spatial information by using pattern rules with morphological analysis, and there are cases when incorrect spatial information is acquired. In order to solve this problem, address database that contains correct address will be used. In this research, “address postal code download service” offered by Japan Post will be used to produce address database. By checking if the spatial information extracted by using morphological analysis exists in the address database, incorrect address can be deleted. With this technique, the accuracy of spatial information acquisition can be improved.

2.2.4 Extracting disaster prevention information

In this process, disaster prevention information are extracted using morphological analysis similar to the acquisition of spatial information in the last process. Here, again, we use the Java "Sen" morphological analysis system to locate the appropriate part of speech and extract "nouns," "adjectives" and "verbs." Furthermore, disaster prevention information is acquired by making to match extracting information and a term list of disaster prevention.

2.2.5 Acquiring Coordinates

In this process, coordinate information is determined from the address information acquired by the process described in Section 2.2.3. Determination of coordinate information is realized through address matching (Figure 3) using a Comma Separated Value (CSV) address matching service (Sagara 2000) developed by the Center for Spatial Information Science at the University of Tokyo. By using this service, the address information is converted to coordinates, such as latitude and longitude, making it possible to supply attribute links to the object on a digital map.

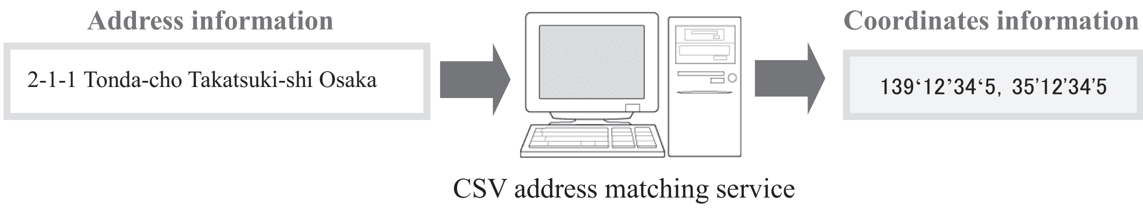

Fig. 3: Acquiring Coordinates by Using Address Matching

2.2.6 Outputting Spatial Information

In this process, the URL, address information, coordinate information and disaster prevention information collected by each of the previous processes are outputted as a file in XML form using XML-DOM technology. As XML data, the information can be read and modified easily. Figure 4 shows an example of collected spatial information output in XML form.

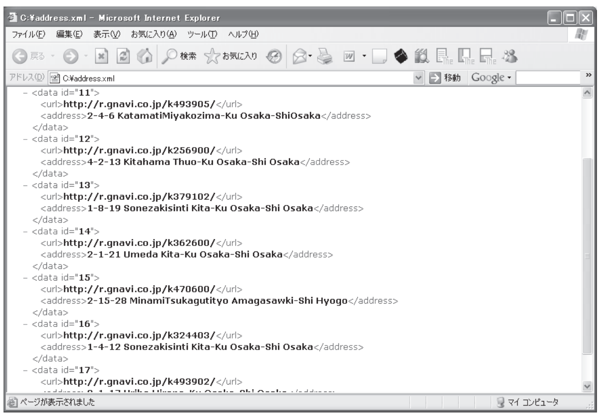

Fig. 4: Example of Attribute Information Output in XML

2.3 Application of the extracted spatial information to disaster prevention

The source of the spatial information which this system extracted is WWW. Therefore, the information by citizen which published by a blog and bbs, etc. is also acquirable. The information related to disaster prevention is included in that huge information. Furthermore, that information has the feature of having the real-time nature which can respond to a rapid change like local heavy rain.

Then, it becomes possible to plot the information of a dangerous position, a safe position, etc. on a map by using the disaster prevention information extracted by using this system, and the coordinate information which accompanies it.

In this research, the disaster prevention system to offer information by a mobile phone is proposed as an application system using the spatial information about that disaster prevention information. The following chapter explains the details of the system.

3. SYSTEM FOR OFFERING DISASTER PREVENTION INFORMATION BY MOBILE PHONE

3.1 Outline of the system

Services for providing spatial information like GPS or GIS are increasing recently, and these services are easily used by a personal computer or a mobile phone. The various researches and services (Sasaki 2004, Mizushima 2005, Osada 2004) which used space information especially with the mobile phone are offered. Moreover, atrocious crime and crime which aimed at the child occur frequently, and concern about crime prevention is increasing.

On the other hand, the disaster prevention map is exhibited as part of disaster measures by a country and cities, towns and villages. By using a disaster prevention map, citizen's awareness of disaster prevention can be raised more, and the damage caused by disaster can be decreased. However, in the existing disaster prevention map, a user needs to check a disaster prevention map, needs to memorize a dangerous position, and needs to be conscious of the position at emergency. So, in this research, we developed the system which tells users about danger when they approaches a dangerous position through a mobile phone. Figure 5 shows the outline of the system.

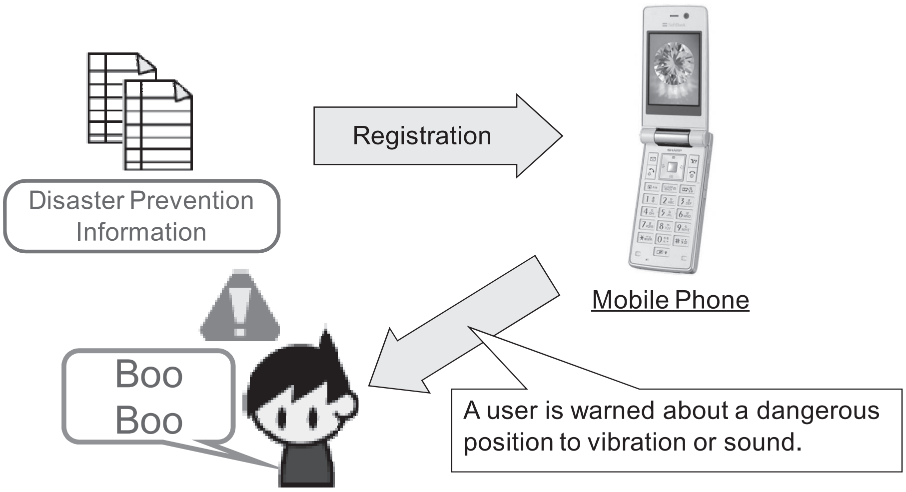

Fig. 5: Outline of the system

3.2 Details of the System

In this research, information of dangerous position is registered into a mobile phone, and when a user approaches a dangerous position, the mobile phone tells a dangerous position with vibration or sound. This system consists of 3 processes: 1) Acquisition of dangerous position information; 2) Registration of dangerous position information; 3) Notification of danger. Details of each function will be explained below.

3.2.1 Acquisition of dangerous position information

This function uses the disaster prevention information extracted by "System for extracting spatial information on WWW" explained in former chapter. The information to register serves as text data which consists of the disaster prevention information, including a landslide, rise of water, etc. and coordinate information corresponding to them.

Moreover, dangerous position information is also acquirable from the disaster prevention map currently exhibited on web. Since the disaster prevention map currently exhibited on web differs in form by the local governments or company, it is necessary to change it into text data. Then, dangerous position information is acquired by changing dangerous position and the kind of danger, such as a landslide and rise of water into text data and making the data read into a system.

3.2.2 Registration of dangerous position information

In this function, the dangerous position information acquired by the former function is registered into a mobile phone. The area in which a user is present is inputted, and the dangerous position information corresponding to the area is acquired and used.

3.2.3 Notification of danger

In this function, when a user approaches a dangerous position registered, the mobile phone tells a dangerous position with vibration or sound. By the warning of the danger, the user can look out for the surroundings and can raise awareness of disaster prevention. The method of warning is changed according to the kind of danger, and then the user can distinguish the kind of a risk in an instant.

In this system, a user's present location is acquired by GPS on a cellular phone. Then, according to the kind of danger, a mobile phone warns a user dangerous area of arbitrary radius from the center of a dangerous position.

By this function, the disaster prevention information on the real time from WWW is acquired at emergency, and refuge which avoided the dangerous position is realized. Moreover, it is thought that the usual awareness of disaster prevention by citizen improves. Furthermore, in order to give disaster prevention information only with vibration and the sound of a mobile phone, there is also an advantage which can be easily used for a user with little information literacy like children or elderly people.

4. CONCLUSION

In this paper we developed two systems. One is a system which extracts the spatial information about disaster prevention from the information on WWW automatically. Another is a system for offering disaster prevention information by mobile phone. By using these systems, a user can escape dangerous position and a user's awareness of disaster prevention can be raised.

As a problem of the present condition of this research, while the information on WWW has the features, like excelling in real-time nature, or there is much amount of information, the cautions about the accuracy of information are required. Moreover, though disaster prevention information was indicated to the blog or bbs, since it is necessary to indicate detailed address information along with it, the process in which a user can indicate address information easily.

Based on these problems, an improvement and an actual proof experiment of these systems are advanced from now on. Then, we will develop the systems which can acquire the information about disaster prevention more easily.

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IX. USER INTERFACE

Cross-sectional space design method in real-world and virtual-world that uses the contents oriented spatial model

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ABSTRACT: *We would like to propose a new spatial model, the "Contents Oriented Space", conforming to the physical senses experienced in the 3D virtual worlds, as well as providing an appealing spatial experience, and present a design methodology making use of this new model. There are three necessary conditions for such "Contents Oriented Space": 1. The contents are visible from the outside; 2. The contents are directly accessible; 3. By being directly accessible, the contents become "spatial". By applying such a spatial model, it is possible to realize the architectural space in the 3D virtual worlds, conforming to the physical senses experienced in such environment, at the same time providing an attractive spatial experience. It is a new design methodology, able to be widely applied in the architectural space design for the 3D virtual worlds in general. The experimental use of the proposed methodology in the physical interface expanding this design methodology is also currently on going.*

KEYWORDS*: Second Life, Virtual Worlds, Architecture, Design, Art, Google Earth*

1. INTRODUCTION

In this article, the new spatial model, the "Contents Oriented Space", conforming to the physical senses experienced in the 3D virtual worlds, as well as proving an appealing spatial experience unique to the virtual worlds, and the design methodology making use of such model will be proposed through looking at specific examples.

In recent years, 3D virtual worlds services have started to be popularized, as represented by Second Life[1]. In these services, 3D form making tools have been released, and space has, in a way, become "open source". Here, it is possible to freely create objects such as architectural buildings. Using this characteristic, many 3D virtual worlds architectural buildings modeling the real world space have been created. However, these models are not conforming to the physical senses experienced in the 3D virtual worlds, and have not been so attractive to the general users.

Although few in number, there exist unique cases that conform to the physical senses experienced in the 3D virtual worlds, created by nameless/anonymous "residents". Nevertheless, these are not created under a common design methodology, therefore, the degree of each completed work will depend on the ability of each user; and it lacks the possibility of reproduction.Also, it is not possible to say they provide the appealing spatial experience unique to the virtual worlds, equivalent to that experienced in architecture in the real world.

The "Contents Oriented Space" is a new architectural space model in the 3D virtual worlds designed by the authors, based on the aforementioned cases. The three necessary conditions of the "Contents Oriented Space" are as follows: 1. Contents are visible from the outside; 2. Contents are directly accessible; 3. By being directly accessible, the contents become "spatial". By applying this spatial model, it is possible to conform to the physical senses experienced in the 3D virtual worlds, as well as realize the architectural space in such environment, providing an attractive spatial experience. It is a new design methodology able to be widely applied in the general architectural space modeling in the 3D virtual worlds.

The authors have applied the "Contents Oriented Space" in the past, designing a large number of architectural/art works for the 3D virtual worlds [2][4][9][10].

2. EXISTING DESIGN METHODS

In this chapter, the existing architectural spatial design methods in the 3D virtual worlds will be examined by reviewing specific cases.

2.1 Imitation of Real World Architectural Buildings

Figure 1 shows an example of a real world architectural building imitated.

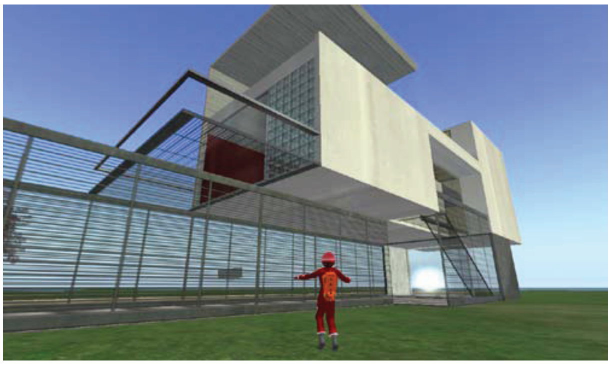

Figure 1. A Case of Real World Architectural Building being Imitated.

In this case, the measurements and forms of a real world building are faithfully reproduced, and on the surface, it seems to be same as the building in actual existence. However, in experiencing the space through the 3D virtual world body, or the avatar (the other self), the interior of the building feels smaller than in reality. It becomes a stressful space as you hit the walls or get stuck in the spatial gaps. For the users used to navigating freely in space, not being restricted to the collision checking in the 3D virtual worlds, the walls and ceilings imitating the real world building become obstacles preventing movement, resulting in a stressful experience. Furthermore, there is a fundamental difference in the physical senses, where the real world is experienced through the entire “body”, the 3D virtual worlds is experienced through an interface such as the personal computer.

2.2 Case of an Architectural Space Characteristic of 3D Virtual Worlds

In this section, examples of unique architectural space, conforming to the physical senses experienced in the 3D virtual worlds and which do not exist in the real world, will be shown. Further, these cases do not follow any common design guideline, and are individually created by each user (the “resident” of the 3D virtual worlds). Figure 2 shows a case of a foot bath in the 3D virtual worlds. Although it is not possible to reproduce a real-life foot bath in the 3D virtual worlds, where there is no sense of temperature, this 3D virtual world version of a foot bath is busy with many avatars. Since it is not an indoor foot bath, but an outdoor one, the group of avatars is easily seen and observed from afar.

Figure 2. Case of the Foot Bath.

The avatars that arrive can directly access the foot bath without being blocked by any wall or roof. The visibility and the accessibility from the outside is both high, and it has become a place convenient for avatars to gather.

Figure 3 is an example of an architectural space which is accessed through the search word "Freebies (a slang in Second Life, Freeware)". No wall or roof exists here, and all the contents (freeware) are revealed to the outside. The imitation of the real-life spatial element is completely eliminated, and the architectural space is constructed by means of the contents alone. Similar to the foot bath, the contents within the architectural space is easily observed from the outside, and they can be accessed directly without being obstructed by wall or roof. It is a highly convenient architectural space for the users hoping to attain the freeware.

Figure 3. Case of the Freebies.

Figure 4 is an example of an architectural space which is accessed through the search word "Door". Similar to the Freebies, no roof or wall exists, and the contents, in this case the doors, are revealed just as they are to the outside. Its visibility from the exterior and accessibility are both high, and it is an architectural space composed solely by the contents. These cases realize the spatial placement and access methods unique to the virtual worlds through the use of real world architectural elements. As a result, a site that is "popular" as well as "populated" is produced. In the next chapter, a new architectural methodology will be discussed, based on these cases conforming to the 3D virtual worlds physical senses.

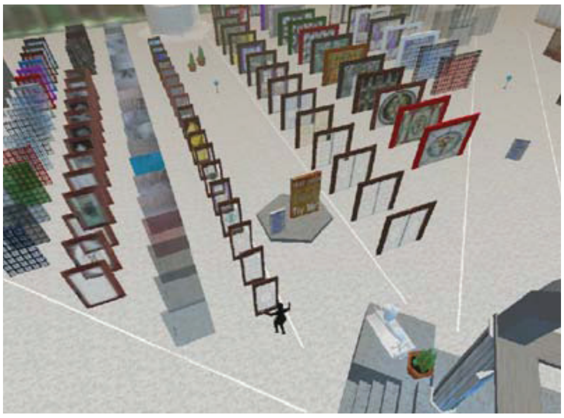

Figure 4. Case of the Door Shop.

3. INTRODUCTION

3.1 The Need for a New Design Methodology

Presently, no common methodology designing architectural space exists, that is appropriate for the 3D virtual worlds physical senses. In the case of section 2.2, space is created based on the ability of an individual user, and it is a "spontaneously generated" architectural space, so to speak. However, in the following few years, further popularization of 3D virtual worlds and its use in broader spectrum of fields is predicted[13]; and there are actual reports of increase in the number of its users. In the near future, the need for a common architectural space design methodology for the 3D virtual worlds to realize an appealing user experience is a must. Since the spontaneously generated example given in section 2.2 conforms to the physical senses experienced in the 3D virtual worlds, it is possible to come up with a new design methodology based on such a case.

In the next chapter, as a clue to proposing the above mentioned methodology, past cases of architectural space design methodology in the real world will be discussed.

3.2 Architectural Design Methodology in the Real World

Architects, including Kazuhiro Kojima, proposed the "Space Block" [16], which modeled the architectural space that generated spontaneously. They have applied it to a new architectural space design and have successfully realized the architectural space that inherits its original quality [Figure 5].

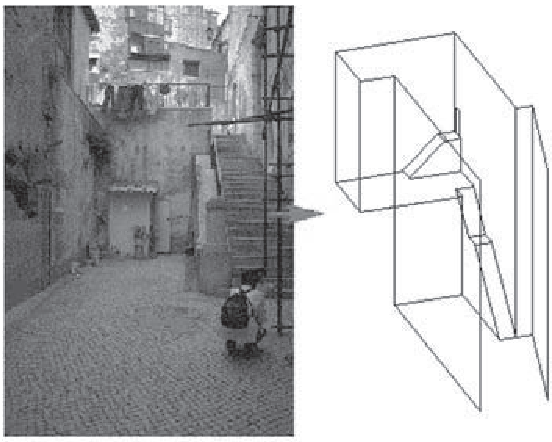

Figure 5. Conceptual Drawing of the "Space Block".

Although this "Space Block" is a result of sampling and layering various elements from the real world, it is not intended to reproduce the original space. The "Space Block" is utmost a "Space Model" as a means to achieve a goal, and different design techniques in order to realize a model in the actual design process have been explored. Of course, the design methodology that the "Space Block" is applied to aims at designing architectural space for the real world environment, therefore, it is not possible to use it in the 3D virtual worlds directly. However, the technique to apply to the newly designed architectural space in general, by modeling the cases of "spontaneously generated" architectural space, is effective even in the 3D virtual worlds.

By referring to this technique, it must be possible to create a new design methodology which can be widely applied to the architectural space in the 3D virtual worlds in general. At first, in the next section, architectural space of the real world environment and the case of section 2.2 will be each made into a model to be discussed.

3.3 Architectural Design Methodology in the Real World

Figure 6 shows the architectural space of the real world and the 3D virtual worlds as a model.

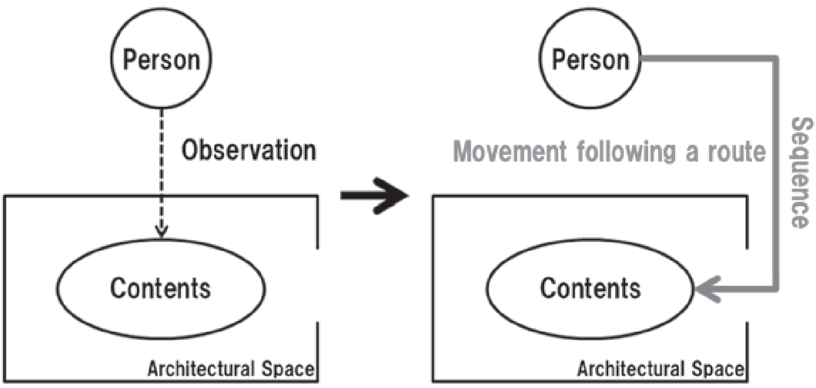

Figure 6. Model of Architectural Space in the Real World.

The architectural space of the real world is made up of physical elements such as the roof/wall. At this time, imagine the flow within the architectural space for a person to arrive at the contents. Assuming the contents to be books in this case, the books within the bookstore will be observed through the glass window (dotted line arrow). In the general sense, it is obviously not possible to "penetrate through" the window in order to move. The person will have to follow a roundabout route, go through the entrance in entering the bookstore, and arrive at the books (solid line arrow).

At this point, the continuous change in the scenery, the sequence, brought about by following the route, is the "spatial experience" perceived by a person; and it is one of the attractive elements the real world architectural space possesses. However, as already stated in section 2.1, it is not possible to recreate such "spatial experience" just by imitating and reproducing the real-life architectural space within the 3D virtual worlds.

Next, the case in section 2.2 is shown as a model in Figure 7.

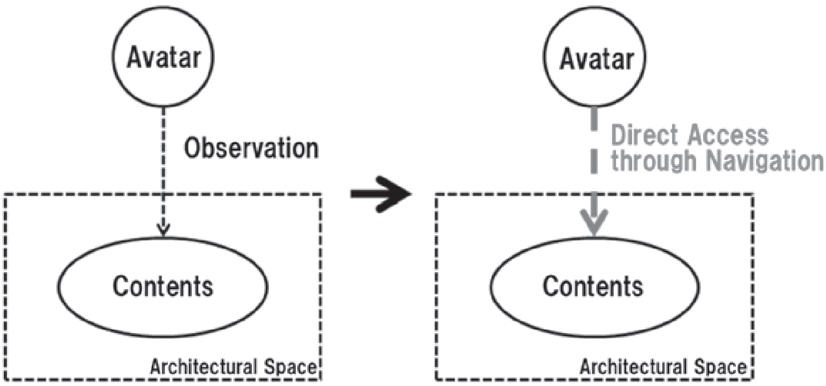

Figure 7. Architectural Space Model Unique to the 3D Virtual World.

In this model, the user/avatar observing the contents will directly access it following the navigation process (instantaneous transportation by a click). Even with the placement of a 3D object as a pretended architectural space in the surrounding area, it is possible to "penetrate" and arrive at the contents, if the collision check is off. This point conforms to the physical senses experienced in the 3D virtual worlds. However, unlike the model in Figure 6, the continuous change in the scenery, the sequence, does not exist; therefore, no "spatial experience" is generated.

In order to generate the appealing spatial experience "unique to the 3D virtual worlds" that is equivalent to that of the real world, it is necessary to produce the continuous change in scenery following a navigation process. In the next section, the behavior of Windows GUI will be discussed as a clue to this possibility.

3.4 "Making Contents into Space"

Figure 8 is a screen shot of Windows GUI behavior. The content is shown after double-clicking the folder within the window.

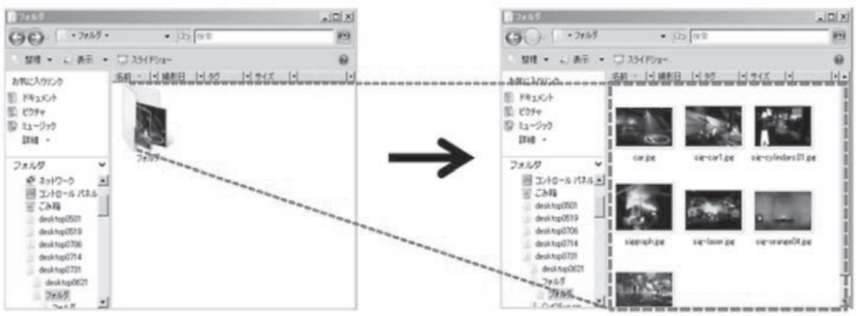

Figure 8. " Contents made into Space" in the Windows GUI

This behavior is reinterpreted in accordance with the model in Figure 7. When the user directly accesses (=double-clicking) the observed content (=folder icon), the substance of the content (=folder) is reached. The architectural space (=window) itself does not change, but the contents (=folder) is developed into a new architectural space (new window) where the scenery (= appearance) continuously changes. That is to say, through the user's direct accessing, the "contents are made into space", and the "change of scenery" are generated at the same time.

With this chain of events as a clue, the authors developed an architectural space model for the 3D virtual worlds, the "Contents Oriented Space", which conforms to the physical senses experienced in the 3D virtual worlds, and that which provides a more appealing "spatial experience". The next section will explain about this model.

3.5 The Model of the "Contents Oriented Space"

Figure 9 is a spatial model brought about by projecting the "contents made into space", stated in section 3.4, in the 3D virtual worlds.

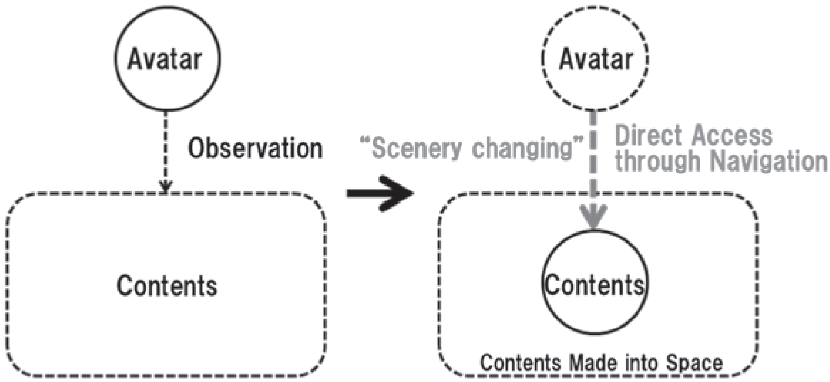

Figure 9. Spatial Model of "Contents Oriented Space"

In this model, the "contents is made into space" through the direct access of the avatar, and the contents understood to be just objects up until then, changes into the space enveloping the avatar. The change of scenery generated here is understood by the user to be the "spatial experience".

This model is based on the case stated in section 2.2, and conforms to the physical senses experienced in the 3D virtual worlds. Furthermore, it is also based on the concept of the "contents made into space" stated in section 3.4, and it provides the "spatial experience" equivalent to the architectural space of the real world. It is not necessary to state that this "spatial experience" is non-existent in the real world, but is unique to the 3D virtual worlds.

The authors named this spatial model the "Contents Oriented Space". The necessary conditions to realize this "Contents Oriented Space" is as follows:

- The Contents are visible from the outside.
- The Contents are directly accessible.
- By being directly accessible, the contents become "spatial".

This "Contents Oriented Space", similar to the Space Block stated in section 3.2, is utmost a "spatial model", and is a means to achieve a goal for an appealing architectural space design in the 3D virtual worlds. Accordingly, unlimited number of design techniques, applying the spatial model of the "Contents Oriented Space" and fulfilling the above mentioned conditions, are feasible. These design techniques accumulated will be established as the design methodology possible to be applied widely in the general architectural space design in the 3D virtual worlds.

In past group of works, the authors have tried various design techniques, where the spatial model of the "Contents Oriented Space" was applied. These works not only received high appraisal from users of the 3D virtual worlds, but won prizes and were selected for international festivals and conferences [3][4][5][6][7][8][9][10][11][12]. In the next chapter, specific architectural space design techniques for the 3D virtual worlds the authors used to apply and realize the "Contents Oriented Space", and its result will be discussed in reference to appropriate examples.

4. THE APPLICATION OF THE DESIGN METHODOLOGY AND ITS RESULT

In this chapter, the authors will discuss the results of applying the design methodology making use of the "Contents Oriented Space", while referring to past pieces of work. As stated in the previous chapter, the authors have accumulated and investigated these design techniques in expectation of the future, and aims to establish the common "architectural space design methodology for the 3D virtual worlds" in the end.

4.1 The "Archidemo"

The "Archidemo"[2][3][4][5] was held as an art collaboration with the aim to explore the possibility of architectural/city planning design in the 3D virtual worlds, with the cooperation of Nikkei Architecture (Nikkei BP), from the period of August 2007 to January 2008. During this period, total of 24 researchers, creators, and students participated. This section will present the collaboration with the science fiction writer, Hirotaka Tobi, the "Numbers Beach", as an example of a work applying the "Contents Oriented Space" concept. This work uses the theme from Tobi's work, "Grand Vacance".

Figure 10. "Costa Del Numero"1

The entire space of this "Costa Del Numero" is made up of an all-sky periphery panoramic image of a business district, covered by a texture-mapped giant cube (64m square).Within its interior, several small cubes (16m square) are floating. The small cubes have a group of all-sky periphery panoramic images of a resort hotel textured-mapped; and furthermore, since the outward polygon is made transparent, the panoramic image (contents) within is visible from the outside [Figure 10].

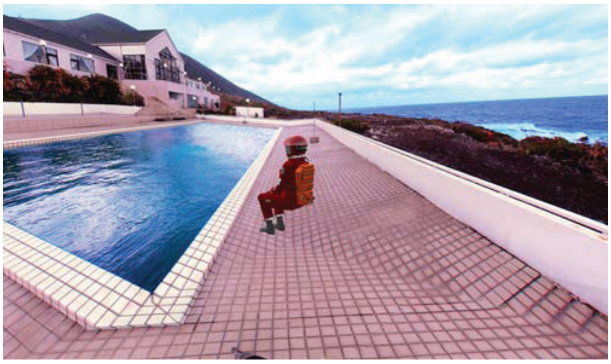

Figure 11. "Costa Del Numero"2

When the user clicks on the small cubes, the user is teleported (directly accessing) into each interior space [Figure 11]. In this instance, the small cubes, recognized as the contents up until then, unfolds into an all-sky periphery panoramic image (contents made into space) surrounding the avatar.At this stage, the user will be virtually experiencing the architectural space of the resort hotel. By repeating the clicking process, it is possible to move between different contents one after another to experience its space.

By applying the spatial model of the "contents oriented space" in such a way, it was possible to achieve both a stress-free spatial movement and a dynamic spatial experience.

4.2 3D Image Database of Oscar Niemeyer

The year 2008 was the centennial year of the start of the Japan- Brazil diplomatic relationship, and the "Japan-Brazil Exchange Year Project" (Niappaku 2008) was carried out by the Foreign Ministry and the Japan-Brazil Exchange Year Executive Committee. The author created the "3D Image Database of Oscar Niemeyer" [9] as part of its official project, the "Japan-Brazil Architectural/City Planning Internet Archives". This project entailed reconstructing a group of images within the internet relating to Oscar Niemeyer, the representing architect of Brazil, as an image database possible to be operated and viewed intuitively. This work was exhibited at the "File-Electronic Language International Festival Sao Paulo 2008" held in Sao Paolo.

In the first state, group of cubes (2m square), with images related to Oscar Niemeyer texture-mapped, float in space[Figure 12]. As you can see from the figure, the image (contents) of each cube can be viewed from the outside.

Figure 12. "3D Image Database of Oscar Niemeyer" 1

When the user clicks on the cube of choice, the image box (6mx8m) held within the cube appears, and approaches the avatar quickly (within 1 second), and it surrounds the avatar [Figure 13]. In this piece of work, by the contents approaching (direct access) the avatar, the concept of the "contents made into space" is achieved. Furthermore, when the image box is clicked on, the website where the contents appear will pop up and be shown.

Figure 13. "3D Image Database of Oscar Niemeyer" 2

In this way, by applying the space model of the "Contents Oriented Space", it was possible to realize both a stress-free interface for the viewing of image/web contents, and an appealing spatial experience.

4.3 SIGGRAPH Archive in Second Life

"SIGGRAPH Archive in Second Life" is the past group of venue photographs of ACM SIGGRAPH Emerging Technology/Art Gallery, reconstructed into an image database space which is possible to be operated and viewed intuitively. This piece of work was exhibited at the Art Gallery of "SIGGRAPH Asia 2008" held in Singapore in the year 2008. In the first state, the plates with different years are floating in space.When the plate of choice is clicked on, a group of image boxes (6m x 8m), with the venue photographs of each year texture-mapped within, spurts out into space and unfolds extensively [Figure 14].

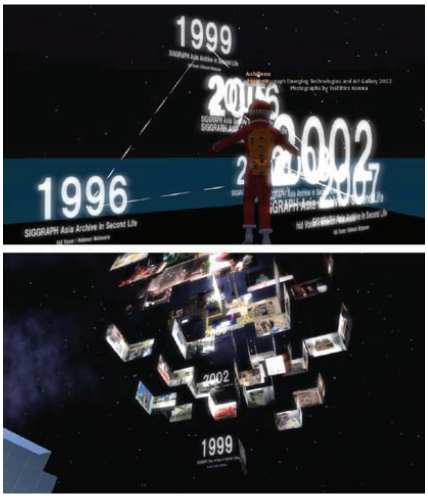

Figure 14. “SIGGRAPH Archive in Second Life”1

Since the outward polygon alone is made transparent, the photographs (contents) within are visible from the outside.When the image box is clicked on, the user will be teleported (directly accessing) into each interior space [Figure 15]. In this instance, the image box, recognized as the contents up until then, covers the entire field of view, and unfolds around the avatar as a form recognizable as space (contents made into space).

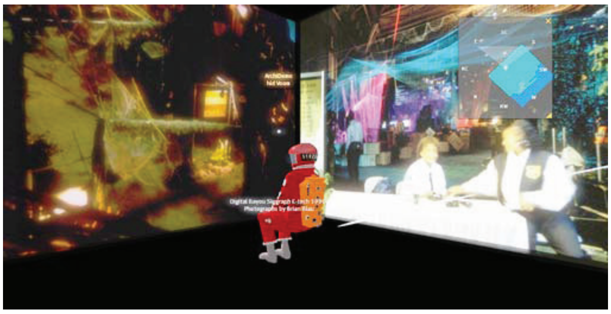

Figure 15. “SIGGRAPH Archive in Second Life”2

In this way, by applying the space model of the “Contents Oriented Space”, it was possible to realize both a stress-free interface for the viewing of the photo contents, and appealing spatial experience.

5. CONCLUSION

Through the activities starting with the group of projects shown in Chapter 4, the design methodology of the “Contents Oriented Space” has begun to be substantial. From seeing the facts that the past group of works have won prizes and were recognized in international festivals and conferences, as well as receiving constant appraisal, it is possible to consider our design methodology to have validity.

Although the spatial model, “Contents Oriented Space”, discussed in this article was developed with the most suitable 3D virtual worlds platforms available at present, the Second Life, as the basis, it is possible to apply in other 3D virtual worlds in general that have similar characteristics. From now on, we plan to further enhance the design methodology by means of the actual use of the physical interface in experiments, as stated in Chapter 5, as well as carry out activities in platforms other than Second Life.

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A SPATIAL CONTEXT GESTURE INTERFACE

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ABSTRACT: *The paper proposes a spatial context gesture interface. The interface recognizes a system action (e.g. commands) by integrating gesture information with additional context information within a probabilistic framework. Two ontologies of spatial contexts are introduced based on the spatial information of gestures: gesture volume and gesture target. Prototype applications are developed using a smart environment scenario that a user can interact with digital information embedded to physical objects using gestures.*

KEYWORDS*: Spatial Context, Gesture Interface, Gesture Recognition*

1. INTRODUCTION

With advances in sensor and network technologies, physical environments are getting embedded with computer systems [CFBS97]. In recent years many researchers have recognized the value of such new computing environments and have suggested computing paradigms such as mobile computing, ubiquitous computing, and wearable computing. They focus on understanding human capability and maximizing the opportunity to access digital information regardless of time and location.

Various applications have driven the research of a large scientific community including computer vision, human-computer interaction, and computer graphics. For instance, gesture is used as a means of pointer and manipulator in different displays namely desktop monitors, tabletop displays, large wall displays, and immersive VR displays. Gesture is also applied to command execution aiming for complete eyes-free interaction in mobile and wearable computing domains [BLB+03]. Although a lot of solid research has been done, it has been mainly designed to test the system performance for gesture recognition. Little is applied to the actual use. Therefore, the success of current gesture interfaces has been restricted to relatively controlled environments requiring a special hardware setup and well-defined gestures. Their practical utility has mostly been ad-hoc and not presented within a generative design framework.

Another challenge of gesture recognition is that in intelligent environments with a large number of devices a large number of interactions are possible as well. There are, however, only a limited number of simple, useful gestures. This is because gestures that can easily be performed and remembered are preferred by most users. Additional context information can be used to resolve ambiguous recognition, since some gestures are more likely within a specific context. E.g. it is more likely the user wishes to turn on the lights if it is dark outside. Furthermore, gestures can be interpreted differently if they are performed in a different context. Thus, gestures can be reused, which reduces the total number of gestures to be recognized.

This paper presents a spatial context-aware gesture interface that improves the usability of gesture-based inputs by combining gesture information with additional context information. There is a large amount of research dedicated to studying the use of context information in human computer interaction. Obviously, it is a far-reaching and difficult goal to define the general application of the context information to the design of gesture interfaces. Here, the paper focuses on specific context information which is related to spatial objects of gestures (locations and objects of a gesture) easily featured together with 3D spatial gestures. We call this particular context information spatial context. Using spatial contexts, we aim to reduce the recognition error and improve the usability of gestures. In this system, the user performs a 3D gesture, which is typically performed in 3D space. 3D spatial gesture preserves a certain spatial relationship between gesture and the environment where the gesture occurs [Kwo07a].

This paper is structured as follows. In the following chapter some related work about gesture recognition techniques and context aware systems is resumed. After a short overview of the architecture of context model, we present the spatial context model which supports registration and selection of spatial contexts. Then it explains how a gestural command is recognized using the selected spatial contexts. Dynamic Bayesian Network (DBN) is developed to integrate the result of the gesture recognizer with other context information for command recognition. We developed two prototype applications which use 3D spatial gestures to control functions embedded with physical objects.

2. RELATED WORK

Deictic gestures are particularly important for spatial inputs requiring information about the position and spatial location of the user when the gesture is performed. Spatial inputs have been used in different applications. Bolt presented the Put that there [Bol80] where users can interact with an object on a large screen display through pointing. Similarly, virtual reality systems often enable users to point and select the virtual objects using gestures. Recently, spatial inputs have been widely applied to applications for smart environments. With the advance of sensor and network technologies, our environments are designed and programmed to understand gestures automatically to a certain degree. These smart environments understand the user's intention, and provide a set of programmed functions such as turning on/off lights and controlling temperature.

In this smart home scenario, spatial information plays an important role in understanding the gesture correctly. Wilson [WS03] presented a gesture interface where users can interact with the smart environment using gestures (selecting and controlling appliances through pointing, turning it on/off and moving the volume up/down).

Spatial inputs are also employed to facilitate the use of context in HCI. "Context is the set of environmental states and settings that either determines an application's behavior or in which an application event occurs and is interesting to the user" [CK00]. Dey et al. [DHB+04] presented CAPpella (context-aware prototyping environment) designed with the concept of programming by demonstration. In this system, end-users can program desired context-aware behaviors (situation and associated action) by demonstrating them to the system and by annotating the relevant portions of the demonstration.

Jih el al. [JHT06] developed a context-aware elderly care system for smart environments. The system interacts with the elder through a wide variety of appliances for data gathering and information presentation. The system tracks the location and specific activities of the elder through sensors, such as pressure-sensitive floors, cameras, bio-sensors, and smart furniture. The status of the elder is monitored and used to provide appropriate system actions. For example, when sensing that the elder has fallen asleep, the system switches the telephone into voice mail mode, and informs and plays back any incoming messages when the elder awakens.

Chen and Kotz [CK00] describe two ways of using context: active and passive context awareness. In an active context aware system the application adapts automatically to the discovered context whereas in a passive context aware system the application only presents the context information to the user or saves it for later retrieval. In this paper, we build an active context aware system. We introduce the novel concept of gesture target and gesture volume focusing on contextual information such as spatial user context, temporal context and context history. The system supports context sensitive command recognition, where a command is a combination of a gesture and related context, such as an object the user is pointing at. The context includes the position of the user, the pointed object, daytime and previous commands, but more context information could be added easily due to the extensible system design of a DBN.

3. OVERVIEW

The proposed system was developed based on the design framework for a 3D spatial gesture interface. The framework supports both gesture acquisition and the modeling of the physical and expressive characteristics that are unique to an individual gesture [Kwo07a]. This chapter describes the hardware that acquires the 3D spatial gesture, the software that recognizes the acquired gesture information with the spatial context information.

3.1 HARDWARE OVERVIEW

Gesture acquisition is performed both in hardware and software components. The key idea is to use both visual and body sensors to get optimal gesture features for robust gesture recognition and support various requests of target applications such as 3D object manipulation and scene navigation. Figure 2 shows an overview of the gesture acquisition system. When a user performs gestures, the system acquires the gestures through body sensors and visual sensors. Different body sensors are integrated into a gesture input device that the user attaches to the body or holds in the hand. The device is equipped with a micro-controller for collecting sensor data and Bluetooth wireless technology for transmitting the measurements to a computer. The current setup uses two machines: one for the acquisition system and one for the application. Necessary data is transmitted via the network between two computers. The acquisition receives data from the input device via Bluetooth and from video cameras via Firewire ports. We use the Java Communications API package to develop a module to receive the transmitted body sensor data. The acquisition module for visual sensors tracks the positions of LEDs on the captured image frames and computes 3D positions. The acquisition machine runs small functional units called filters that process corresponding sensor data in a specific way (converting it to another data type)..

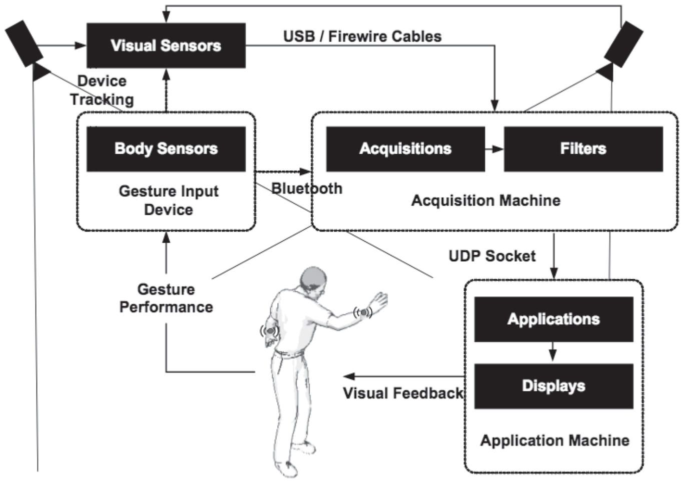

Fig. 2: Overview of the hardware and software framework for gesture acquisition.

3.2 SOFTWARE OVERVIEW

As illustrated in Figure 3, the overall framework of our spatial context gesture interface for two major tasks: spatial context modeling and command interpretation. Acquired sensor data is forwarded from the gesture acquisition module. The spatial context model handles the abstraction and registration of the context data using two types of spatial objects: gesture volume and target. The current status of spatial objects is traced with the performed gestures. The spatial context model provides an efficient way of extracting and retrieving the gesture volume and target. Therefore, system developers can register their own spatial objects and test different configurations in their applications. The command interpretation is accomplished by combining a list of the current context values and the recognized gestures using the gesture model.

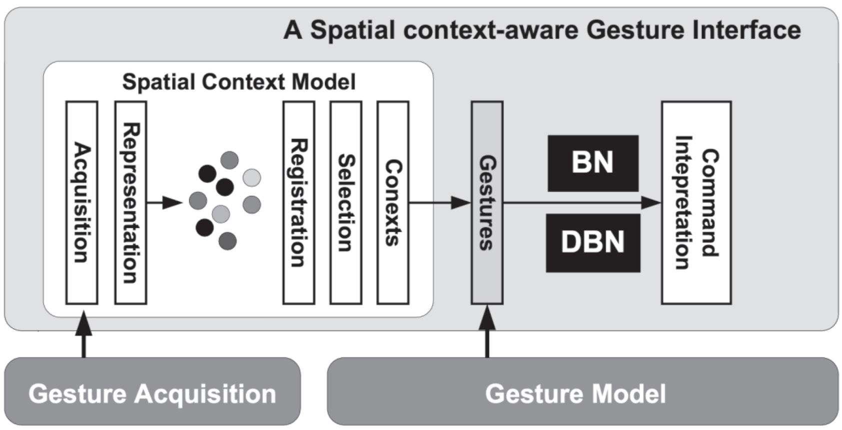

Fig. 3: An overview of a context-aware 3D spatial gesture interface.

4. . SPATIAL CONTEXT OBJECTS

In general, the collection of implicit contextual information through available resources is a major challenge in the development of context-aware applications. For the application designer, it is important to decide what context information is relevant to the applications and then test it. The ultimate goal is to improve the usability of the application by optimizing the context information. We focus on the problem of defining the contextual information as it relates to specific gesture information called the spatial information.

4.1 Gesture Targets and Volumes

Spatial information is one of the four aspects of gesture as proposed by Hummels and Stappers [HS98a]. 3D spatial gestures usually relate to objects and locations. The relevance of objects and locations is a key idea in using context information for 3D spatial gesture interfaces. Based on this observation, we defined two types of spatial objects for 3D spatial gesture: gesture targets and gesture volumes.

Gesture targets are physical objects which users can select by moving a gesture input device close to an object or pointing it at an object. They can be physical or virtual objects. Gesture volumes are interaction zones where a set of gestures are planned for the application. Using gesture volumes and targets, we can define gesture candidates during gesture recognition. Therefore, we can minimize the computational complexity by only processing associated gestures within the current contexts.

For instance, kitchen space can be defined as gesture volume and the individual components in the kitchen, like a microwave and a refrigerator, can be defined as the gesture target. During the system design, application developers define gesture targets and volumes while considering their design policy about using gestures with the related locations and objects.

4.2 Registration

In our framework, spatial context objects are represented as a three-dimensional Gaussian blob with mean μ and covariance Σ as the center and shape of the object as shown in Figure 3. These Gaussian blobs are modeled and registered based on a series of 3D positions that users provide during the system setup. In Figure 4, a user is registering the 3D position of an object. A user simply locates the device at the position of the object, and registers it by pressing one of the pressure buttons while holding the device on the object's position. The bright color LED of the device allows accurate tracking in various background conditions. We call this direct registration touching. Touching enables users to register the position of the object from the actual position of the object. However, this technique is only available when the object can be reached by the hand inside of the camera volume (i.e. the object should be visible on both camera images).

We use another technique called pointing as proposed in Wilson [WS03]. This pointing technique allows registration when the target objects are outside of the camera volume or when the users cannot reach the position of the target object. For instance, as shown in Figure 5, when a user wants to register objects on the wall that can't be captured with the current camera setup, then the user can use this pointing technique.

The main purpose is to find the object location by computing the intersection of the multiple pointing rays $\mathbf{w_i}$ from different locations$\mathbf{p_i}$. We can find the covariance of the object μ by solving the linear system of equations via least squares which can be represented as:

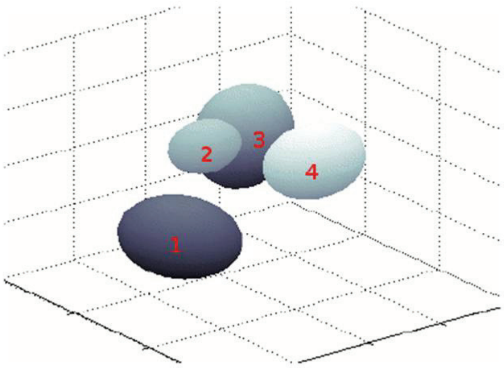

Fig. 3: Representation of spatial objects. Each object is modeled as a 3D Gaussian distribution with mean μ and covariance matrix $\sum$ with a center point c_j, a distance d_j and a variance σ_j^2

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Fig. 4: Registering an object using touching. A user is locating a gesture input device (mWire) at the location of the object and registering the positional data to the system by pressing the button of the device.

$$\mathbf{p_i} + s_i\mathbf{w_i} = \mu$$

where $\mathbf{p_i}$ is the device position and w_i is the pointing ray for the *i*th pointing observation, and the distances s_i to the object are unknown.

The covariance matrix Σ can be computed by summing up the spread of the differences between calculated target location μ and its estimates $\mathbf{p_i} + s_i\mathbf{d_i}$ and adding some minimal covariance $\sum_0$ i.e.,

$$\sum = \sum_0 + (p_i + s_i d_i - \mu)(p_i + s_i d_i - \mu)^T$$

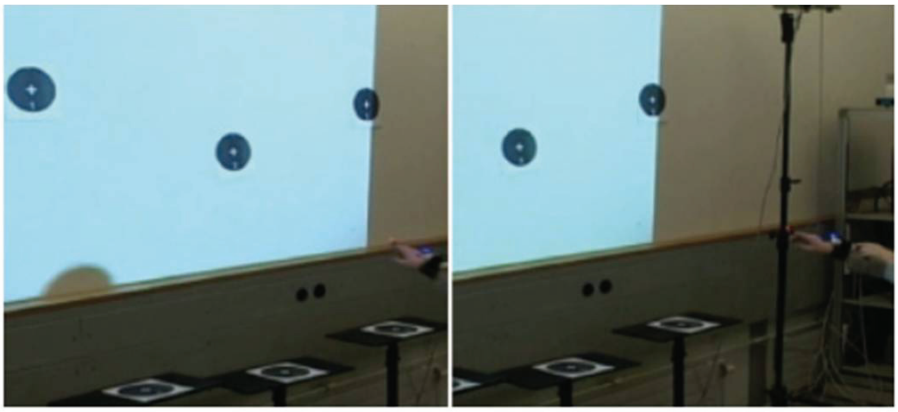

Fig. 5: Registering a spatial object using pointing. A user is performing multiple pointing gestures to the same object from different locations

The pointing direction should be accurate for increased pointing accuracy. Currently, we use the prototype input device by connecting two LEDs (one n the index finger and another on the wrist). Given these two 3D positions, we compute a pointing direction. The accuracy in pointing highly depends on the accuracy of the tracking of the two LED positions. This method is improved using different input mechanisms. For instance, we can use a 6-DOF input device like a 3D mouse that can provide more accurate orientation information even though it is not a wireless device. In addition, we can derive the orientation of the device by combining the digital compass and accelerometers.

4.3 Selection

When the spatial context objects are registered to the system, we then consider the task of object selection. The basic idea is to find objects which are close to the place where users perform 3D spatial gestures. Since each gesture object is modeled as a 3D Gaussian blob as explained earlier, the result of selection is the probability computed from the geometrical relationship between an object and a 3D spatial gesture.

Similar to the registration, there are two different selection techniques: *touching and pointing* depending on whether the object is reached by the input device. As the name suggests, touching selects an object by bringing the input device near the object that the user wishes to interact with.

The system determines which object is closest to the position where the 3D spatial gesture is performed. Each object needs to be modeled as a 3D Gaussian blob with mean μi and covariance $\sum_i$. A simple technique is to compute the likelihood l_i of selecting object *i* and evaluating the Gaussian distribution at the point. The likelihood of pointing at target *i* is

$$l_i = g(\mathbf{p}, \mu_i, \textstyle\sum_i)$$

where $g(x,\mu, \sum)$ is the probability density function of the multivariate normal distribution, $\mathbf{p}$ is the 3D position of the device.

For pointing selection, we evaluate the Gaussian distribution at the point that is the same distance away as the hand is from the target and along the ray cast by the hand. The likelihood of pointing at an object *i* is given by:

$$l_i = g(\mathbf{p} + |\mu_i - \mathbf{p}|\mathbf{d}, \mu_i, \textstyle\sum_i)$$

where p is the position of the hand and w is the ray along the hand.

4.4 System Action Interpretation using BN

In the previous section, we defined spatial context objects (gesture volumes and targets) and described how they can be registered and selected based on the geometrical relationships between the gesture and various objects over various distances. Using this spatial information, we make a better interpretation of the gesture meaning in case it is ambiguous. Now, we explain our system action interpretation technique by combining the selected spatial objects with the gesture recognition results.

To integrate different information statistically, we can create Bayesian network (BNs) that provides a powerful tool for dealing with uncertainty. They enable efficient representation and manipulation of conditional probability distributions for a large number of variables [HGC94].

A Bayesian network is a directed acyclic graph that describes the dependencies among random variables. Each node of the graph represents a random variable. The directed edges define the conditional dependency relations among these variables. This graph structure allows modular representation of knowledge, as well as local, distributed algorithms for inference and learning and facilitates modeling using the intuitive and possibly causal interpretation.

Figure 6 illustrates the Bayesian network used to interpret system actions. The dependencies are modeled with discrete nodes between a system action, a gesture, spatial contexts, and additional contexts. Arrows between the nodes indicate the causal relationship between the action and attributes. The two main attributes are a type of the recognized gesture, and selected targets. Additional context information, time and system functions, can be integrated for minimizing misinterpretations.

In particular, our network uses temporal integration based on the concept of dynamic Bayes network (DBN), a special type of Bayesian networks for time-series events. Depending on the application scenario and user, there are a certain sequence of commands that the user must follow to complete tasks. Therefore, the next command is partly predictable by the previous command history. For example, in a file-operation scenario, the probability of doing the past action becomes much higher when copy or cut is executed recently. Our recognition engine incorporates this prediction information to recognize the final command. The reliability of the gesture recognition engine is improved with this additional information.

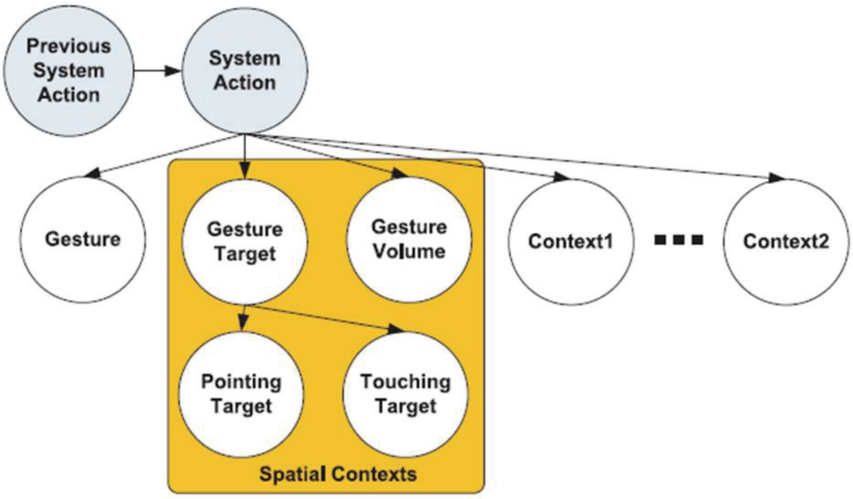

Fig. 6: Topology of the DBN for command recognition. A topology is the predefined connecting of different nodes namely gesture classes, gesture targets and gesture volumes.

For better understanding the use of network in gesture interface, we created make a simple example in a smart environment application. In the application scenario, the interpreted system action is equivalent to a certain command that runs on the system. For example the action "show weather forecast" can be executed as a command when a user is pointing at a window target and performing the *show* gesture. The result is used to execute the command that shows the weather information on the system's display screen.

When the user is pointing at the light, the PointingTarget variable in the Bayes net is set to Light, for example. This causes the Command node to assign equal probability to the “TurnOnLight” and “TurnOffLight” variable settings, since these are the only admissible commands on lights. When the user performs ″turn on”, the gesture node is set to “TurnOn” and the distribution over the A node collapses to “TurnOnLight”. The system then uses the appropriate command to turn on the light.

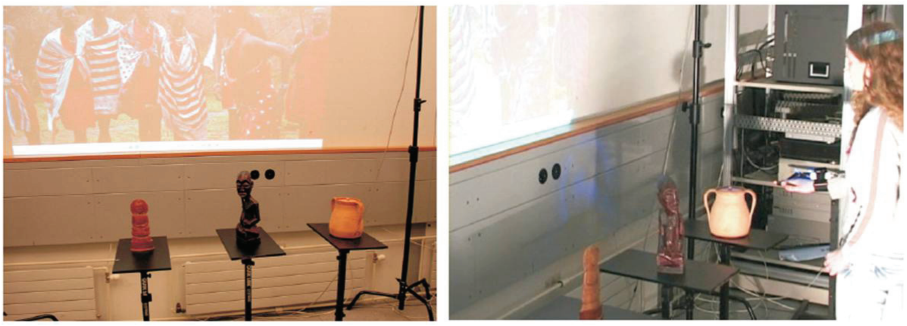

Fig. 7: Gesture-based interactions in a smart museum environment. (Left) Exhibition items and visual information projected on the wall. (Right)

4.5 Prototype Applications

We developed two prototype applications based on the concept of smart environments [CD04]. We demonstrate the effectiveness of using spatial context information in reducing recognition error and disambiguating 3D spatial gesture performances.

4.5.1 A Smart Museum Environment

In this application, we developed a smart museum environment where users can interact with physical exhibition items to get related additional audio and visual digital information (Figure 7). For example, users can point at a certain item and listen to an audio description by performing a “turning on” gesture.

For gesture acquisition, we used two cameras installed in positions that efficiently cover the location and orientation of users. During the system setup, the location of each exhibit item is modeled as a 3D Gaussian blob. To train the Gaussian distribution of an item, a series of 3D positions of the LEDs was collected when the pressure button was pressed at the items's location.

The system selects an exhibit item randomly when the hand is close to the item or is pointing at it. After successful gesture recognition, the system provides audio-visual feedbacks such as music or photos associated with the selected target item.

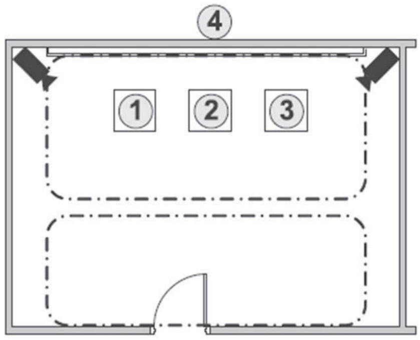

Fig. 8: The setup of the smart museum environment. Number 1 -3 are the targets for exhibit items and the target number 4 is on the wall. Two gesture volumes exist, one for the entrance area and one for the exhibit items respectively.

Figure 8 shows the prototype setup of the smart museum. There are four gesture targets: three (number 1, 2, 3) for exhibit items and one for wall objects (number 4). There are two gesture volumes: one around the entrance area.

The typical user audience is the public. It means that this application is used for a relatively short period. Therefore, we designed the gestures so that users can easily learn and perform them without errors. We used a total of 10 system commands (turning on/off audio and video information), 4 gestures (on/off and up/down), and 4 gesture targets for the exhibit items, and 2 gesture volumes for the entrance and exhibition areas.

4.5.2 A Smart Home Environment

We designed a smart home environment where users can execute system commands with 3D spatial gestures. We show how the proposed context-aware gesture interface is applied to control home electronics (such as TV, audio system, and lights) in a living room environment.

Figure 9 shows the living room layout used in our application scenario. There are three gesture volumes, *entrance, sofa, and bed*, designed with the main functional areas of the living room environment. When the user enters the room then the entrance volume is activated, the sofa volume is used when the user is listening to music on the sofa. The bed volume is mainly used for sleeping at night. These examples clearly show how gesture volume is related to time and action.

We used five gesture targets: (1) ceiling light, (2) alarm clock by the bed, (3) coffee maker, (4) audio system, and (5) a bookshelf. They are located in the appropriate position for their use in the designed architectural plan. Since we do not have the actual devices, tagged paper boxes represented the devices and their operations were simulated on the computer.

Currently, there are 10 gesture based commands mainly for controlling the gesture targets such as switching on the lights and alarm clocks, and operating the audio system. These are registered as a gesture command which is a combination of a gesture and a target. These commands can be activated by pointing at or touching the gesture targets.

Different from the previous museum application, the typical user of this application is a private user and the system can be customized to a particular user. Therefore, we use gesture registration of our framework to prepare user-designed gesture sets. Typically when the system starts, users are asked to perform a single gesture for each command to setup their own gesture templates.

Once this short initialization process is finished, the application recognizes the new input gestures by comparing them to the same-user gesture sets, and evaluates the performance in relation to reference gesture sets trained by another user for instruction. When the gesture is recognized, its associated command is executed. Obviously, if the user knows how to perform the required 3D spatial gestures, the gesture registration and evaluation process can be skipped. The DTW recognizer can be switched to the HMM recognizer if enough training data is available.

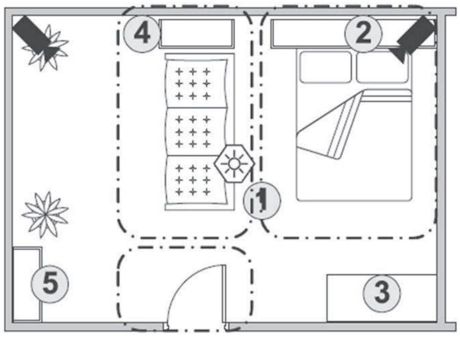

Fig. 9: An experimental setup for a smart home environment. There are four gesture volumes (entrance volume, sofa volume, and bed volume) and five gesture targets (ceiling light, alarm clock, coffee maker, audio system, and a bookshelf).

In addition to these spatial contexts, we used two other context information: typical using time and previous commands. For instance, the user is more likely to turn on the ceiling light at night, and the command to turn on the TV will logically be followed by turning off the TV.

Table 1 shows the suggested sequence of gesture commands using the time and gesture volume information. An example is when a person enters the room, first the user switches on the light followed the audio system. While various different cases could be acquired, we applied a specific architectural knowledge to the various target users. Based on this information, conditional probability for the context information is estimated with the context usages and commands.

During the development of this application, we asked two subjects to use 3D spatial gestures to control the devices in the living room environment described above. They were asked to perform all tasks using the 3D spatial gestures with gesture targets and volumes. During these tests, every 3D spatial gesture performed was transcribed together with the recognition hypotheses, context information at the time of gesture performance and the user's intended command.

We evaluated the accuracy of the baseline system and compared with the one that does not use context information at all. Initially, there were eight gesture recognition errors, two target selection errors and four commands errors. By associating the gestures with spatial objects (gesture targets and volumes) and additional contexts (daytime and previous commands), we resolved gesture recognition errors.

Table 1: A list of command sequences with the used time and the used gesture volume.

ID	Command Sequence	Used Time.	Used Gesture Volume
1	4,1,6,8,10	morning(1)	bed(2)
2	7,2,5	morning(1)	door(1)
3	1,6,10	evening(1)	door(1)
4	9	evening(1)	bed(2)
6	7,3,2	evening(1)	sofa(3)

The most prominent phenomenon was that the type of 3D spatial gestures could be misclassified in the gesture recognizer. However, we could eliminate these errors using the spatial context information that defines the relationship between the gestures and the gesture volumes and targets. For example, once the gesture target is selected, we could filter out some of gestures that are not related to the selected gesture target. First the evidences of all other nodes but the gesture node are computed and entered into the network. By inferring the gesture node, we eliminated the gestures with zero or very small probabilities and only compute the likelihood for the other gestures. We also checked the effects of each of the context used. In particular, we analyzed how command recognition errors are reduced using a particular set of contexts. Even though our experiments were for specific tasks, it shows how command interpretation improves by incorporating additional contexts.

5. . CONCLUSION AND FUTURE WORK

The paper presents a context-aware 3D spatial gesture interface. Spatial contexts are presented as a specific context for 3D spatial gesture. The paper presented the methods to register and select the spatial contexts, to recognize the final system action. Two prototype applications demonstrated how the proposed interface can be used in real life: the smart home environment and smart museum environment. Each application showed how users can interact with various objects using 3D spatial gestures in digitally augmented environments.

A dynamic Bayesian network for context aware command recognition can be useful to further improve the recognition rate and allow references to objects. This kind of network could be applied in many scenarios, such as an intelligent home, Both improvements of gesture recognition as well as command recognition are possible. For instance better features for gesture recognition or more accurate pointing with a compass sensor can be used instead of two LEDs. A further extension of gesture recognition would be to recognize sequences of gestures with connected HMMs and to support online adaptive learning.

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X. ENVIRONMENTS IN VR

ENVIRONMENTAL ASSESSMENT OF BUILDINGS USING BIM-IFC

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ABSTRACT: *The use of Information Modeling combined with simulation capabilities is extremely promising for addressing complex and multidisciplinary issues related to the environmental impact of the construction sector. In particular, the coupling of BIM (Building Information Model) with information about environmental dimensions of building materials and components (e.g. carbon footprint, energy performance …) allows simulation packages to predict the effects of using different materials / components in various conditions. This will produce significant advantages to the designer by allowing to take into account the environmental impact of the building over its lifecycle. Many factors can then be considered such as the use of potentially lower carbon footprint materials and their energy performances along with trade off's associated with the cost implication and the use of renewable energies.*

In that context, the paper explores the possibilities of using a BIM based on IFC (Industry Foundation Classes) to assess the environmental impact of a construction project and presents the development of software tool called "BIM-IFC Configurator". This configuration tool automatically proposes to the user industrial components and systems adapted to his project and his aims in terms of building performances. The layout plan is then automatically generated using the assembly rules defined by the manufacturers and integrated in the BIM-IFC. The quantity take off of materials and building products used for the construction are then calculated and used for an estimation of the environmental impact of the building using a tool developed by CSTB called Elodie. The designer can then play what-if scenarios and to compare various design options.

KEYWORDS*: Design visualization, Life Cycle Assessment, Environmental Product Declaration, Building Information Modeling (BIM), Industry Foundation Classes (IFC)*

1. CONTEXT AND OBJECTIVES

The Construction Industry is currently facing an overwhelming number of challenges. In addition to challenges common to all industrial sectors of the 21st century such as globalization, economic slowdown and the need to reduce carbon footprint, the construction sector adjoins intrinsic weaknesses. Indeed, this sector is highly fragmented with a wide variety of professional stakeholders (e.g. architects, engineers, contractors, vendors …) and non-professional stakeholders (owners, users, real estate agents …) interested by the same project but usually pursuing divergent goals. Successful initiatives to improve quality and productivity in this sector using innovation are still rare due to the lack of a lead position in the value chain for the adoption of new technology and practice along with a cultural state of mind that leaves the construction sector lagging behind other industries in applying innovation to improve its work processes.

At the same time, things are bound to change. Indeed, the construction industry is one of the biggest consumers of energy, either directly for lighting and thermal comfort (heating and air conditioning) or indirectly for the production of building materials. It also largely contributes to the massive use of some critical resources (such as energy, water, materials and space…) and is responsible for a large portion of greenhouse gas emissions. Therefore, any serious strategy aiming to reduce greenhouse gas emissions and reduce energy consumption will have to include the construction industry.

We consider that the construction industry is facing a time of great change. This change is driven by many factors among which sustainable development and the growing emphasis on carbon use. These factors push to go beyond current business models and working methods to address:

- Environmentally sustainable construction (in a context of limited resources – resources being of course energy but also water, materials and space)

- Meeting clients and citizens needs in terms of health (following indoor and outdoor exposures), security (against natural and industrial hazards) accessibly and usability for all (including disabled and elderly) and enhanced life quality in buildings / urban environments.

In that context, the use of Information Modeling combined with simulation capabilities appears to be extremely useful in addressing these complex and multidisciplinary issues. Various disciplines (technical performances of the envelope, comfort conditions, health and safety, cost analysis …) can be integrated in an interdisciplinary and holistic approach supporting a "global optimum" search that allows designers to confront options in order to identify and handle conflicts.

Environmental dimensions of building materials and components (e.g. carbon footprint, energy performance …) can also be integrated and combined with simulation packages thus allowing to predict the effects of using different materials / components in various conditions. This will produce significant advantages to the designer by allowing to take into account the environmental impact of the building over its lifecycle. Many factors can then be considered such as the use of potentially lower carbon footprint materials and their energy performances along with trade off's associated with the cost implication, the use of renewable energies …

2. STRUCTURE OF THE PAPER

The paper is structured in the following manner. Section 3 will underline the importance of improved interoperability and the use of BIM as a mean to do so. Section 4 presents how BIM-IFC is used to support a configuration tool that automatically proposes various industrial systems adapted to the project. Section 5 demonstrates the exploitation of a BIM-IFC (containing information about industrial construction systems used) through environmental impact assessment of the building. To conclude section 6 introduces to the ongoing work and the perspectives of this research.

3. INTEROPERABILITY AND BIM IFC

Virtually all of the surveys carried out in the construction industry place interoperability as a key issue for the use of Information and Communication Technologies (ICT) [WIX2009]. The evidence for available cost benefit comes from a study conducted by the US National Institute for Standards Technology (NIST) in which the lack of interoperability was estimated in 2004 to cost US industry more than US$15 billion per year [NIST2004]. However more recent estimates suggest that this figure might be too low.

The key to interoperability is that there must be a common understanding of the building processes and of the information that is needed for and results from their execution. This is where Building Information Modelling (BIM) plays a key role since it is the term applied to the creation and use of coordinated, consistent, computable information about a building project in design, in construction and in building operation and management [BIM2009]. The term has been adopted within the building and construction industries to replace 'Computer Aided Design' (CAD). With CAD, the emphasis was on the creation of a representation of the building geometry using basic geometric entities such as lines, arcs, circles. BIM places the emphasis on the objects from which the building is constructed or that describe the process of construction such as walls, windows, tasks, approvals. The emphasis is placed on 'information' and 'modelling'. BIM is sometimes referred to as a 'virtual design and construction (VDC)' [KUNZ] because it can be used as simulation of the real building.

Building Information Modelling is the process of using modern software tools to deliver a 'Building Information Model' which is the collection of objects that describe a constructed item. Both the process and the result use the term BIM. It should be noted that whilst the word 'building' is used, BIM can be applied to any constructed artifact including bridges, roads, process plants and others.

An object represents an instance of 'things' used in construction. These can include:

- physical components (e.g. doors, windows, pipes, valves, beams, light fittings etc.),
- spaces (including rooms, building storeys, buildings, sites and other external spaces),
- processes undertaken during design, construction and operation/maintenance,
- people and organizations involved,
- relationships that exist between objects.

An object is specified by its identity, state and behaviour:

- each object has a unique identifier that makes it distinct from any other object even where they are otherwise exactly the same,
- state is determined by the values given to the data attributes of that object,
- behaviour specifies how the object reacts to operations carried out on them.

Within BIM, the geometric representation of an object is an attribute. This differs from CAD in which geometric representations of objects is critical.

A BIM handles objects as though they were real things and not just as a representing shape. Shape is an attribute (or property) of an object in exactly the same way as cost or construction time or the material from which the object is constructed.

Quite often, a BIM is discussed as a 3D object model. Use of '3D' makes the attempt to characterize BIM as being geometry driven as CAD is. A BIM will often be represented as 3D. However, it could also be represented as 2D.

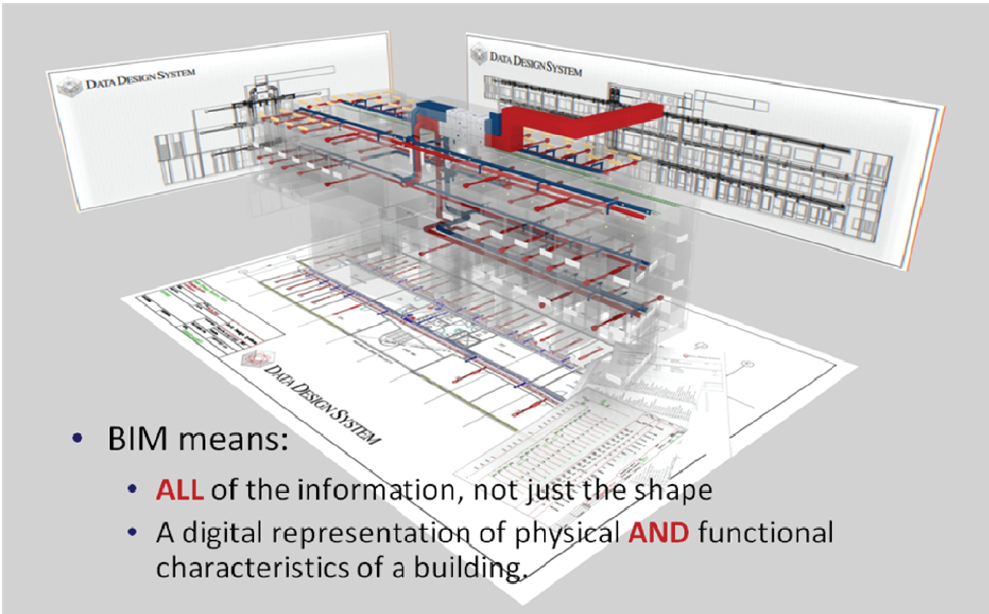

Figure 1: The relationship between CAD and BIM

BIM software is typically seen as being the large mainstream applications such as Revit, Bentley, ArchiCAD and similar. Increasingly however, downstream applications such as those used in structural, energy and HVAC applications are becoming BIM applications. The definition of 'what is BIM software' needs to be wider than has been considered. It is possible even that BIM is not one single software application but is the result of multiple software applications working collaboratively.

IFC (Industry Foundation Classes) emerged as the major standard for BIM implementation in the scope of construction industry information exchange [IFC2x3]. Its development is the result of an industry consensus building process over several years and across many countries. IFC contains common agreements on the content, structure and constraints of information to be used and exchanged by several participants in construction and FM projects using different software applications. The result is a single, integrated information model representing the common exchange requirements among software applications used in construction and FM specific processes. It is currently registered with ISO as a Publicly Accessible Specification [ISO16739] with work now proceeding to make it into a full ISO standard.

4. CONFIGURATION TOOL

In order to make BIM a central element for the entire building lifecycle including the process of construction and facility operation, it is of paramount importance to include in the model relevant information about the industrial components and systems used. This will allow to show information about systems, assemblies and their sequences and also to extract information about quantities and materials in order to assess various dimensions of the project such as sustainability analyses including building assessment (such as LEED or BREEAM), energy performance and life cycle costing.

In most cases, the BIM-IFC yielded in early design phases does not contain information about all the industrial components and systems used. Indeed, BIM is these phases is usually based on a 1/100 scale and contains only rough information about the thickness of the walls and insulation and some generic description of components.

This is obviously a problem:

1. for the precision and completion of the model,
2. for the accuracy of the simulations and assessments done using this model

In that context, a collaboration with a major manufacturer – Saint-Gobain (http://www.saint-gobain.com/en) – aimed to integrate with the BIM-IFC coming from the early design phase the description of industrial components and systems used given that:

1. this description should express the construction guidelines of the systems
2. the geometry and position of the products are constrained by the specific characteristics of each construction project
3. products should be chosen according to regulation constraints but also according to the performances the designer wants to achieve.

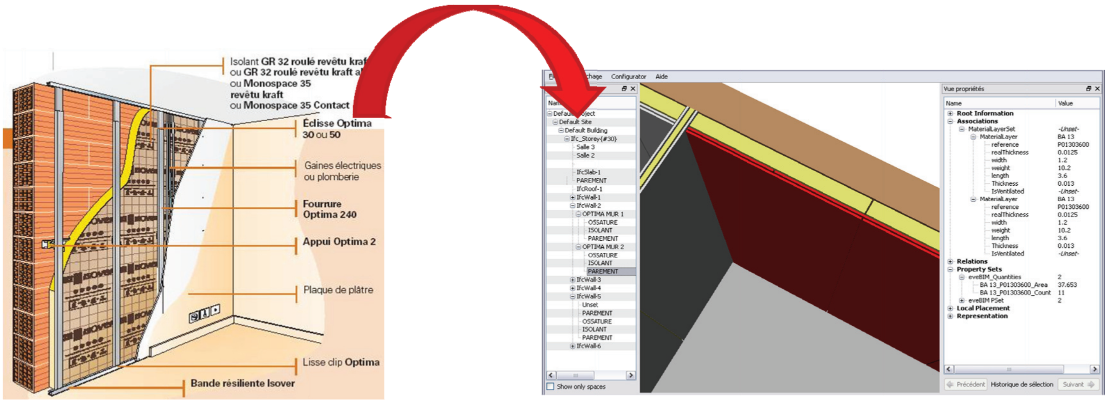

Figure 2: Description of an industrial system using BIM IFC

The process of use of the application developed is the following: a simple BIM comes from the architect who exports it in IFC format using the export function of his CAD tool. Depending on the performances to achieve (e.g. the annual energy consumption), the application will automatically check in the industrial catalogues of Saint-Gobain (in fact in a database describing these catalogues) and then proposes to the user relevant systems adapted to his project and the performances he wants to achieve. No choices are made automatically by the application which simply suppresses from the list systems that are not relevant depending on the context thus facilitating the task of the user who ultimately makes the decisions.

Then, once, the user selects the systems in the list proposed by the application, the latter will automatically propose the layout plan taking into account:

- the geometry of the project
- the assembly guidelines defined by the manufacturer.

The result, which is the BIM IFC enriched with the systems in place, contains therefore all the information needed about quantity take offs and products used in order to be used by various simulators and assessment tools.

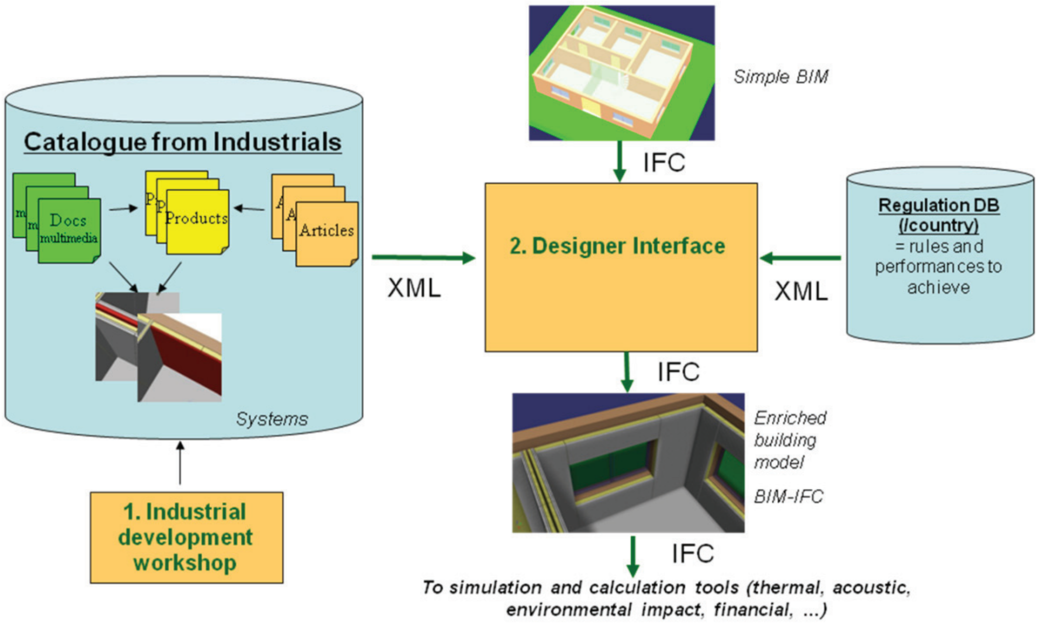

Figure 3: Architecture of the BIM IFC configurator

Through this collaboration, the aim of Saint-Gobain group was to accompany stakeholders of the construction process by giving them precise information about technical and practical aspects of its systems. The group is aiming at achieving the target of 50kWh/m²/yr not by using technical equipments but by better implementing insulation systems, knowing their performances and their mutual interactions. The catch phrase of the group is indeed that the cheapest energy is the one that is not produced at all.

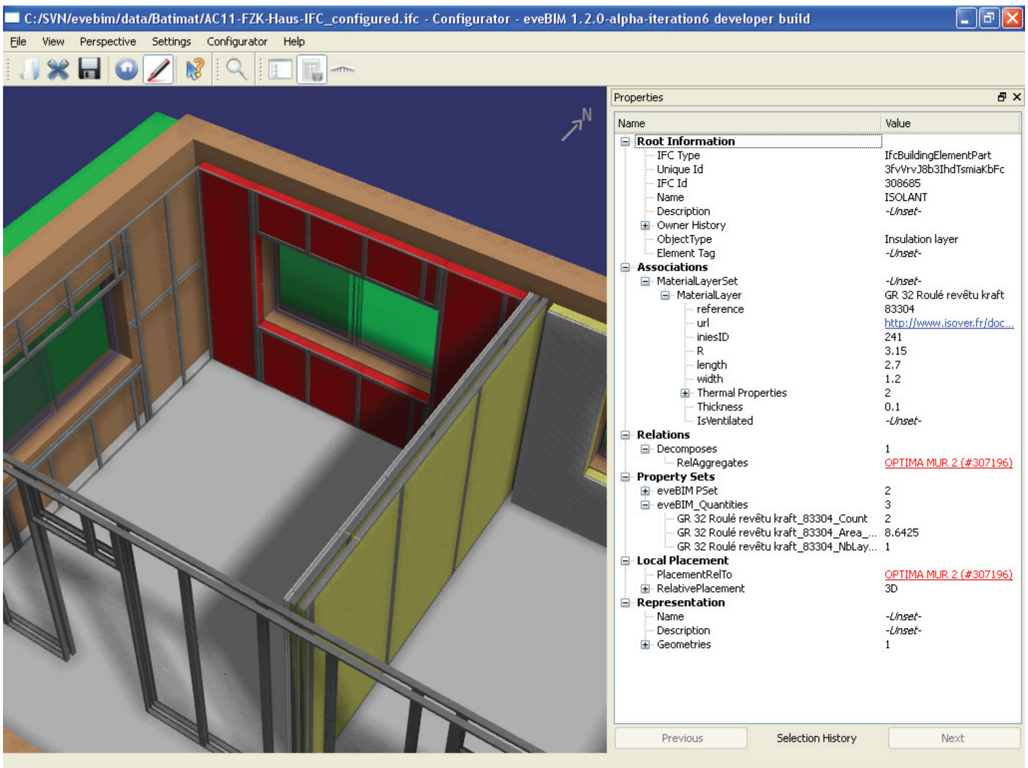

Figure 4: example of the application of a layout plan for internal insulation systems with the metallic frames along with the various layers. These components are assembled using the guidelines provided by Saint-Gobain.

5. ENVIRONMENTAL IMPACT ASSESSEMENT

Keeping in mind that various applications can exploit BIM-IFC for instance to assess energy consumption or cost evaluation, this paper will focus on the exploitation of BIM-IFC for the assessment of the environmental impact of the building.

In order to meet the need of the construction sector in quantifying the environmental building performances and to use the environmental data produced by manufacturers, CSTB started in 2007 to develop a tool named Elodie. Based on a Life Cycle Assessment approach it is particularly adapted to the use of a methodology based on the product scale data included such as the one included in EPD's (Environmental Product Declaration).

ELODIE provides assistance for the choice of environmentally friendly constructive solutions. It allows comparing several alternatives for the same building or for the same part of work realized with different components, different materials, and even different constructive modes. Within few years, it will become a complete environmental assessment tool (with environment, but also health and comfort dimensions) and will be developed in coherence with sustainability assessment tools. It will be consistent with standardization basis and SBA (Sustainable Building Alliance - http://www.sballiance.org/) work about a core set of indicators shared by number of countries and the French HQE approach. Based on a life cycle approach and on the standard XP P01-020-3, the software can be used to set up models of new buildings or existing ones.

5.1 Calculation Model

The model is based on the quantification of the flow's balance. At the building scale, these flows are named contributory elements. The model (illustrated by the following figure) considers the sum of the impacts of various flows as material and products, as energy and water consumptions.

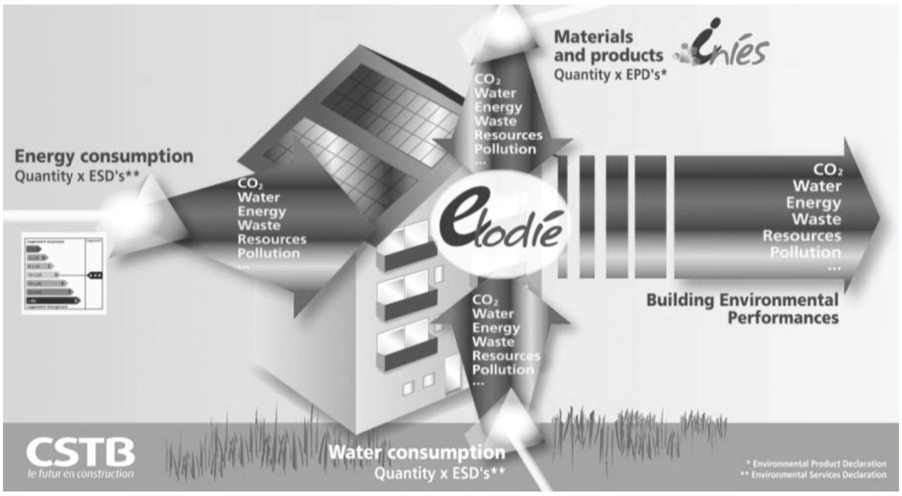

Figure 5: The building environmental performance calculation model.

The quantification of the contributory element "product and material" is based on the FDES (French EPDs). This decision led to the development of a standard, (i.e. NF P01-010) issued in 2004. The adopted methodology for the EPDs establishment is based on Life Cycle Assessment (LCA) approach and includes also the health and comfort aspects. In order to improve the dissemination and the accessibility to these declarations, the EPDs, a public free access data base, has been created in 2004 (see INIES database at www.inies.fr). At present, there are about 420 EPDs. The LCA is based on a cradle to grave analysis including packaging, and complementary products.

5.2 Materials and products contribution

ELODIE calculates the environmental impact of a building from the quantity of each product inserted in this building and their FDES (functional units must be the same). It is also possible to use other sources of environmental data for one product. To calculate the results, the model requires an estimated lifetime for each product, which is taken as the lifetime of the FDES initially but can be adapted to the project and the service life of the building. Consequently ELODIE calculates the number of replacement for each product, the quantity to insert, and then the environmental contribution of each product. The sum of the impact of the products is one part of the environmental profile of the building.

5.2 Energy consumption contribution

ELODIE allows connecting energy concerns to environmental ones. From the impact of placing energy at disposal, and amount of consumed energy resources during the building service life**,** ELODIE calculates the environmental impacts of the site energy consumption. These impacts are dependants of factors such as: the losses in production, transmission and distribution of energy on the grid scale, generation and distribution efficiency in the building itself, nature of combustible (coal, wood, fuel, etc.), etc. Among the multicriteria results, the amount of primary energy used to provide end users site energy is specified.

5.4 Water consumption contribution

ELODIE estimates the water consumption of a building using as input data: 1) some building characteristics such as floor area and its geographical location 2) the number of occupants and their behaviour 3) some characteristics of the water distribution network such as the hot water production device and the presence or not of the water pressure regulator 4) the characteristics of the water-using equipments (toilet flush type, shower flow, washing machine type etc.). The user can choose several types of equipment intended for the same use (e.g. a 6L toilet flush and a 6L/3L dual flush toilet) as well as the equipment which he wishes to integrate in total calculation (e.g. to not take into account the consumption of the washing machine or to take into account only the inside uses etc). ELODIE could also estimate the cost of consumed water and to highlight the equipments whose impact is most important on the total water consumption.

5.5 Coupling between BIM-IFC and Elodie

Since IFC can store intelligent objects, with geometry (if it has) and properties on building elements, the quantity take off can be computed automatically to extract input data needed by Elodie. Furthermore, additional information can be added to model in order to store it and pass it to other stakeholders.

The process of coupling between BIM-IFC and Elodie is to apply FDES to buildings entities and then to export the model in an ELODIE file format.

A specific perspective has been developed (to work only with the data we are interested with). The idea is to manipulate the model and explore it. From this model, we can sort the building elements by type or/and by materials or/and by spatial structure (e.g by storey…). From it, we can then attribute FDES to a group of selected elements. For example we can store all the elements by type and material and thus select all the windows with the material 1 and apply an FDES.

For the storage of the model, the FDES are added in the IFC. To do, an analysis of the environmental standard was undertaken and a proposition was made to integrate within the IFC standard the environmental impact indicators. The new release of the IFC (IFC 2x4), will contain new environmental impact properties. These are :

• Total Primary Energy Consumption	• Renewable Energy Consumption
• Water Consumption	• Non Renewable Energy Consumption
• Hasardous Waste	• Resource Depletion
• Non Hasardous Waste	• Inert Waste
• Climate Change	• Radioactive Waste
• Atmospheric Acidification	• Stratospheric Ozone Layer Destruction
• Photochemical Ozone Formation	• Eutrophication

5.6 Elodie's results

ELODIE provides, as a principal result, an environmental profile of the building, which compiles all the contributions of the various products, the site energy consumption and the water supply. This profile corresponds to the environmental indicators of the NF P01-010 standard, preserving all of them for a better transparency of the results. ELODIE allows considering distinctively the contributories impacts: building products, energy and water supply.

The calculation of the contribution of the construction products gives as results the opportunity for construction stakeholders (designers, client, project managers…) to apply a environmental friendly approach: it makes possible to compare several alternatives for the same building or for the same part of work realized with different components, different materials, and even different constructive modes.

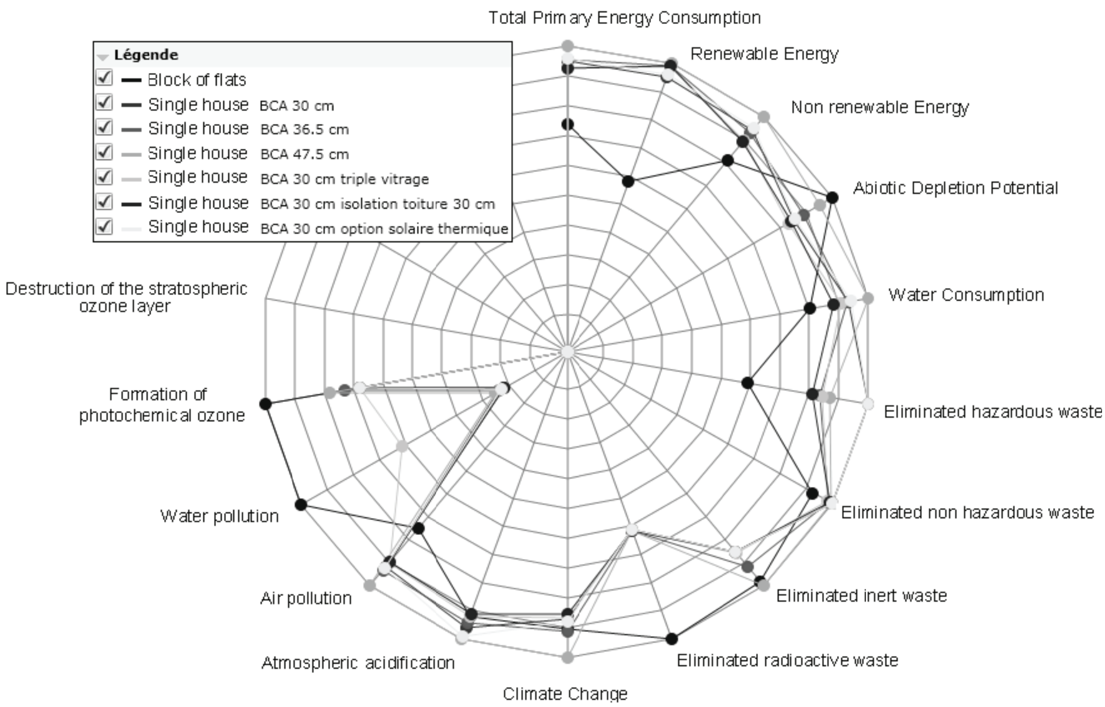

Figure 6: Analysis of results. Comparison of various constructive solutions for a single house

6. CONCLUSION AND FUTURE RESERACH

Pressure to study energy conservation is increasing rapidly due to questions about fossil resources availability and concerns about climate modifications. In the construction sector, the first step to reduce energy consumption and limit environmental impact is to simulate the behavior of buildings. Many models have been developed over the years but these models tend to use partial information about the building and its components thus raising questions about the confidence one can have in the results.

New technology allowing to enrich BIM-IFC with detailed information about the industrial components and systems used without this being a tedious task for the user will permit to make relevant and complete information about the project available to various assessment tools. This will raise confidence in the results and allow to compare various constructive solutions from different points of view (energy consumption, environmental impact, cost …). We are convinced that over the next 5 years, this usage will grow to become a core method within the construction sector.

Finally, future research will focus on the improvement of the environmental assessment tool, in order to go towards a decision-making tool. One of the next steps will be to propose an evaluation model adapted to every typology and every design and construction stage.

Acknowledgements

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Visualization technique of outdoor thermal environment using a VR avatar

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ABSTRACT: *Urban thermal environment is closely related to human's amenity. Therefore, the thermal environment should be simulated or evaluated during the planning of design process and various studies have been done to indicate the converted temperature based on the air temperature, humidity, wind, shadows, emitted heat, etc. However, the result of such simulation is represented on 2D dimension or still computer graphics. Thus, in this research, a new visualization technique was proposed using a Virtual Reality (VR) Avatar. The VR Avatar Thermal Environment (VRATE) System was developed and validated by applying it to a university campus.*

KEYWORDS: *Outdoor Thermal Environment, Avatar, Virtual Reality, Visualization, Virtual Experience*

1. INTRODUCTION

In recent years, urban areas face thermal environment problems such as heat island phenomenon. Planting more trees and increasing green areas would give a good impact on such problems. In the urban planning and design process, city planners can investigate the anticipated effect by performing various simulations, which are the result of recent research on the converted temperature based on the air temperature, humidity, wind, shadow, emitted heat, etc. Since there are a number of stakeholders, including project developers, residents, city planners and citizens involved in public planning in cities, mutual understanding and consensus building are necessary. However, most outputs of thermal environmental simulations are usually represented in 2D drawings, which are hard to understand the 3D spatial distribution of heat in the environment. Even if the output looks 3D, the representation does not provide stereoscopic, dynamic, or immersive effect (Yoshida et al, 2000 and Yamamura et al, 2003). It is not easy for those who have little knowledge of thermal and fluid dynamics to understand the urban thermal environment.

Recently, researchers and practitioners have started using Virtual Reality (VR) for urban planning and public hearings. VR systems that enable the user to feel heat, wind, shadow of the urban environment has been developed (Kushiyama et al., 2006, Kosaka et al., 2006 and Kato et al., 2002). But most of them need huge space, special tool and a lot of cost to perform. Now the avatar is paid attention in movies and amusement industry. An avatar is a virtual person in a 3D virtual environment. The user can identify the avatar as him/herself. An avatar has been used in a field like the disaster prevention and the education (Taniduka et al., 2005 and Kato et al., 2002). The authors came up with the idea that VR users may be able to experience the thermal environment by the avatar.

In this research, a new visualization technique was proposed using VR and an avatar. The system allows the user to experience the 3D thermal virtually environment through the avatar, providing the user with stereoscopic, dynamic and immersive effects.

2. METHODOLOGY AND RESEARCHES IN THE PAST

2.1 Outdoor thermal index

Outdoor thermal index is used for representing effects on human thermal comfort out of doors. It is applied in the heating, ventilating, and air conditioning (HVAC) engineering and meteorological fields. Several outdoor thermal indices have been proposed so far such as, sensible temperature of Missenard, SET*, MRT, PMV and Beaufort Wind Force Scale, which are described in the following subsections.

2.1.1 Sensible temperature of Missenard

The sensible temperature of Missenard is a human sensible temperature which is easily calculated with the influence of humidity, wind and temperature. Because neither the influence of the transferred heat by radiation nor the physiological activity of the human body is tempered, the evaluation is likely to be different from actual human temperature feeling.

$$T = 37 - (37 - t)/(0.68 - 0.0014h + 1/A) - 0.29t(1 - h/100) \tag{2.1}$$

$$A = 1.76 + 1.4v^{0.75} \tag{2.2}$$

T : Sensible temperature of Missenard [^{o}C]

h ：Relative humidity [%]

t ：Temperature [^{o}C]

v ：Wind speed [m/s]

2.1.2 SET* (Standard new Effective Temperature)

SET* is a human sensible temperature which is calculated with the influence of humidity, radiation, amount of clothing and physiological activity of the human body. It is often applied in the thermal environment although it was developed for indoor thermal evaluation. But there are some problems such as the reduction of accuracy in the high temperature area.

$$\begin{aligned} C+R+E_{sk} &= F_{cls}\cdot f_{cls}\cdot h_s\cdot(t_{sk}-SET^*) \\ &\quad + w\cdot LR\cdot F_{pcls}\cdot h_{cs}\cdot(P_{sk},s-0.5PSET^*,s) \end{aligned} \tag{2.3}$$

C :Convective heat transfer from skin [W/m^2•sec•K]

R :Conductive heat loss from skin [W/m^2•sec]

E_{sk} :Evaporative heat loss from skin [W/m^2•sec]

F_{cls} ：Rate of coating with clothes [-]

f_{cls} ：Surface thermal resistance of clothes [m^2•K/W]

h_s ：Summary heat transmission rate [W/m^2•K]

t_{sk} ：Mean skin temperature [^{o}C]

SET^* ：Standard new Effective Temperature [^{o}C]

w ：Rate of skin wet area [-]

LR ：Lewis number [^{o}C /kPa]

F_{pcls} ：Exposure rate of skin [-]

h_{cs} ：Convective heat transfer coefficient [W/m^2•K]

P_{sk},s ：Maximum vapor pressure to cutaneous temperature [kPa]

$PSET^*, s$: Maximum vapor pressure in temperature SET* [kPa]

2.1.3 MRT (Mean Radiant Temperature)

MRT is a concept arising from the fact that the net exchange of radiant energy between two objects is approximately proportional to their temperature difference multiplied by their ability to emit and absorb heat (emissivity). MRT shows the temperature conversion in an uneven emitted field. It is calculated by the following equation.

$$MRT = \sqrt[4]{\sum_{i=1}^{n} F_i T_{si}^{\ 4}} - 273 \qquad (2.4)$$

MRT : Mean Radiant Temperature [°C]

F_i : Configuration factor in surrounding each surface [-]

T_{si} : Temperature in surrounding each surface [°C]

2.1.4 PMV (Predict Mean Vote)

PMV is a heat stress of the human body proposed by Fanger, and is standardized as ISO-7730. PMV is calculated based on the thermal loading of the human body. The thermal loading of the human body is the one that deflection in assumption was shown from thermal neutralization by the calorie. PMV is on a dimensionless scale. And the hotness is shown by positive values of PMV, while the coldness is shown by negative.

$$PMV = \left(0.303e^{-0.036M} + 0.028\right)\left(M - W - E_d - E_s - E_{re} - C_{re} - R - C\right) \qquad (2.5)$$

PMV : Predict Mean Vote[-]

M : Metabolism [W/m^2]

W : Mechanical workload [W/m^2]

E_s : Evaporative heat loss from skin [W/m^2]

E_d : Insensible perspiration [W/m^2]

E_{re} : Latent heat loss by breath [W/m^2]

C_{re} : Sensible heat loss by breath [W/m^2]

C : Convective heat loss [W/m^2]

R : Radiation heat loss [W/m^2]

2.1.5 Beaufort Wind Force Scale

Beaufort Wind Force Scale is an index concerning the wind. The wind force scale is strength of wind, which is measured with human's eyes. The strength of the wind is divided into 13 classes (from 0 to 12) by the movements such as sea waves and object shakings. The Japanese Meteorological Agency established the indicator of the strength of the wind based on Beaufort Wind Force Scale.

2.2 Estimation and Visualization of outdoor thermal environment

In recent years, many scientists have executed research on the methodologies to estimate outdoor thermal environment by using the Computer Fluid Dynamics (CFD) analysis. The methodologies depend on the scale of the targeted external space. In the macro scale, such as a whole city, a city is delimited with the mesh at intervals of several kilo meters and its thermal environment is simulated by the movement of the atmosphere and the heat budget within the range. In the micro scale, such as a city block, the techniques for calculating the heat budget from several meters or several centimeters were proposed (Yamamura et al., 2002 and Yoshida et al., 2000). Since the information of the thermal environment calculated by such techniques is represented as numerical data, it is difficult for people to understand. Thus, visualization of the numeric output data can enhance the human's understanding level. The techniques of visualization can be classified as three kinds, i.e., 2D, 3D and 4D.

First, in the 2D method, thermal environment is represented on a plane. Scalar quantities, such as mass, length, energy, temperature and etc., are represented by contour lines, and vector quantities, such as power, electric field, momentum and etc., are shown in the vector diagram by using the arrow. With these two dimensional techniques, a plane thermal environment can be easily understood. However, 3D thermal environment may not be easily captured. Second, in the 3D method, the thermal environment is visualized in three dimension space. The 3D method includes surface rendering, volume rendering, etc. In the surface rendering, surfaces of 3D models are colored. The volume rendering uses voxels to represent 3D objects. It is possible to represent the inside of an object and the object that cannot define its surface. Finally, the 4D method is the combination of the 3D method and time-dependent dynamic representation.

2.3 Virtual Reality and an Avatar

Virtual Reality (VR) is a technology that conveys the virtual information produced by the computer to man's senses through some media. The characteristics of VR include a real-time spatiality of three dimensions, interaction and the self-projection. Here are some examples of VR technology that is related to reproduction of thermal environment. Some are visual approaches; there are methods of using the above-mentioned (chapter 2.2) techniques of visualization. For example, in the VR space of the housing, the temperature and the air flow were visualized by the three-dimensional technique (Ono et al., 2003). As a result, the indoor thermal environment is visually imaginable. However, the actual sense of heat cannot be experienced in the visual approach. The others are tactile approaches. In these approaches, heat is actually reproduced through special equipments such as infrared rays, electrically-heated wire. In the recent research, the touch panel of heat, "Thermoesthesia", was developed (Kushiyama et al., 2006), and it enable a human to feel the change of heat in response to computer graphics. However, there is a weak point that cannot easily do the technique by making to the sense of touch because costs or a special machine is necessary.

Moreover, the avatar is a person who behaves as user in virtual spaces such as VR and the Internet. The avatar has been used in fields of the entertainments or of the computer game. Academically, the effect of avatar is evaluated in point of the absorption feeling to a virtual space. With this effect, the avatar is used as a tool for training or education. For instance, the training of the disaster is important to act safely or calmly in a real disaster. But actually it is difficult to imagine the situation of the disaster. Then, the system which can experience a fire disaster was developed using an avatar (Taniduka et al., 2005).

3. VR AVATAR THERMAL ENVIRONMENTAL (VRATE) SYSTEM

3.1 Outline of system

The outdoor thermal environment system using VR avatar developed in the present study. This system was named VR Avatar Thermal Environment (VRATE) System. The VRATE System evaluates a three-dimensional virtual thermal environment by visualizing the thermal surroundings of the VR avatar. Figure 1 shows the interface design of VRATE System. Here, the VR space and the VR avatar are displayed on the screen, and the thermal index (sensible temperature of Missenard, MRT and SET*) and the winds are visualized. In the lower right of the screen, there is a menu bar which selects the technique of making to visible, and the user can select the techniques of visualization. In the left side of the screen, there display the position of VR avatar and the information of wind, index of heat, analytical date, and etc. In addition, it is also possible to show information on the route that the VR avatar passes and information on the thermal environment at that time, and the user can calculate PMV or draw the graph of the PMV in the external file.

Before using VRATE System, the thermal environment is analyzed, and obtains the result by the form such as text files on the object site. Second, the object site and the circumference are made with 3D CAD software, and its data is output to the VRATE System. Then, the thermal environment analysis output file is import to the VRATE System, and the thermal environment in the VR avatar surroundings is displayed. The user can virtually experience the environment of the design space by operating the VR avatar.

In this research, thermal environment simulation analysis result (Yoshida et al., 2002 and Kishi et al., 2009) was used. 3ds Max (3DCG modeling software of Autodesk Co.) was used to make a 3D model to represent the campus with buildings for VRATE System. And the main program of VRATE System and the VR avatar were developed using Virtools 5.0 (VR software of the Dassault Systems Co). As the operation of the VR avatar, three actions (walking, turnabout, and geostationary) were created.

3.2 Visualization techniques

The VRATE System provides with three kinds of visualization modes, i.e., Thermo-box, Particle, and both using together. Figure 2 shows three visualization techniques and the layout of each object.

First, Thermo-box is a 100mm cube and its color shows value of thermal index. Thermo-box is put by centering on the VR avatar at 500mm intervals, and it shows the thermal environment in the cubic area of 2,000mm. If the

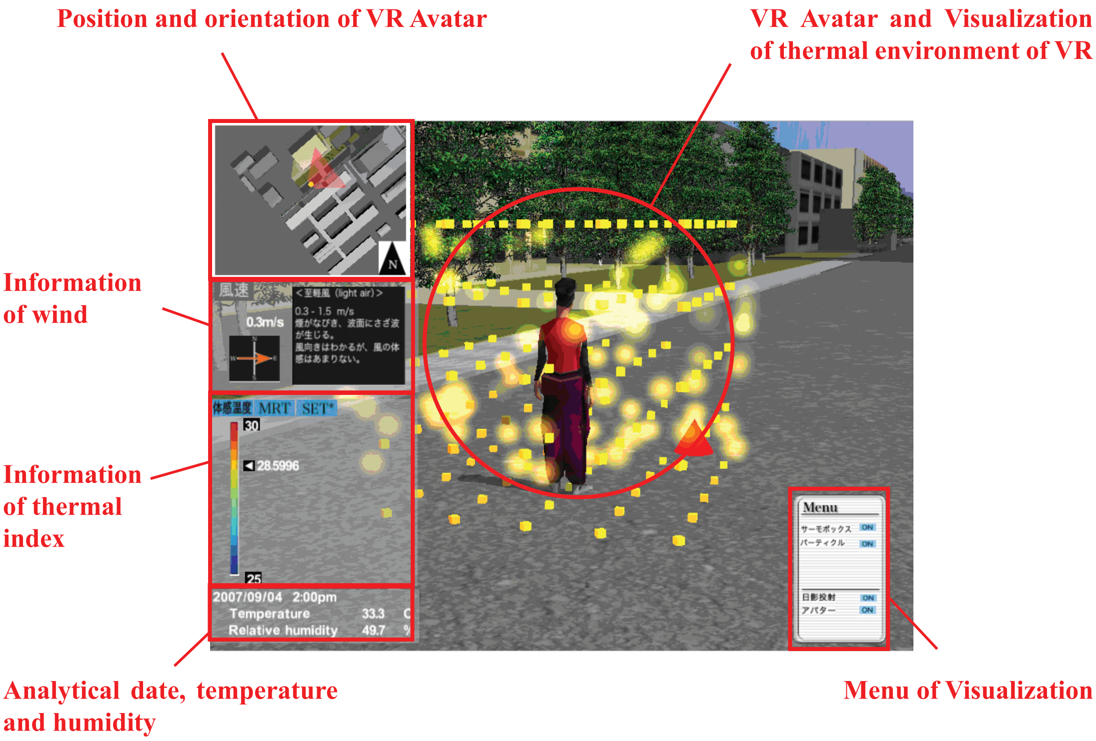

FIG. 1: The interface design of VRATE System

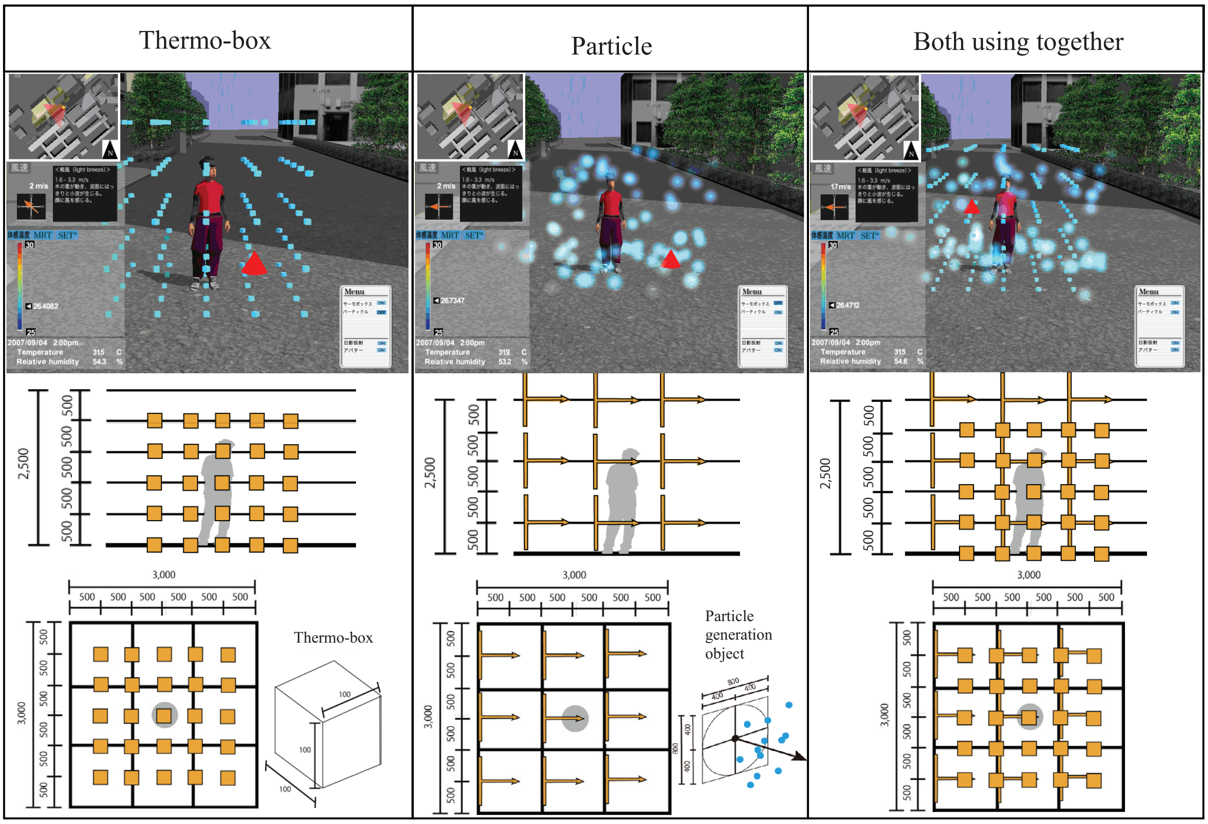

FIG. 2: Three visualization techniques and the layout of each object

thermal index is high, the color of Thermo-box gets red. Adversely if the thermal index is low, its color gets blue. Second, Particle is a small object generated from the VR avatar surroundings. And Particle is generated from the particle generation object. The particle generation objects, which are not displayed on the VR space, are arranged at 1,000mm intervals in VR avatar surroundings. Particle color shows the height of the thermal index like Thermo-box, and Particle movement shows the wind speed and direction. Moreover, since the particle is set as very light material, the speed and direction of the wind is faithfully reflected. Finally, both using together is the method of using Thermo-box and Particle techniques together at a time. Thermo-box and Particle color shows the height of the thermal index and Particle movement shows the wind speed and direction. Furthermore, the visualization flow is as the following. First, positional coordinates of the VR avatar and its surrounding are acquired. Next, the coordinate which is the closest to positional coordinate is found, and the thermal environment information and thermal index of that coordinate is taken out. And then, in case of Particle, Particle generation objects are reflected in wind information and turn around in the direction. Afterwards, the color of Thermo-box and/or Particle changes according to thermal index. And Particle is generated from the particle generation object.

3.3 Other functions

The numerical value of visualized information and the meaning of the thermal index are displayed on the screen of the system. When the visualized area is selected with the mouse and information of the thermal environment at that position is displayed on the screen. Obtained information includes information on heat and information on wind. Information on heat is a numeric data of Sensible temperature of Missenard, MRT and SET* and a text data of MRT and SET*, which was based on researches in the past (Gagge, 1971 and Fangar, 1973). In information on wind, the speed of the wind shows numerical value and the wind direction is displayed as an arrow. And a text data, which was based on Beaufort Wind Force Scale, of wind speed is shown. And more, it is also possible to memorize and export the data on the thermal environment that VR avatar experienced. With the data, the user can try other thermal evaluation or draw the graph of the thermal stress of VR avatar in the external file.

4. USABILITY EVALUATION

4.1 Propriety of visualization display

4.1.1 Experimental methodology

In this experiment, the propriety of visualization display was investigated by the questionnaire. The examinees are 20 people, including students of Osaka University and the author's acquaintance, and Table 1 shows the specialty of them. In the questionnaire, they evaluated the easiness to understand of the thermal environment by five stage evaluation after the movies of the VRATE System had been presented to them. In five stage evaluation, “5” means the most easiness of the thermal environment, and “1” means the least easiness of the thermal environment. The movies are prepared by two patterns, which are different from the view points and the route of the VR avatar passing. The first pattern is a display of the VR avatar keeping the height of 2.0m above ground level. In this route, the change of the sensible temperature of the VR avatar takes place easily since the VR avatar passes over the road of asphalt, the shadow of a building, and the shade of a tree. The second pattern, changed the route of the VR avatar, is displayed from a bird's eye view. In this route, the north wind of force of the wind 4 changes gradually into the west wind of force of the wind 2. In the questionnaire, these changes had shown, and the user easily understood to how thermal environment of the VR avatar changed. Questionnaire items included “A: The easiness of understanding of the thermal index”, “B: The easiness of understanding of the wind”, “C: The easiness of understanding of the relativity between the space composition object (such as a tree and lawn, etc.) and the thermal environment”, “D: The easiness of understanding of the relativity between sunshiny and the thermal environment” and “E: The easiness of understanding of the environmental design”.

4.1.2 Experimental result

Figure 3 shows the mean value of all examinees’ evaluations based on the five stage evaluation system. Figure 4 shows the mean value that the only examinees, who answered “no correspondence” in Table 1, evaluated. From the result of Figure 3, it was obtained that Thermo-box had higher mean values than other techniques of visualization in the item A, C, and D. Because Thermo-box had a high score of 4.7 in D, it was understood that Thermo-box is an applicable display method for the users to understand the relativity between sunshiny and the thermal environment. However, Thermo-box had a low score of 3.5 in the question B because some users could not easily understand the wind from the Thermo-box. In the case of Particle, the score of the wind is 4.2 and the highest of three techniques of visualization. Therefore, Particle had the superiority in the wind evaluation. In case of both using together, there was no remarkably outstanding evaluation as Thermo-box or Particle. Since it had evaluations of about 4 of all questionnaire items, it was suggested that the users can understand the thermal environment and the relations of thermal environment with this technique. And Figure 4 denotes the same tendency of Figure 3. But, in the question B, the evaluation of Thermo-box is much lower as compared with Figure 3. Thus, Thermo-box is not an applicable display method for those who have no technical knowledge shown in Table 1 to understand the wind.

Table. 1: The examinees' specialty

		Number of people
Technical knowledge	Urban engineering	8
	Architecture	5
	Thermal engineering	7
	Information technology	5
	Meteorology	6
	Ecophysiology	2
	No correspondence	11

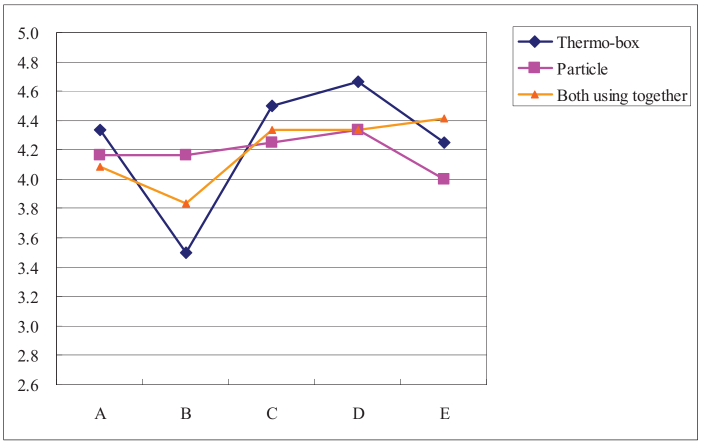

FIG. 3: The result of the five stage evaluation of each visualization technique（all examinees）

Questionnaire items

A: The easiness of understanding of the thermal index

B: The easiness of understanding of the wind

C: The easiness of understanding of the relativity between the space composition object (such as a tree and lawn, etc.) and the thermal environment

D: The easiness of understanding of the relativity between sunshiny and the thermal environment

E: The easiness of understanding of the environmental design

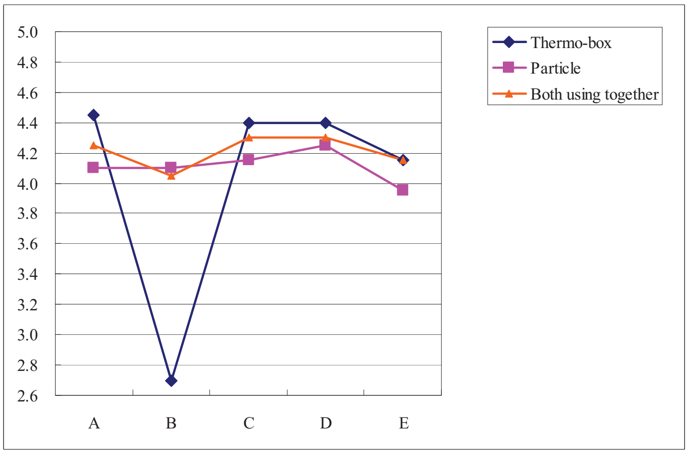

FIG. 4: The result of the five stage evaluation of each visualization technique（only no correspondence）

4.2 Operability of system

4.2.1 Experimental methodology

In this experiment, operability of system was investigated by the questionnaire. The same examinees in 4.1.1 used the system freely for about five minutes after explanation of the system. And then, they evaluated the easiness to operate VRATE System. They actually operated VR avatar (walking and turnabout), the camera switching (zoom and rotation) and the visualization switching.

4.2.2 Experimental result

Figure 5 and Figure 6 show the result of the questionnaire. In both figures, the examinees as whom the operation had chosen "Easiness" both exceeded the majority. 70% of the examinees answered "easiness" in the operation of the VR avatar, and 60% of them in the operation of the camera switching of the system. There was no examinee who answered from the result, "It tends to be difficult" and "It is difficult" although several examinees who were more than 50 years old were included. Therefore, the system has a good operability regardless of the age.

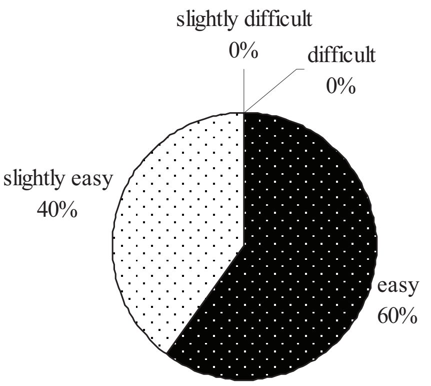

FIG. 5: the operability of VR avatar

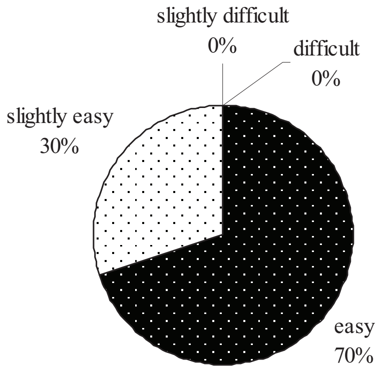

FIG. 6: the operability of the camera switching

4.3 Evaluation of outdoor thermal environment during VR avatar walking

4.3.1 Experimental methodology

In this experiment, a prototype of VRATE System which measures outdoor thermal environment during VR avatar walking in real time was evaluated. The VR avatar walked in the route shown in Figure 7, and the time change of the PMV value was drawn in the graph. The graph drew by Microsoft Office Excel 2007. As a result, it could be evaluated how stressful the VR avatar felt thermally by the time the VR avatar reaches its destination.

4.3.2 Experimental result

Figure 8 shows line chart of PMV value per a second. PMV value was close to three from 0 to 13 seconds. Because the VR avatar was walking on the asphalt road at this time, it could be seen that the VR avatar felt a high thermal stress. However, it was understood that PMV value decreases to about 0 or 1 and the heat stress was eased greatly from 13 to 48 second. This is because the VR avatar was walking on the shadow area covered with the lawn. And then, VR avatar was leaving the shadow area and walking on the asphalt road from 49 to 60 seconds. PMV value increased again. Thus, the amenity of the walking route can be appreciated by the use of the VR avatar. And, if the various routes to the destination are evaluated by VRATE System, the each heat stress of all routes can be understood before walking in real world. Therefore, VRATE System is useful when the user studies the more comfortable route.

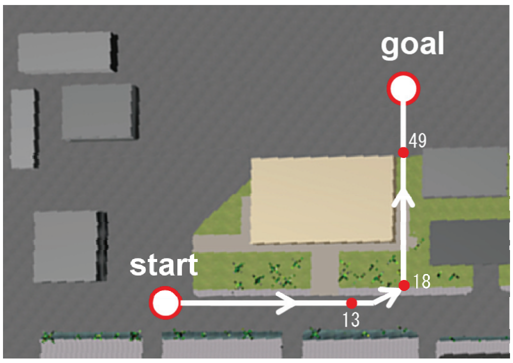

FIG. 7: The route of VR avatar walking

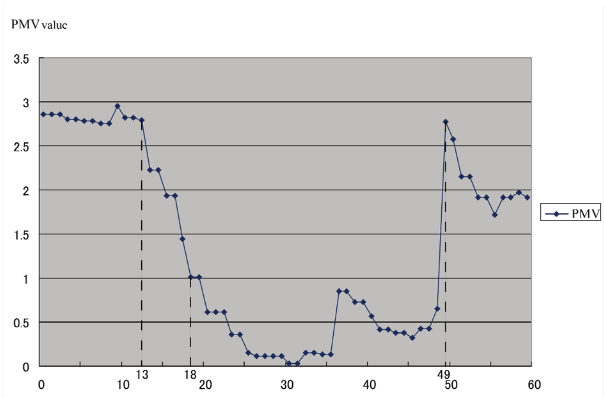

FIG. 8: line chart of PMV value per a second

5. Discussion

As for visualization, Thermo-box was evaluated as an applicable display method to understand in the most of questionnaire items, regardless of expertise. This is because the position of Thermo-box doesn't change from the VR avatar. Hence, the user easily understands a three dimensional extension and the change of heat that surrounds the VR avatar. On the other hand, the expression of the wind gained a low score. This is because when Thermo-box visualizes thermal environment, it displays the only numerical data on the screen for the wind. In Particle visualization, the expression of the wind gained a higher score than that of Thermo-box. Hence Particle is effective to show a three-dimensional wind environment. However, the problems for the expression of Particle still remain in the examinees' opinion such as "The movement of the particle is complex" and "The shape is not suitable because round shape is not appropriate way to visualize the wind direction". In Both using together, the high score is received and it can be said that it is the most effective expression technique in three kinds of visualization techniques. However, there were opinions such as "Since a lot of visualization methods were done in Both using together, the appearance of buildings or trees is hard to see". Therefore, it can be said that using both Thermo-box and Particle is the most appropriate way to visualize thermal environment, but it is necessary to improve functions such as changing the number and Thermo-box or Particle.

In the operability of system, there was no examinee who answered, "It tends to be difficult" and "It is difficult". Therefore, it is thought that there is no big problem for operation of VRATE System. It is possible to operate the VR avatar and the other functions using only the keyboard and the mouse, so the user can operate VRATE System easily even if he has no expertise of PC. Additionally, the opinions for the improvement of the operation existed. For examples, when the VR avatar moves the long distance, it takes much time because VR avatar only can walk. It is necessary to add the function that the walking speed of VR avatar can be changed. Moreover, if it is possible to operate only by the mouse, the user can operate more convenient.

In the evaluation of outdoor thermal environment during VR avatar walking, line chart of PMV value per a second was able to be evaluated. As a result, it is useful for the evaluation of the thermal stress of the VR space. And the thermal environment can be evaluated with buildings, trees and etc. of VR space. However, because the position of the VR avatar during walking is hard to understand line chart of PMV value per a second, it is necessary to improve the function to evaluate both the time and the place simultaneously in the future.

6. CONCLUSION AND FUTURE WORK

The achievement of the present study is as follows.

- A new visualization system was developed using VR and an avatar.
- VRATE System allowed the user to evaluate the 3D thermal environment in the VR space by the virtual experience through the VR avatar.
- VRATE System had a good operability regardless of the age.
- VRATE System was an applicable display method for not only a specialist of architecture or thermal environment but also a non-specialist of that.
- VRATE System allowed the user to evaluate the amenity of the walking route. And, if the various routes to the destination are evaluated by VRATE System, the each heat stress of all routes can be understood before walking in real world.

It is necessary to add the improvement of the technique of visualization of the wind as future works. Also it is necessary to improve it to evaluate the time axis and the place easily. Moreover, if the avatar has metabolism, thermal stress can be more accurately simulated.

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VIRTUAL REALITY SIMULATION OF WIND POWER PLANTS USING SOUND AND 3D ANIMATED GRAPHICS

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ABSTRACT*: Despite the popularity of wind power generation as a recycled energy, problems on environmental impacts are pointed out, such as landscapes, noise, and shadow flicker phenomenon. Although there have been some research on each of these problems, research on the integrated system development has not been heard yet. Thus, a virtual reality (VR) system was developed in this research to evaluate the landscape change, to simulate the noise from windmills, and to show shadow flicker phenomenon in the integrated system environment for the purpose of consensus building with surrounding citizens. First, a general system development method was proposed for wind power plants. Then, the noise level computed by a simulation software package named SoundPLAN and the measured noise level at an existing wind farm were compared, and they had good agreement. Next, a VR system for the wind farm was developed based on the proposed general method. The simulated noise levels and measured ones at locations different from the one measured before were compared and they had good agreement. The VR system was used for trial by 25 people at Osaka University, and its usefulness and effectiveness for explanation and consensus building with citizens were confirmed by the questionnaire.*

KEYWORDS*: Wind power, Noise simulation, Landscape evaluation, Virtual Reality, 3D animation, Shadow flicker.*

1. INTRODUCTION

As wind power generation is a kind of recyclable energy and is considered to be environmentally friendly, it is expected to build more wind power stations (NEDO, 2008). On the other hand, wind power has problems of low energy density, wind fluctuation, concerns on environmental impacts and on building consensus with local citizens. As for the environmental impacts, disturbance to landscapes, noise, and shadow flicker phenomenon are described below.

Firstly, development of wind power stations can be a significant impact to landscape. As the tip of large wind turbine rotors can reach nearly 100 meters, there is a concern that wind mills may impair scenery. On the other hand, a set of dozens of wind mills in a perfect array or in an orderly manner can become a sightseeing resource. The landscape of wind power stations have ambiguity or double meaning.

Secondly, noise of wind turbines has become an environmentally important issue. Some citizens were reported to claim that they had felt ill after the nearby wind power station had started its operation (Nikkei, 2008). Although infrasonic sound, or infrasound, has been noticed recently, the impact to humans is not well known yet. In Japan, special committee of the Central Environment Council of the Ministry of the Environment (MOE) added commercial wind power generation to the list of enterprises which environmental assessment is required. Thus, MOE starts in-situ survey of about 1,500 wind mills from 2010 to obtain actual sound data. Acoustic noise of wind turbines has been well researched in many countries (Hubbard and Shepherd, 1990; Wagner et al., 1996; Fregeant, 1999). Rogers et al. (2006) summarized current studies of general acoustics and noise of wind turbines.

Thirdly, shadows created by rotors can be observed as an oscillating phenomenon when rotor blades spin around. This phenomenon is called shadow flicker and it is disturbing to people nearby. To avoid troubles by shadow flicker, developers should investigate whether shadow flicker occurs or not in both commercial and residential areas, roads, railways, and parks (Park and Sato, 2005).

To solve above mentioned problems, VR is deemed effective (Ohata et al., 2004). Honma et al. (2002) developed a landscape planning process model of wind power stations and a method of distinguishing areas where wind mills are visible using Geographical Information System (GIS). Aikawa et al. (2003) compared a composite photograph method and an animation method and performed impression evaluation of the relationship between wind mills and skylines. Prediction methods and countermeasures for these problems were developed by Yoshida and Shimizu (2007). Although Lou (2006) added a sound function to a VR software package, precise simulation could not be done because masking objects in the sound propagation path were not considered. Park and Sato (2005) developed a model for predicting the area where shadow flicker can occur. However, this system did not show the shadow flicker phenomenon in the VR environment. Furthermore, a VR system which can simulate sound, landscape and shadow flicker as a total system has not been developed yet.

Therefore, the objective of this research is to develop a framework of a VR system which can simulate noise, landscape, and shadow flicker in an integrated manner. The framework can contribute to develop an actual system which supports developers in the design of wind power stations and in building consensus with citizens nearby. The following is the aggregated development items:

1) Development of a method for the simulation of noise in a VR environment,

2) Development of a method to simulate the shadow flicker phenomenon,

3) Development of an integrated VR system for the simulation of landscape, noise, and shadow flicker.

Note that the infrasonic sound problem is not treated in this research because it is beyond the application of VR.

2. METHOD OF DEVELOPING A WIND POWER VR SYSTEM

This section describes a method of developing a wind power VR system proposed in this research. To develop the system, basically, the following three kinds of information are necessary: 1) a map which covers the whole area of the wind power stations and nearby region with contours, 2) detailed drawings and specifications of wind power stations, 3) detailed acoustic data of wind turbines for performing sound simulation. One third octave-band pressure level data would be preferable.

2.1 Terrain and structure modeling

Scanned 2D contour maps can be converted to digital vector data, and then each contour line is assigned its elevation data so that the data can be converted to Triangulated Irregular Network (TIN) or grid data. On the other hand, recently more and more digital terrain data in a grid format can be obtained from the government. Next, aerial or satellite photograph data which can be obtained the government or Google should be pasted onto the digital terrain model data using texture mapping technique. If there are structures, trees, etc., 3D models are created with 3D CAD software and in-situ photographs are pasted as well.

Since wind mills are special structures in the system, the models should be more carefully made. Especially, rotors must spin at certain speed which can be controlled by the user or the system. To spin rotors, animation function is necessary for the VR system.

2.2 Representation of shadow flicker

The VR system needs a function to calculate the solar orientation and altitude from the time, date, and longitude and latitude of any location on the earth. Then, the location of the light source can be determined. Next, the shadows of wind mills and other structures are projected to the terrain. Shadows must be able to be synchronized with the animated spinning rotors.

2.3 Sound simulation

In order reproduce sound in a VR environment, actual sound source data which has been preliminarily recorded should be played at certain loudness level corresponding to the distance and ambinet, determined by acoustic numerical analysis simulation. However, since actual comparison between the in-situ noise level and computed sound pressure level had not been done in terms of current large-scaled wind power stations, quantitative comparison was executed. At certain wind power station, sound pressure level data was observed at many locations. At the same time, wind velocity, electric power level, etc. were recorded. Then, a sound simulation software package named SoundPLAN was used to execute numerical analysis simulation using necessary sound power level obtained from the wind mill. They had good agreement.

Next, color coded noise level contours created with the sound simulation software are converted to a grid data, where each square represents the average of the sound levels at the vertices of the square. A number of numerical simulations were executed corresponding to various sound levels and the data is embedded in the grid. When the user enter into each square, the sound of wind mills is played at the adjusted sound level.

2.4 Environment of the VR system

The above-mentioned components are integrated and the VR system is developed. Once the system is developed, it should be operated in an appropriate environment. Ideally, an anechoic room is preferred to perform precise VR noise simulation. However, since it is usually difficult to use such a room, the following conditions of the room are recommended. The room should have walls with sound-absorbent material and should be large enough. To monitor sounds, speakers should be used instead of earphones because typical sound including wind turbine noise can be reached to ears with air vibration. Furthermore, the volume of the speakers should be adjusted beforehand so that the sound pressure level at the user's position in the room is equal to the computed one. Finally, the screen should be large enough for the user to feel immersed.

3. DEVELOPMENT OF A VR SYSTEM FOR A WIND POWER STATION

Based on the method described in the previous section, a VR system was developed for a wind power station in Japan.

3.1 Terrain and structure modeling

We obtained a 1/2,500 scale map and scanned it, and then converted it to 2D CAD data (DXF) with Adobe Illustrator. Although the original contours were 2m pitch, we used only 10m pitch, considering the data size and necessary efforts. As there are roads and wind mill flat areas, outlines of roads and flat areas were also converted to 2D CAD data. The 2D CAD data of contours was exported to a 3D modeling software package, Autodesk 3ds Max, and then, elevation data was given to all contours. Next, TIN data was made from the 3D contour data. On the other hand, an aerial photograph of the region was obtained from the Geospatial Information Authority of Japan, and trimmed to fit the map area with Adobe Photoshop. The trimmed aerial photograph was pasted to the TIN data using the texture mapping technique. Roads and flat areas were made with Autodesk Civil 3D. All these data were exported to a VR simulation software, 3DVIA Virtools. The bird's eye view of the area is shown in Figure 1.

As for wind mills, 3D CAD data (DXF) was made based on the 2D drawings with a 3D CAD software package, ArchiCAD. Then, the 3D model data was exported to 3ds Max. Some digital photographs of the wind mills were taken and processed with Photoshop and pasted to the 3D model using texture mapping technique (Figure 2).

In order to incorporate the revolution of rotors into the VR environment, an animation program was developed in Virtools environment. Since the revolution speed depends on the wind velocity, we observed wind velocity at the site and made a computing program.

3.2 Shadow representation

To represent shadows by the sun based on the time, date, and location, we used a program which was developed before (Fukuda et al., 2007) in Virtools. Virtools provide two real time shadow rendering methods, i.e., the shadow volume technique and the shadow mapping technique. In the shadow volume technique, projection of rays from the light divides the world into shadow volume where any point inside is in shadow and lit volume, and if a whole or a part of an object is inside the shadow volume and if it can be seen from the viewpoint, shadow is rendered. In the shadow mapping technique, visible areas from the light are mapped in pixel and then, when rendering objects, if a whole or a part of the object is outside the visible areas, the shadow is rendered on the object. Generally, the shadow mapping technique has more precise rendering quality because it judges whether each pixel is in shadow or not. However, it has a drawback that it is slower in rendering than the shadow volume technique. Thus, in this research, since shadows of spinning rotors must be rendered, we adopted the shadow volume technique.

Shadows on the ground or structures are generally not black because of scattered or reflected light. Light shadows rather than black shadows should be used as shown in Figure 3. In the VR system, if the user's viewpoint is in the rotor's shadow area, the user can experience shadow flicker phenomenon.

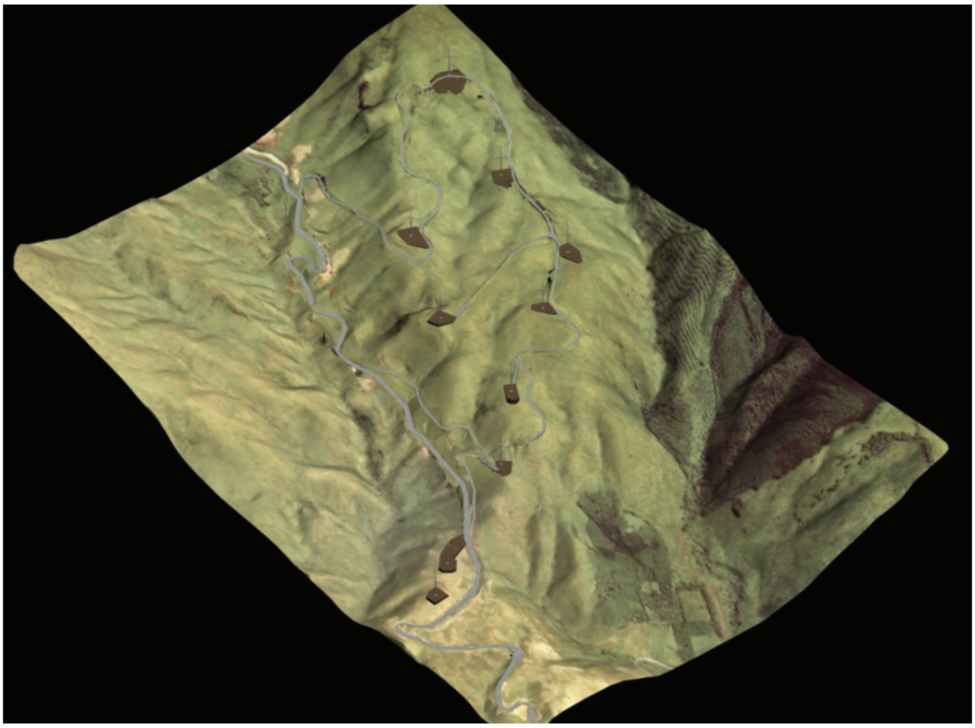

Fig. 1: Terrain and structure model of a wind power station.

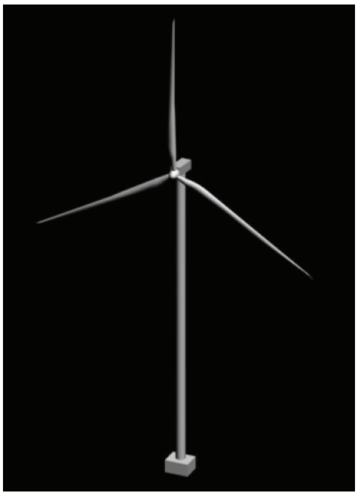

Fig. 2: 3D model of a wind mill.

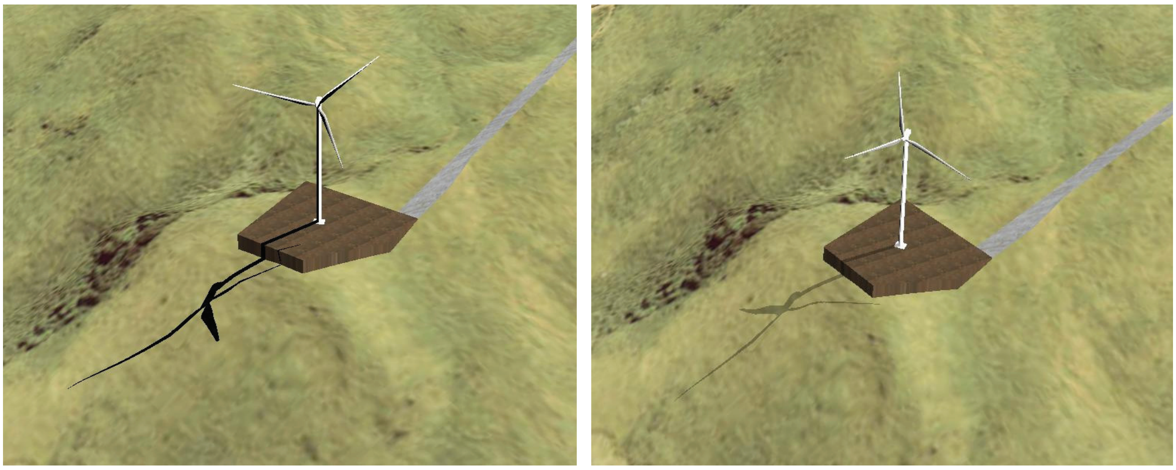

Fig. 3: Shadow of a wind mill. Black shadow (left) and light shadow (right).

3.3 Sound representation

Data of sound power levels of the wind turbine was obtained from the manufacturer. The data is not disclosed to public. The authors were allowed to use it only for research by the manufacturer. As for the directionality of the sound pressure level, as observed at the site, we set the right and left sides have 2dB smaller than front and back of the rotors. The sound source is a point and is located at the center of the rotor. Then, we executed sound numerical analysis simulation for wind velocity cases of 4, 5, 6, 7, ..., 13, 14m/s. For each case, sound pressure level contours were drawn. Contour interval was 2dB. Then, the contour drawing was exported to Photoshop as DXF data and color processing was done (Figure 4).

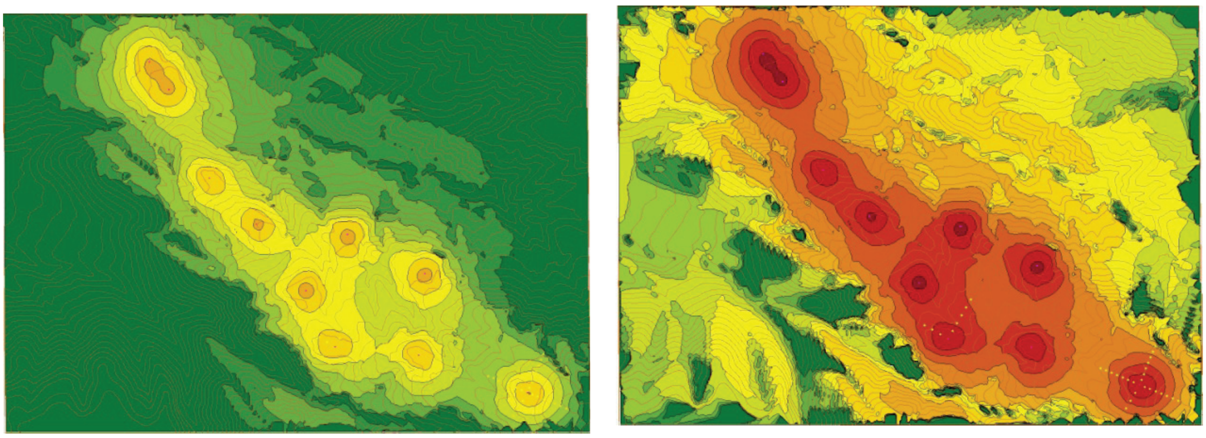

Fig. 4: Sound pressure level contour drawings (left: sound pressure level = 97dB, right: 107dB).

Next, the contour data was imported to 3ds Max and converted to grid data. Then, this data was input to Virtools. In the Virtools, when the user's viewpoint enters into a square of the grid, the volume of the sound was set according to the sound pressure level of the square. The background noise was also recorded and was played all the time.

Finally, the sound pressure level contour drawing, which was processed with Photoshop, was pasted on the terrain model using the texture mapping technique. Thus, the user can select either the view of the aerial photograph or sound pressure level contours, as shown in Figure 5. The sound pressure level contour drawing change automatically according if the use change the wind velocity.

4. VERIFICATION OF THE SYSTEM

4.1 Comparison between the in-situ sound pressure level and simulation data

In order to check whether the sound pressure level data of the simulation has a good agreement with the in-situ sound pressure level, we compared the in-situ and simulation data at the locations B and C (Figure 6) when the wind velocity was 8m/s. Both B and C are 85m distant from the wind mill A. However, the location B is below a cliff so that the wind mill is invisible from B while it is visible from C. The cliff at location B plays a role of sound barrier. Thus, the sound pressure level of simulation at B was 42 - 44 dB while at C was 50 - 52 dB.

The observed sound pressure level was 45dB at B and 52dB at B. Thus, the observed data has good agreement with the simulation data.

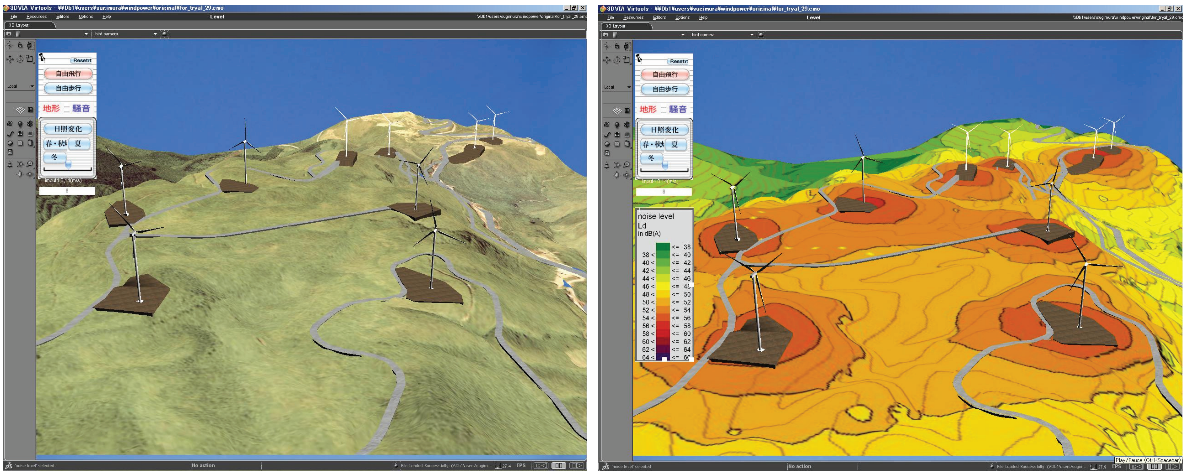

Fig. 5: Window mode change (left: aerial photograph, right: sound pressure level contour drawing).

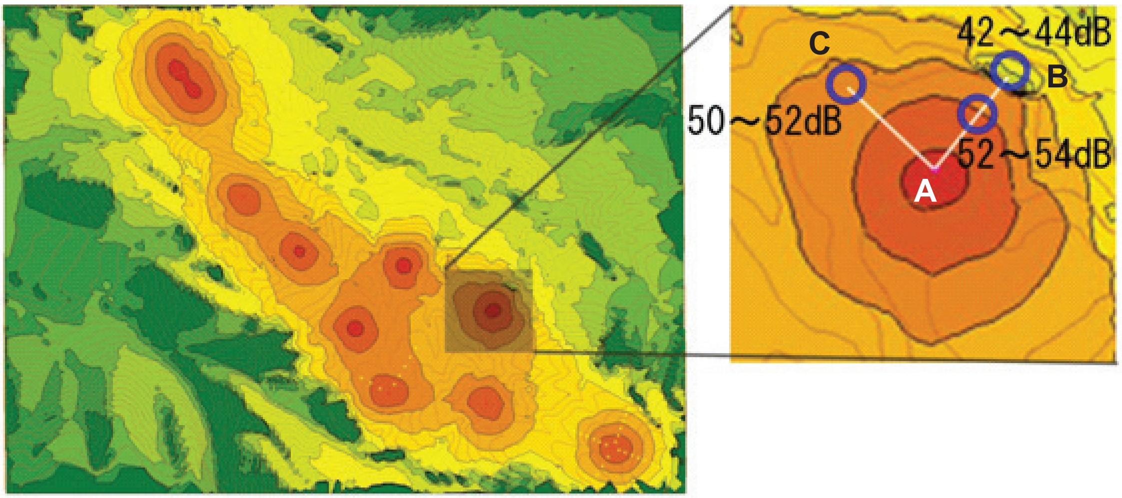

Fig. 6: Locations where in-situ and simulation data were compared.

4.2 Evaluation of the VR system by potential users

To check the applicability and practicality of the developed VR system, we executed the walk-through demonstration of the VR system, showed live-action video of the site, and asked questionnaires to 25 students at a large classroom of Osaka University. The test subjects consist of 11 male and 3 female undergraduate students and 8 male and 3 female graduate students of School of Engineering. They compared the VR simulation and live-action video answered questionnaires. The experiment was executed for the comparison of two cases, i.e., (A) walking from 200m distant from a wind mill for 20m toward the mill, and (B) walking from 30m distant from the same wind mill for 10 toward the mill.

Table 1 shows the questionnaire result about the comparison. Each value is the average of the reviewer's evaluation points of the VR simulation compared to the live-action video. The score is evaluated assuming the live-action video is 100 points. According to the questionnaire result, most of them agreed that the VR simulation was similar to the live-action video in terms of “wind mills layout and shapes,” “spinning of rotors,” “volume of sound.” On the other hand, they said the “texture of wind mills and terrain” is not relatively similar.

Figure 7 shows the questionnaire result about the VR system as a whole. They highly evaluated the bird’s eye view of VR simulation, and said that the VR system would be useful and effective for landscape investigation and noise evaluation. They especially highly evaluated the VR simulation of shadow flicker phenomenon. They also said the sound simulation gave them the feeling of being at the actual site because the sound became larger when the viewpoint was getting close to the wind mill. Finally, the rate of “think so very much” and “think so” to “VR can be used for public hearing” was 92%, which implied the developed system could be practical and useful for open hearings and meetings with citizens and residents. On the other hand, since the test subjects were students, the feeling of actual local residents may be different from them.

Table 1: Questionnaire result

Evaluation Item	Case (A): walking from 200m distant from a wind mill for 20m toward the mill	Case (B): walking from 30m distant from the same wind mill for 10 toward the mill
Wind mills layout and shapes	80	81
Texture of wind mills and terrain	50	56
Spinning of rotors	80	80
Volume of sound	76	74
Quality of sound	58	68

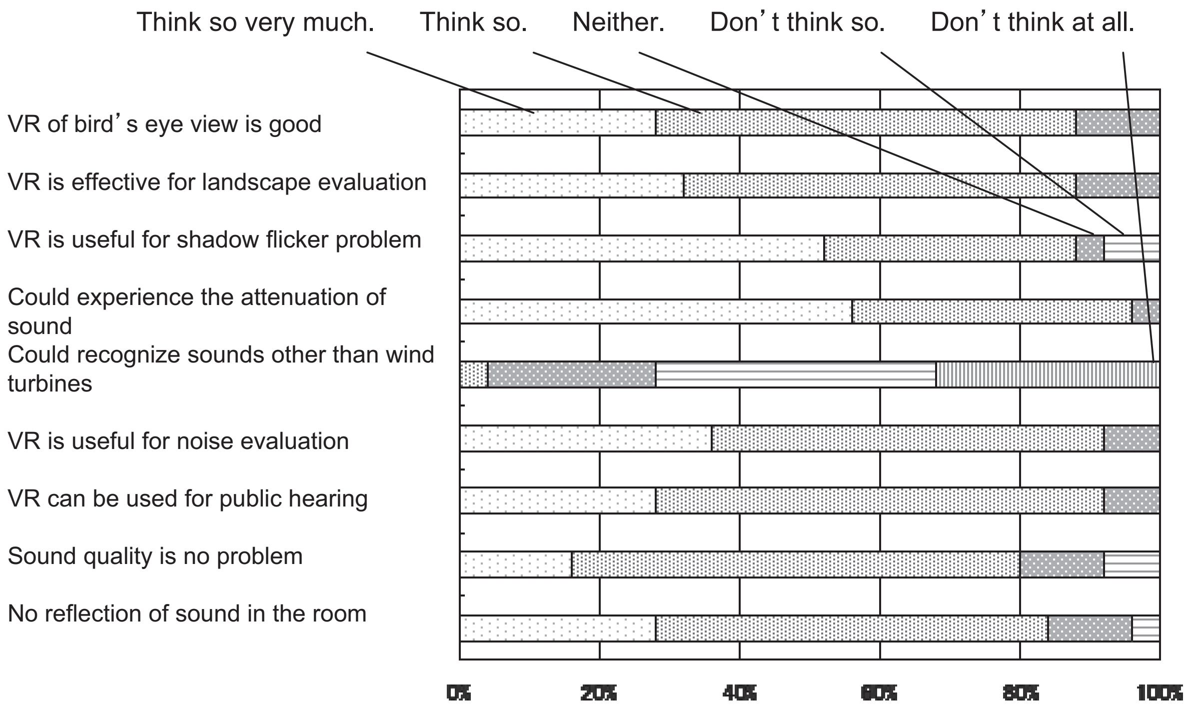

Fig. 7:Questionnaire result about the VR system.

5. CONCLUSION

In this research, we developed a VR system which can simulate sounds of wind turbines, landscape, and shadow flicker and which integrates these capabilities into a total VR system. The conclusions of this research are the following:

- We developed a general development methodology of a VR system to support the environmental assessment and open hearings with local residents in terms of noise, landscape, and shadow flicker.
- We developed a sound reproduction system using the sound numerical analysis simulation and the recorded actual sound at the wind power station. The system can give the users the feeling of actually being there.
- We compared the sound pressure level data observed near the actual wind mill and simulation result at a flat area and below the cliff. Both data agreed well.
- We incorporated the shadow flicker into the VR system, which is useful and effective for the users to perceptually understand the issue and to solve it.
- The VR system was demonstrated to 25 students and the questionnaire result showed that the system was thought to be applicable to actual open hearings because they felt the layout of wind mills, terrain shapes, sound volume and quality, and rotation velocity of blades.

We firmly believe that the developed system in this research will play a significant role in and contribute great deal to planning and design of wind power stations. Firstly, it will prevent unnecessary impairing of landscape. Secondly, residents and local public agents will be able to understand how the wind power stations will look like, how large the wind turbine noise will be, how shadow flicker look like and can be prevented by locating wind mills properly. The wind power VR system will reduce distances between the developers and local citizens by sharing the virtual world.

As there are several limitations of this research, the followings are some of the future research actions.

- The sound sources stored in the VR system are actual recording at a site. Thus, the sound would vary place to place and time to time. More recorded sound data would be necessary.
- When we visited the site several times, the wind velocity was below 9m/s. We should record the sound of wind mills when there is stronger wind.
- In the current VR system, the sun behind the wind mills cannot be displayed on the screen. By showing the sun, it would give the users stronger feeling of being there.
- If a wind mill is relocated in the planning or design phase, it would take about half an hour to change the VR simulation data. In order to use this system in the open hearing, interactive function should be enhances.

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DEVELOPMENT OF AN EXPERIENCED-BASED ROAD TRAFFIC NOISE EVALUATION SYSTEM USING VR TECHNOLOGY

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ABSTRACT: *This paper presents an experienced-based road traffic noise evaluation system using virtual reality technology. This system has two functions as auralization function and visualization function; the first one expose users the computed traffic noise by auditory information corresponding to the CG animation of traffic, another one expose users the iso-surface of the road traffic noise level by CG image to understand the spatial distribution on the noise level. Users can change the road environment and vehicle conditions by using the controller interactively in VR space. The present system is shown to be a useful tool to evaluate the road traffic noise in planning and designing of road environment.*

KEYWORDS: *Road traffic noise, audio-visual stimuli, geometric acoustic theory, IPT.*

1. INTRODUCTION

The evaluation of road traffic noise is very important for planning and designing of road environment. There have been presented a number of numerical simulation methods in accordance with the development of computer. The theory for numerical simulation can be classified into two approaches; wave acoustic theory (Schenck, 1968; Nomura, 2008) and geometric acoustic theory (Yamamoto, 2010). Each method has merit and demerit, the method based on wave acoustic theory is accurate but it takes a lot of computational time. On the other hand, the method based on geometric acoustic theory, the computational time is very short but the accuracy and applicability to the problem with complicated geometry are low. Therefore, the geometric acoustic theory is useful for the development of the real time simulation system.

Generally, the numerical results are visualized using computer graphics (CG). However it is difficult to understand the noise level intuitively with CG, because the visualization is not auditory information. In order to overcome the problem, several systems that expose road traffic noise as the acoustic information have been presented in the past studies. Nagano et al. (1999) developed a system that allows the user to hear noise by manipulating the regeneration levels of recorded video and sound using ear plug. Makanae et al. (2004) developed a simulator that allows the user to hear noise in synchronization with traffic flow simulation. Mourant et al. (2003) developed several traffic noise simulators for driving simulator. However, there are quite few attempts to develop a system that allows the user to hear noise in various conditions and to view a vehicle animation of stereoscopic view and real scale like reality. Therefore the present author developed a system (Tajika et al, 2009) to expose the numerical results with auditory information using virtual reality (VR) technology. The ASJ-RTN Model 2008, which is the Japanese standard model for road traffic noise, was employed for the model based on the geometric acoustic theory. The system was designed as an interactive system which realizes the real time simulation. However, the system was able to apply to very simple road environment, so the applicability of the system was limited in practical use. Moreover, as the function of visualization of noise level has not developed, therefore the user was not able to understand the spatial distribution of noise level.

This paper presents an experienced-based road traffic noise evaluation system using virtual reality technology which can overcome above mentioned problems of our conventional system. In order to improve the applicability, we add an elevated bridge and a building as structure, and also add the other type of cars to make us to be able to evaluate more complex conditions. Moreover we developed a new function to expose users the iso-surface of the road traffic noise level by CG image to understand the spatial distribution on the noise level. Users can change the road environment and vehicle condition by using a controller interactively in VR space. The present system is shown to be a useful tool to evaluate the road traffic noise in planning and designing road environment.

2. A ROAD TRAFFIC NOISE EVALUATION SYSTEM USING VR TECHNOLOGY

Figure 1 shows a concept of the present system. This system is based on the immersive projection technology (IPT) (Wegman, 2002) for developing the VR space, therefore observer's view is stereoscopic and real scale like reality.

This system presents two types of the presentation methods for computed road traffic noise level, one presents the acoustic information of road traffic noise based on numerical result which is synchronized with the movement of vehicle (The auralization function in figure 1). This function can present not only one vehicle's simulation's result but plural vehicle's simulation's results at the same time. Another one presents the iso-surface of the road traffic noise level by CG image with the road environment's CG to understand the spatial distribution on the noise level (The visualization function in figure 1).

The present system has following three characteristics as shown in Figure 1. First, the observer can move to arbitrary position and can hear the road traffic noise that correspond with the position, since the road traffic noise level is computed in real-time using the position of observer (see (A) in Figure 1). Second, the observer can change the road environment; height of sound barrier, pavement type and passage years after pavement ((B) in Figure 1). Third, the observer can change the vehicle conditions; vehicle type, vehicle speed and running distance of vehicle ((C) in Figure 1). Furthermore, the display function of interface is developed in order to realize the second and third characteristics.

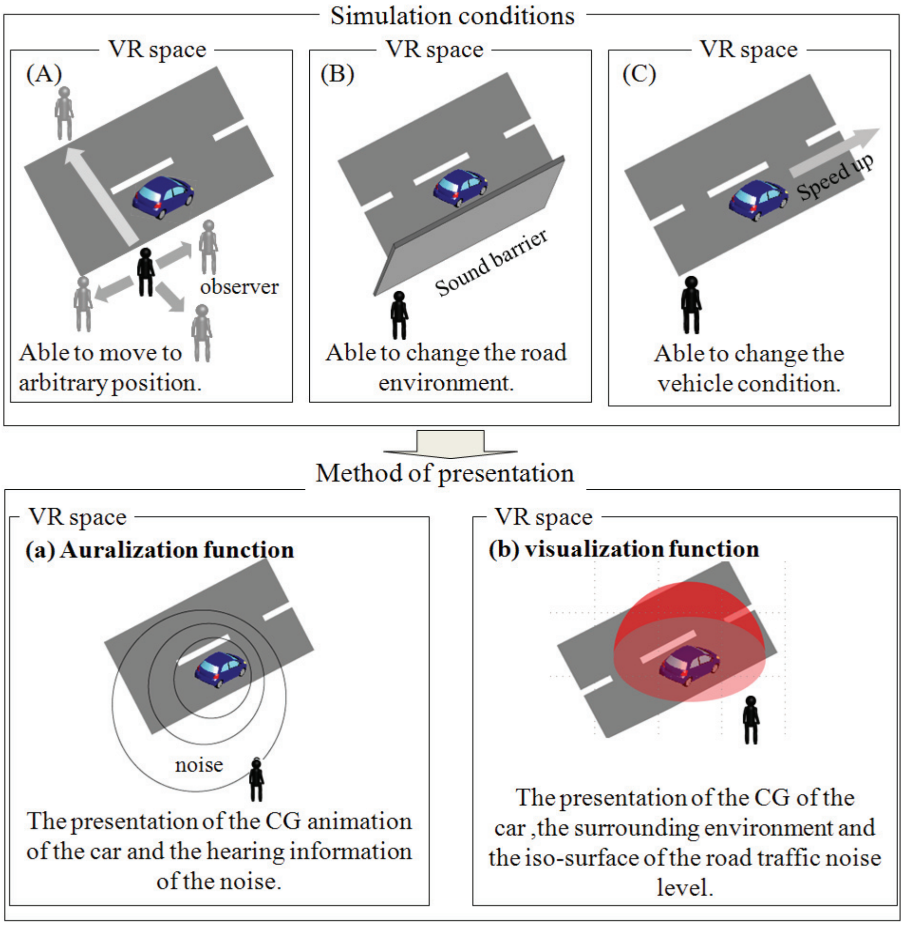
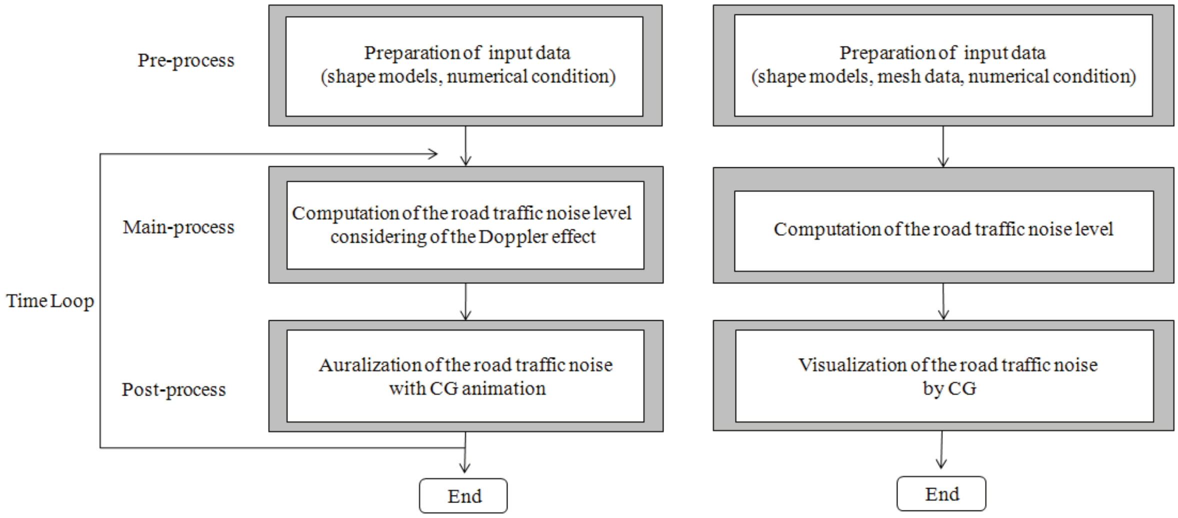


FIG.1: The concept of the present system

The procedure of the auralization function and the visualization function are shown in Figure 2 as a flow chart. The details of each process are explained as the following text by using Figure 2.



(a) Auralization function (b) Visualization function

FIG.2: Flow chart of system

2.1 Pre-process

2.1.1 Input data for auralization function

The shape model of the vehicle and surrounding environment of the roads (such as the building, elevated bridge etc.) are created by the 3D CG and CAD software (3dsMax and AutoCAD: Autodesk). The polygons of shape model are reduced in order to speed up the rendering time. The input data for computation of the road traffic noise level are as follows; the position information of the car, driving condition, and surrounding environment of the road. The position of the reputation sound point is captured all the time by the motion tracking device in the VR space.

The start of vehicle driving animation is synchronized with the operation of the controller when the auralization function is selected.

2.1.2 Input data for visualization function

The mesh data is prepared in addition with the data for shape model and the input data for computation of the road traffic noise. The mesh data is needed for the visualization of the iso-surface of the road traffic noise level by CG image. The mesh is based on tetrahedron element, the total number of nodes and elements are 67,626 and, 375,000 respectively (the mesh size to the horizontal direction of the road cross section, to the plumb direction and, to the depth direction, are assumed to be 2m, 1m, and 2m respectively). The value for iso-surface of sound pressure level is also specified for the input data in the case of the visualization system.

2.2 Main-process

2.2.1 Computation of road traffic noise level

In this system, the road traffic noise level is computed by the ASJ-RTN Model 2008 (Yamamoto, 2010) that is developed by the Acoustic Society of Japan. As the model is based on the geometric acoustic theory, it is possible to evaluate the sound pressure level in real time.

The computation is performed using the position data of the vehicle, the observer, and the surrounding environment in real-time using a motion tracking system. The change of frequency by the Doppler effect is also considered. The details of computation of Doppler effect, A-weighted sound power level L_{WA}, direct sound propagation L_A^d and reflection sound propagation L_A^r are referred to references (Yamamoto, 2010; Tajika et al, 2009; Tajika et al, 2010).

In this paper, the details of computational methods of sound propagation are described in case that an elevated bridge and a building are considered for the surrounding environment of the roads. The mirror image is employed for the computation of reflection sound.

① The computational method considering an elevated bridge.

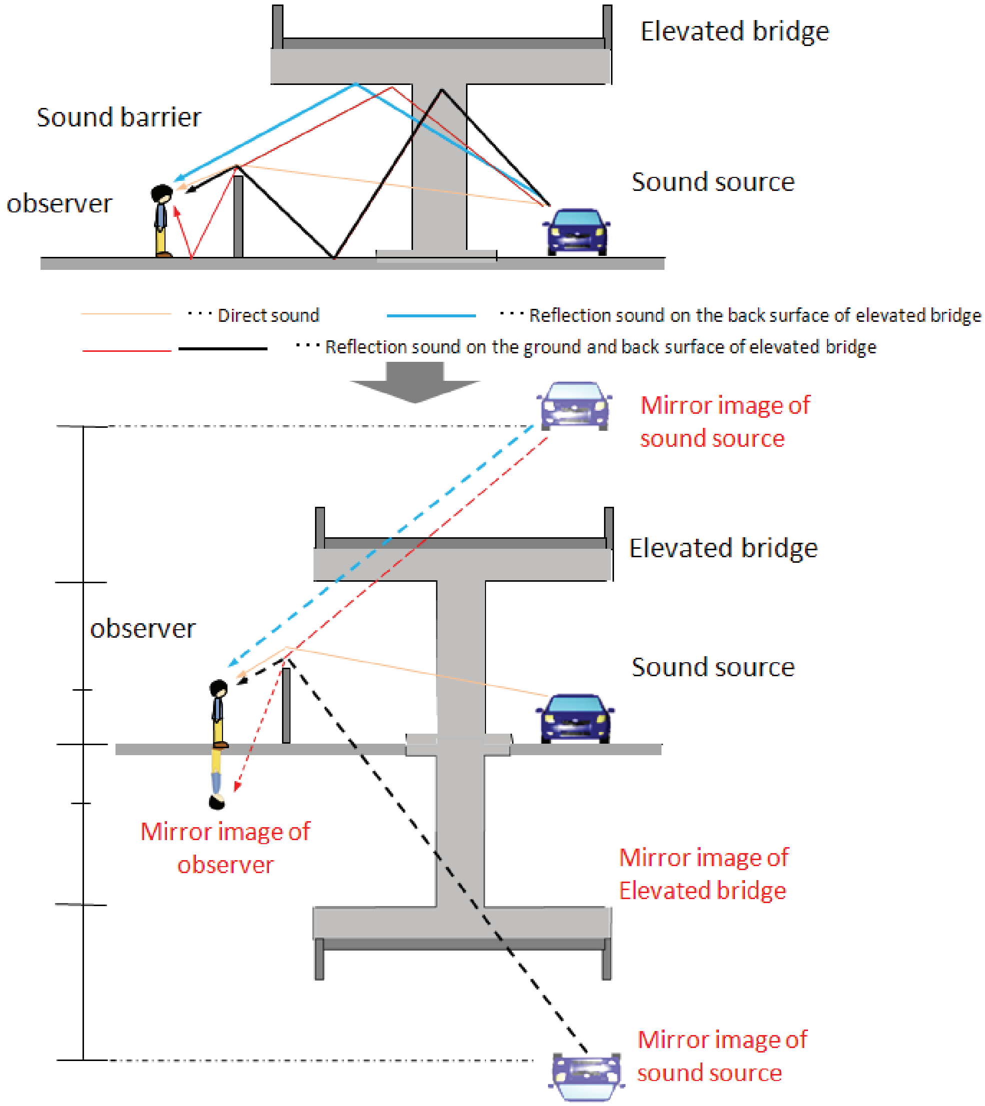


FIG.3: Computational method with an elevated bridge

Figure 3 shows the computational method with an elevated bridge. The upper figure of Figure 3 shows the physical situation for sound source, observer's point, and mirror image sound source. The lower figure denotes the computational situation using mirror image which is equivalent to the physical situation. The A-weighted sound pressure level L_A is expressed as:

$$L_A = 10\log_{10}(10^{L_{A,0}/10} + 10^{L_{A,1}/10} + 10^{L_{A,2}/10} + 10^{L_{A,3}/10}) \tag{1}$$

Where $L_{A,0}$ is the direct sound, $L_{A,1}$ is the reflection sound on the back surface of elevated bridge, and $L_{A,2}$, $L_{A,3}$ is the reflection sound on the ground and back surface of elevated bridge.

$L_{A,1}$, $L_{A,2}$ and $L_{A,3}$ is computed from:

$$L_{A,i} = 10\log_{10}(L_{WA} - 8 - 20\log_{10} r_i + \Delta L_{dif,sb,i} + \Delta L_{refl,slit,i} + \Delta L_{abs}) \quad (i = 1\sim 3) \tag{2}$$

Where L_{WA} is A-weighted sound power level, and r_i is the direct distance from the i-th sound source's point of mirror image to the observer's point. $\Delta L_{dif,sb,i}$ is the correction factor of the diffraction due to the sound barrier from the i-th mirror image sound source, $\Delta L_{refl,slit,i}$ is the correction factor by the effect of the reflection, and ΔL_{abs} is the correction factor of the sound absorption at the bottom of the elevated bridge.

② The computational method considering a building.

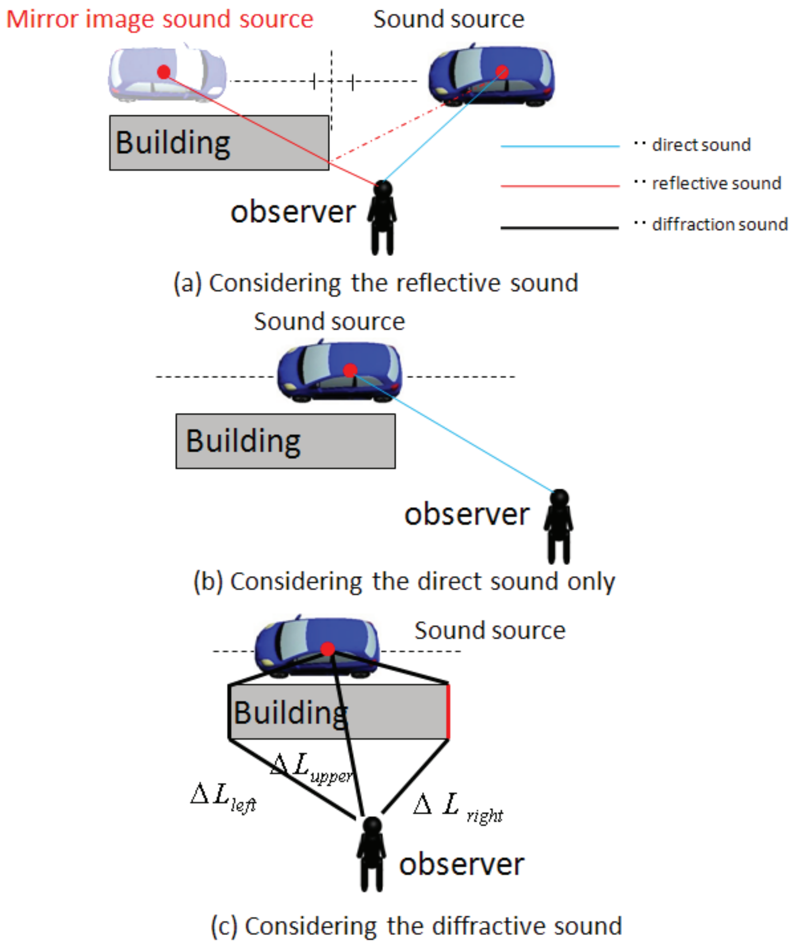


FIG.4: Computational method with a building

Figure 4 shows the several situations with a building. The A-weighted sound pressure level L_A around the building is computed as:

$$L_A = 10\log_{10}(10^{L_{A0}/10} + 10^{L_{A1}/10}) \tag{3}$$

Where $L_{A,0}$ is the direct sound or diffraction sound, $L_{A,1}$ is the reflection sound due to wall.

The wall reflection $L_{A,1}$ is expressed as:

$$L_{A1} = L_{WA} - 8 - 20\log_{10} r_1 + \Delta L_{b-refl} \tag{4}$$

Where L_{WA} is A-weighted sound power level, r_1 is the distance from the mirror image sound source to the observer's position, ΔL_{b-refl} is the correction factor of by the effect of the reflector. The detail of the computation of the direct sound $L_{A,0}$ is referred to references (Yamamoto, 2010; Tajika et al, 2009; Tajika et al, 2010).

2.2.2 Consideration of Doppler effect

The change of frequency by the Doppler effect is considered as follows.

$$f' = f\left(\frac{U}{U - u_s\cos\theta}\right) \tag{5}$$

Here f is frequency of sound source, U is sonic speed, u_s is velocity of sound source (vehicle), θ is angle between straight line from sound source to observer and direction of movement of sound source (see figure 5).

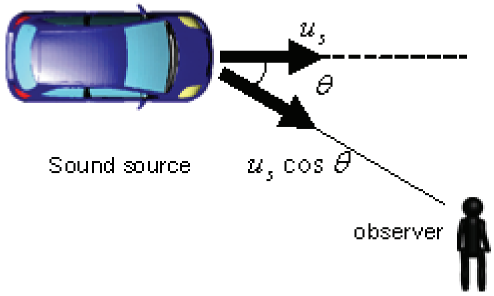


FIG.5: Computational of the Doppler effect

2.3 Post-process

2.3.1 Auralization of the road traffic noise

The CG animation is presented with the acoustic information at every time step. The CG image is created by the visualization system based on the Open-GL and CAVE library. The acoustic information of road traffic noise is created using the Max/msp (Akamatsu and Sakonda, 2006). The road traffic noise level, the frequency and the wave file of vehicle noise are prepared as the input data for Max/msp. Those three data are input at every time step for creating the CG animation with the acoustic information.

2.3.2 Visualization of the road traffic noise

The CG image of the iso-surface noise is created by the visualization software developed by Open GL and CAVE library. User can specify the sound pressure level by using the controller.

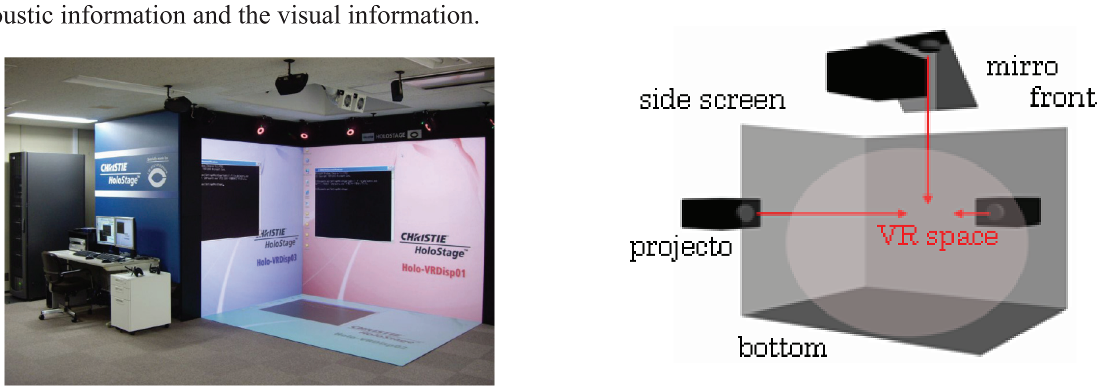
The sound pressure level is computed at every nodes of the mesh for visualization. The iso-surface of the sound pressure level is created at element-wise using the linear interpolation function. In order to improve the solidity, the rendering technique is employed for the visualization.

3. CREATION OF THE VR SPACE

3.1 The outline of VR system

3.1.1 VR system based on IPT

The IPT (Immersive Projection Technology) is employed for VR technology and the immersive display is employed for VR display. Figure 6 (a) shows the VR system “HoloStage” in Chuo University and Figure 6 (b) shows the VR projector and display system. This system is composed of three large and flat screens and high-performance projectors corresponding to the screen. The front and side screens are transmissive ones and the bottom screen is reflective one. The VR space is created by projecting the image on the front and side screens, and the bottom screen as shown in Figure 6(b). This system has 7.1ch sound speakers and the VR space is created by the acoustic information and the visual information.



(a) (b)

FIG.6: VR system based on IPT

3.1.2 Computer hardware and network

The HoloStage has a PC cluster system consists of one master-PC and four slave-PCs. The specifications of the PC cluster are shown in Table 1. The Giga-bit Ethernet is employed for the network of PC cluster. Figure 7 shows the network configurations. A slave-PC computes the coordinates of location of viewpoint sequentially. Other 3 slave-PCs create the stereoscopic image for each screen from the view point.

TAB.1: Specifications of PC Cluster System

Master-PC	
Machine	HP xw9300 Workstation
CPU	Dual Core AMD Opteron (tm) 2.4GHz
Memory	8GB
Graphics Card	Nvidia Quadro FX4500 ×2
Slave-PC ×4	
Machine	HP xw9300 Workstation
CPU	Dual Core AMD Opteron (tm) 2.4GHz
Memory	8GB
Graphics Card	Nvidia Quadro FX4500 ×2

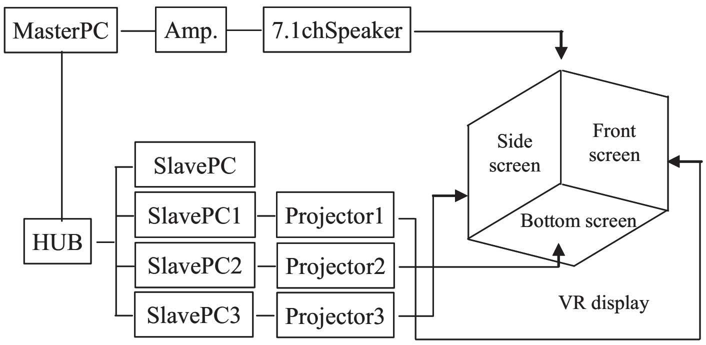


Fig.7: Network Configuration

3.1.3 7.1ch sound speakers

The Holostage has a 7.1ch sound speaker system (7 speakers and a sub-woofer). Figure 8 shows the layout of the system. The speakers are connected to the master-PC (see Figure 7) and output the sound which is reproduced by master-PC. Each speaker outputs the same sound in the system.

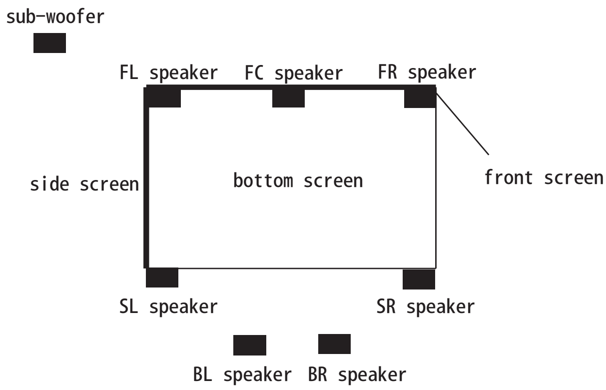


Fig.8: Layout of 7.1ch sound speaker

3.2 Application example for the auralization function

In order to verify whether the computational sound pressure level agree with the traffic noise from the stereo speaker, the output sound was measured by the sound level meter (LA-2560 : ONOSOKKI). The sound level meter was set up on height of 1.4m. Figure 9 shows the condition of the test when the auralization function is selected. Figure 10 shows the unit pattern of the computational and measuring results after calibration. The input data of noise level to MAX/MSP was calibrated to match the computational results to measuring results. From this figure, it can be seen that the computational results are in good agreement with measuring results.

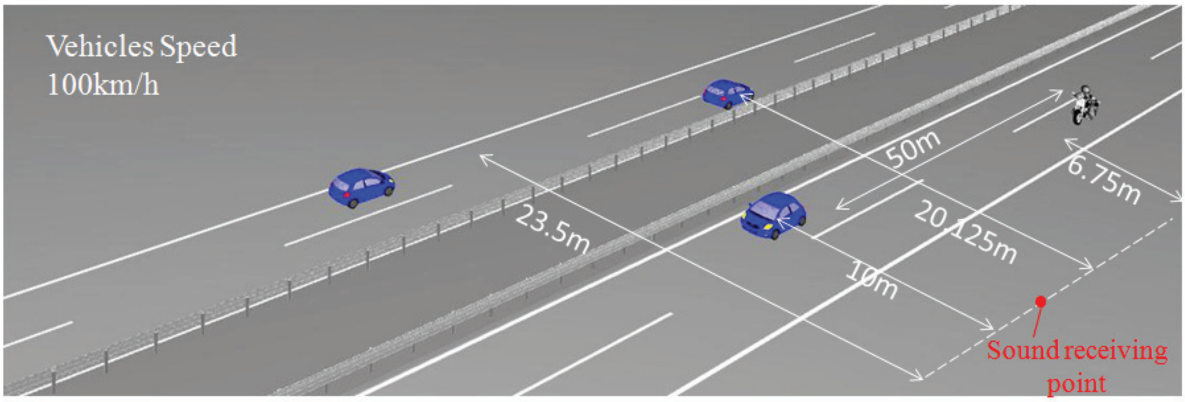


FIG.9: Application example for the auralization function

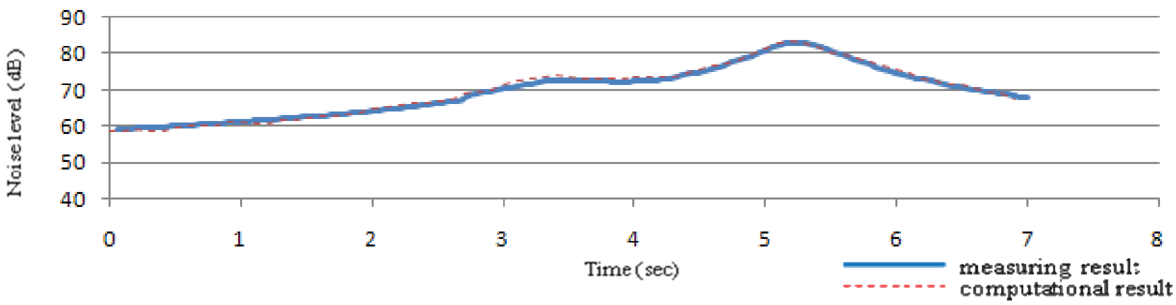


FIG.10: Unit pattern of the example

3.3 Application example for the visualization function

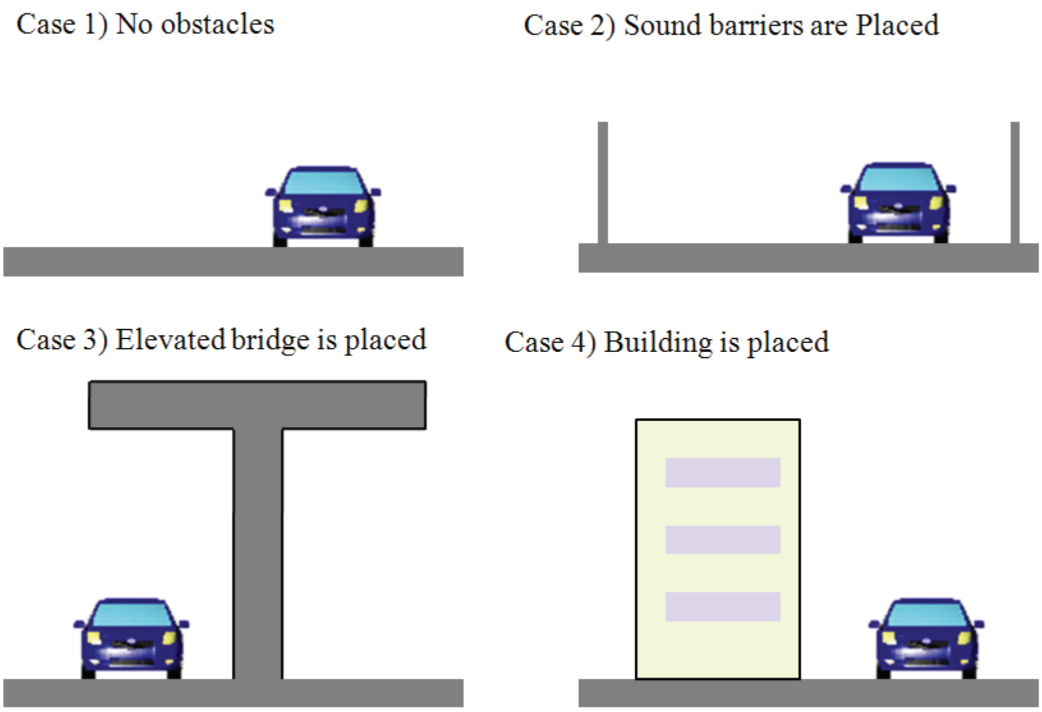


FIG.11: Application examples for the visualization function

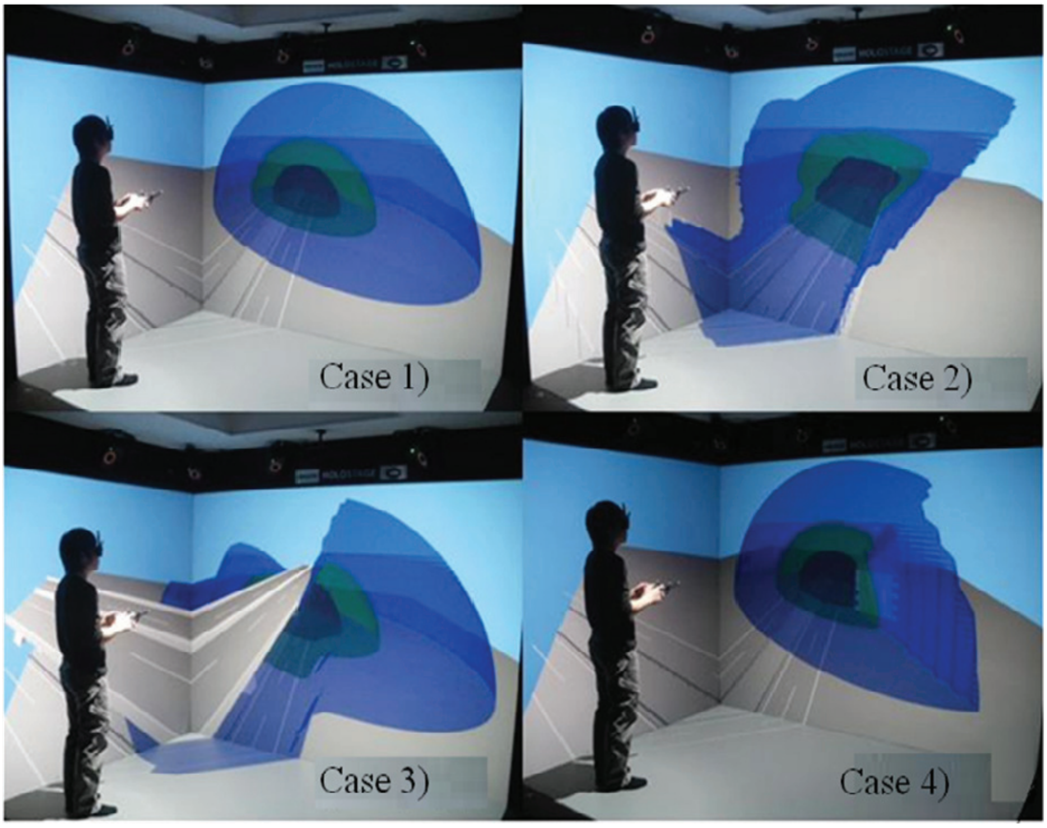


FIG.12: *Computed iso-surface*

Figure 11 shows the numerical examples for Case 1) – 4) when the visualization function is selected. There is no obstacle in the case1), the sound barriers are setting beside the road in the case 2), the elevated bridge is placed in the middle of road environment in the case 3), and the building is placed near the road in the case 4). The sound pressure levels created are assumed to be 50, 55, and 60dB.

The results are shown in Figure 12. It can be seen that the perfect hemisphere is created in the case 1) because there is no structure around the vehicle. In the other cases, it can be seen that the noises are transmitted reasonably with reflection and diffraction, in accordance with the geographical conditions.

User can understand the spatial distribution of the noise level easily by the visualization function.

4. CONCLUSION

In this paper, the experienced-base road traffic noise evaluation system using virtual reality technology has been presented. In order to improve the applicability of the system, the effect of an elevated bridge and a building has been considered for the surrounding environments of roads. Moreover, the system with visualization function that can present the spatial distribution of the noise level has been presented. The key features of the present system are as follows.

・The system with auralization function provides the road traffic noise as the acoustic information with a CG animation. From this system, the user can understand the noise level more naturally and concretely.

・The system with visualization function provides the iso-surface of the noise level. From this system, user can understand the spatial distribution of noise level easily.

From the results obtained in this paper, it can be concluded that the present system provides a useful tool to predict the road traffic noise in planning and designing stage of road. The verification of the present system to the complicated road environment is left in the future work.

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