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A framework for construction safety management and visualization system

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ABSTRACT

With recent rapid advancement of visualization technologies, recognized research work for improving construction safety management practices has been conducted for identifying safety risks as well as worker onsite training. However, most of the previous studies were limited to reflect the site safety management process, which normally consists of planning–education–inspection phases. This study proposes a framework for a novel safety management and visualization system (SMVS) that integrates building information modeling (BIM), location tracking, augmented reality (AR), and game technologies. A prototype system has been developed and tested based on an illustrative accident scenario. The potentials and technical limitations of the prototype SMVS have been evaluated by site safety experts. A case study was also implemented, whose results show that the SMVS has a great potential to improve the identification of field safety risks, increase the risk recognition capacity of workers, and enhance the real-time communication between construction manager and workers.

1. Introduction

Construction accidents are related with various project factors such as site layout, materials, tools and equipment and trade workforces that make up a volatile site environment. The fatal accident rate in the construction industry tends to be higher than that of other industries [32,36]. Various studies related to construction safety asserted that most accidents on the site could have been reduced and prevented with the establishment of proper and consistent safety management process or program of planning, education/training, and inspection. In particular, the safety management process should be well planned so that it enables site managers and trade workforces to not only easily identify and recognize safety risks but also communicate with each other during the construction process [30,34].

In general, the safety information being used on sites does not reflect the factors involved in the real construction work environments, which makes it more difficult to identify latent safety risks and deliver the right information at the right time to the right workforces during construction work [8]. Further, the increasing number of foreign labors in international construction projects requires more visual-based straightforward safety training methods and solutions for better understanding and recognition of safety risks [17]. For these reasons, some notable visualization techniques such as building information modeling (BIM) [18], game technologies [9,23], virtual reality [10], and augmented reality [27] have been utilized to improve the current safety management practices. The proven benefits of these techniques are as follows: (1) improved working memory ability; (2) increased cognitive ability of spatial information; and (3) better reliance on past experience and memory [6,11,14]. However, those studies have focused on the technical applicability on specific safety task and/or phase such as game-based safety education and virtual site modeling for safety control, but have not considered their applicability into the entire process of construction site safety management.

The aim of this paper is to propose a system framework for construction site safety management and visualization system that reflects the continuous process of safety planning, educating, and inspection, within which BIM, AR, location tacking, and game engine technologies are integrated. The technical feasibility of the system has been examined with a real site accident case that occurred in the formwork and reinforcement work of an educational building project.

2. Visualization technology applications for construction safety management

Recently, visualization technologies are being advanced and their application potentials are being increased, yet their utilization in construction practices is not much prevailing in comparison with that of other industries. In this section, current state-of-the-art visualization applications are reviewed in the context of construction safety management process, which normally consists of planning, education, and inspection phases. This section also investigates its application potentials and limitations as well as a way of integrating various visualized technologies within one single integrated safety management and visualization system.

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Safety planning in the construction site begins with the identification of safety risks inherent in the project through a team meeting with the construction manager, safety manager and trade site manager. At the meeting, typical information sources such as drawings, accident cases, and heuristic knowledge are often used to prepare prevention measures against expected safety risks. The problems and limitations of using those information sources for construction safety planning were well identified, which mainly resulted from not being able to reflect real field circumstances [13]. Hadikusumo et al. [10] insisted that the field environments can be reflected in 3D engineering modeling. Li et al. [24] proposed a 3D virtual site modeling that represents real construction site situations such as equipment, temporary facility, stockyard and workforce. With the model, a safety plan of 6-day cycle building construction was prepared and its applicability was examined. Furthermore, several other studies have performed to develop virtual models linking safety information and work schedule. Chau et al. [2] developed a simulation model that enables the linking between geometrical models with CPM or Bar-Chart which could be helpful for predicting the occurrence of potential site problems. Sulankivi et al. [31] exemplified a 4D BIM of a rule-based safety checking system for falling accidents linked with safety guard and railing installation schedule. There are some approaches of interconnecting 3D spatial information with general safety information database like heuristic knowledge, case report, and manual in geometrical schedule simulation model [10] or virtual 3D model [1].

The trades in the construction site need to be educated about the safety risks identified in the planning phase. For effective education and training, the educational materials must reflect specific project site circumstances. Kim et al. [16] insisted that the education and training session should be focused on workers' understanding of site safety risks in terms of 'work location', 'type of work', 'type of risk', and 'behavior risk exposure.' However, it is a time-consuming and costly task to develop a project-specific safety educational material, so the safety education and training in the site, in general, offer the introduction of personal protective equipment (P.P.E.) usage and generalized accident cases and occasionally the utilization of expensive pre-experience facility of fatal accidents [7]. Hence, there have been some studies to develop education and training tools using BIM and game simulation techniques. VTT [18] developed a safety BIM model for education/training and better recognition of safety risks at building job sites. Xie et al. [35] presented a video simulation model using generalized safety information to improve worker's risk cognition. Guo et al. [9] examined the applicability of the game technology to improve the cognition of operating risk of plant facility in advance. Li et al. [23] developed a multiple choice game system using the OSHA guideline for the enhancement of both safety training and visualization of workers' safe behavior. The game engine would be a helpful tool to generate a virtual site model based on geometrical information in BIM software and to link schedule with possible risk information as well. It could allow workers to accomplish their safety missions to eliminate dangers in a virtual reality site for the purpose of safety education and training.

It is the most important task of site safety manager to inspect safety equipment and facility continuously as well as to control workers' behaviors efficiently during the construction process. In general, the safety manager checks as-planned prevention measures and potentially unsafe behaviors of workforce on a regular daily, weekly, and monthly inspection basis [28,29]. The inspector and/or safety manager identifies and records unsafe conditions and inadequate usage of prevention measures and then delivers the safety risk information to trades [5]. During such inspection, materials such as photos, drawings, videos, risk assessments and checklists are limited to facilitate quick and effective communication between inspector and trade workforce [3]. With this regard, AR technology can widen the range of human recognition and their thinking by augmenting relevant activities with digital contents [33]. Mizuno et al. [27] introduced the AR application for displaying hazard information such as pipe locations and electrical lines that would get damaged by road repairing and demolition work. Lee et al. [22] developed an AR application for operation and maintenance work, which appends virtual components to be repaired or maintained to real existing components and enables workers to easily recognize work to do and job location as well.

From the successfully performed projects, there are critical issues to be solved in the site safety management process: one is the efficient identification of activity-specific safety risks and its delivery [12,20,21] and the other one is the communication with trade workers at real-time [3,4,15]. Since the safety risks on the site are often closely related to construction materials, equipment and human locations on the site, positioning these resources by using location-tracking technology would be helpful to deliver the right safety information to the right person in volatile site environments. GPS is capable of identifying the location within 30 cm error by using a receiver, however it is difficult to identify the location and direction of indoor environments [26]. Recent numerous sensor networks such as blue-tooth, active RFID (radio frequency identification technology), and WAP (wireless access point) networks near work sites allow much efficient location tracking [19]. The sensor signal used for mobile utilities such as smartphones and tablet PCs would be beneficial to identify and share the precise location information of where accident risks are.

With this reality in mind, it is worthwhile to mention how the field safety issues would benefit from advanced visualization techniques. It can be summarized as follows: (1) by taking advantages of recent advancement of BIM technology, the generation of virtual reality construction site became much easier; (2) the proven game technology would be utilized as a safety education tool to enable workers to pre-experience activity-specific safety risks; and (3) location tracking technology linked with AR has a great potential to facilitate real-time and location-based field safety management together with mobile devices such as smartphones and tablet PCs. However, to apply these advantages in field safety management, the technologies are integrated in a unified system. Also it is adoptable for field work process [25]. The key issue in integrating these technologies is how the visualization of site conditions and real-time location information can be interactive. The issue can be eased by using a game engine that does not require programming knowledge and has no limits to compatibility among various databases [6].

3. System architecture of SMVS

A framework of SMVS is developed which reflects the typical field safety management process (planning, education and training, and inspection phases). The three phases are modularized in the SMVS. The modules are linked with a visualization engine for the integration of all the information generated in each module within a system. The system architecture of the SMVS and interrelationships between three modules and the visualization engine are illustrated in Fig. 1.

The visualization engine is a hub of the SMVS that imports and exports external information such as BIM-based site model, safety information data, and sensor signal location data that is created in other software engines for its use in each system module. In the development of system module interfaces of the SMVS, the Microsoft XNA Game Studio 4.0 program environment has been employed considering the interoperability of data necessary to the system operation. All the necessary information from/to interfaces of three modules is displayed on visualization engine browser (VEB). The functions of system components of each module are detailed in the following sections.

3.1. Planning module

The planning module is devised for safety managers to identify the risk factors and relative safety information on the basis of project activity. This task would be performed through a meeting of safety managers and trades using a pre-designed virtual project site model

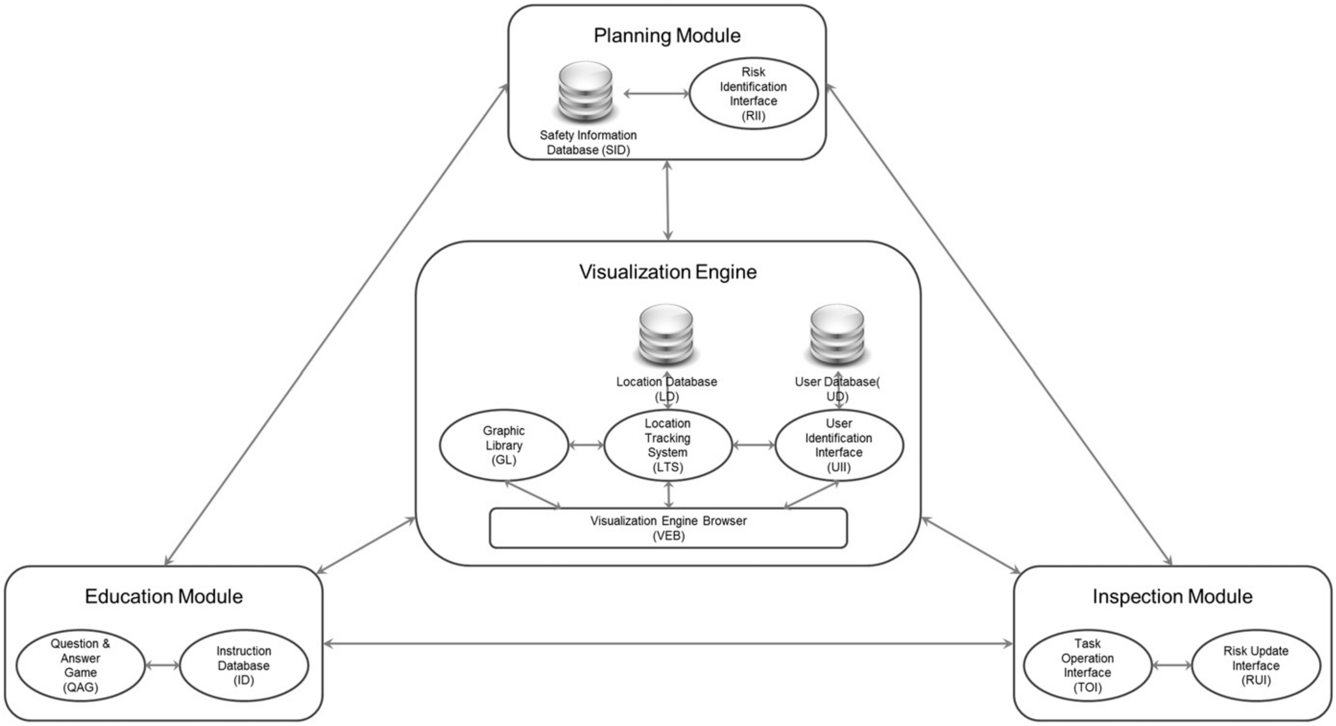

Fig. 1. System architecture of SMVS.

in the graphic library (GL) of the visualization engine that represents 3D design as well as required site safety facilities of a project.

The identified safety risks and relative information such as materials, equipment, unsafe conditions, accident cases, and checklists are extracted from a safety information database (SID) and then interact with the virtual site model for the use of both education and inspection modules. The SID is structured on the basis of a trade-oriented work and activity breakdown and is able to store both permanent and temporary information being processed in the safety planning, education and inspection modules. Whenever the education and inspection tasks have been done by trades and inspector, the SID will be updated.

For the efficient extraction and filtration of activity-related safety information, risk identification interface (RII) has been designed using XNA 4.0 in this module, which allows the safety manger to confirm the current state of workers' safety education as well as the planned field inspection. In addition, some new risk factors found during the safety inspection process would be automatically stored in SID for the future use. (Refer to Fig. 5 for the actual SID and RII screen images implemented in the prototype SMVS.)

3.2. Education module

The risk factors of each activity identified in the planning module are trained by using question and answer game (QAG). The QAG has been designed for workers to pre-experience safety risks virtually prior to the work execution, by which the capability of workers is examined in terms of risk cognition and safety behavior. During the game exercise, a worker avatar moves around activity areas in the virtual project site model and faces a question on how to behave on the pre-assigned site risk situation that is identified in the planning module. Regardless of whether workers choose the right or wrong answer, the safety instruction of relative photos and videos that are stored in the instruction database (ID) are presented to improve workers' cognition of safety risks related to work activities. The game continues until the worker answers correctly.

In this module, the worker's activity location and circulation are automatically tracked by interlocking with a location tracking system (LTS) in the visualization engine. The finished education list of each worker is transmitted to the planning module to be checked by the safety manager. Also, new risks found during the field safety inspection are notified to both education and planning modules for additional education. (Refer to Fig. 7 for the actual QAG and ID screen images implemented in the SMVS.)

3.3. Inspection module

This module has been designed for inspectors to efficiently check accident prevention measures during the field inspection process. The locations of risk element and relative safety information are augmented on a real work place. Using this AR information, cognition of site hazard elements of trade workers could be increased and also site safety inspection task would be performed efficiently.

The inspection module consists of the task operation interface (TOI) and risk update interface (RUI). The TOI allows inspectors or workers to move around the work place looking for the augmented safety information and checklists on a mobile device. A datum point is transmitted to the location tracking system (LTS) and then the location point is interworked with the virtual site model in GL in the visualization engine. Then the finished inspection list is stored in the SID of the planning module. On the other hand, the RUI is designed to store and transmit photos and relative information of the safety risks found during the inspection process to the SID for use in the education and inspection modules during the work process. (Refer to Fig. 6 for the actual TOI and RUI screen images implemented in the SMVS.)

3.4. Visualization engine

The visualization engine of the SMVS has been developed by using the Microsoft XNA Game Studio 4.0, which consists of graphic library

(GL), location tracking system (LTS) and location database (LD), user identification interface (UII) and user database (UD), and visualization engine browser (VEB). All the necessary information required from users of the SMVS modules is displayed through the visualization engine browser (VEB). The visualization engine is mutually connected with all modules of the SMVS via wireless communication and local area network.

The GL imports the BIM-based virtual site model as a library that includes geometrical building model as well as field safety facilities. The location information of the model interacts with LD and LTS according to project schedule and activity. In order to ensure the effectiveness of worker's education and manager's inspection, it is essential to provide the right information for workers and inspectors. The LD contains six kinds of location data: (1) location criteria (ex: scale, direction, datum point etc.) to convert BIM data to virtual construction site model; (2) component locations such as x, y, z, coordination; (3) hazard risk element locations identified in planning phase and inspection phase; (4) boundary condition of risk element to provide educational information; (5) mobile utility location calculated from sensor network signals; and (6) relative distance between risk element and mobile utility. The locations of criteria, components, and risk elements are fixed, while locations of mobile utility and relative distance value are continuously changed. The LD interacts with LTS for the use of education and inspection module.

The user of the SMVS is necessary to be grouped according to the user of each module of manager and trades. The UD stores IDs classified into company, trade, worker, and activity. The UII is a system gate, which authorizes user access to each module and allows providing relative safety information as well.

3.5. Field application process of SMVS

For the clear explanation of the structure and interaction between modules of the SMVS, it is worthy to describe the system application process in the construction site in the order of safety planning, education, and inspection phases, as illustrated in Fig. 2. It should be noted that all of the screen images in Fig. 2 are actual images captured from a case study conducted for the test of field applicability of the prototype SMVS.

At first, the safety manager obtains a project BIM model and adds required safety facilities to create the virtual site model, then the virtual model is converted with the FBX file format and stored into the graphic library (GL) in the visualization engine. Using the virtual site model and project schedule, the activity-based safety risks are identified through a team meeting with the construction manager, safety manager, and trade contractor and also relative safe information is extracted from the safety information database (SID). The relative information interacts with safety risks and utilized for both worker safety education and field safety inspection. Once a safety risk is determined in the planning module (Fig. 3a), the education media and checklist are loaded. By picking a component in the virtual site model, the safety manager assigns risk. Afterwards the safety manager specifies trade contractors working near the safety risks for Q&A game education. When the risk is assigned its location is automatically stored in the location database (LD). The appointed risk is shown in the virtual model as a color point. The color of the point indicates management status. When the point is initially assigned the color is red. Depending on the result of inspection, the color of the dot is changed directly after inspection. If the color remains red, it means trades do not follow the safety management plan. Otherwise, if the mark color is changed to green it means the accident risk is effectively prevented. In the case of yellow, the current plan or safety measure needs additional action (Fig. 3b). By using the colors, the safety manager efficiently gets the status of safety management. Also by sharing the status and listed information through the web environment, trade leads directly get the problem and dynamically make a decision.

For the safety education, trade workers access the SMVS via company and name ID and choose their activities. Then a worker avatar moves around the virtual site. When the avatar comes close to assigned safety risks point, the warning message appears first. Getting closer to the risks allows the worker to face it and the Q&A game begins. The worker must perform the game until he answers the entire risk related question in the virtual construction site. By choosing the answer of the following pictures they will get the result from the module. If the worker does not choose the correct answer, they will see instruction with education media. Also the result of the education module (i.e. percent of correct answers) will transfer to the planning module (Fig. 3c). The result of

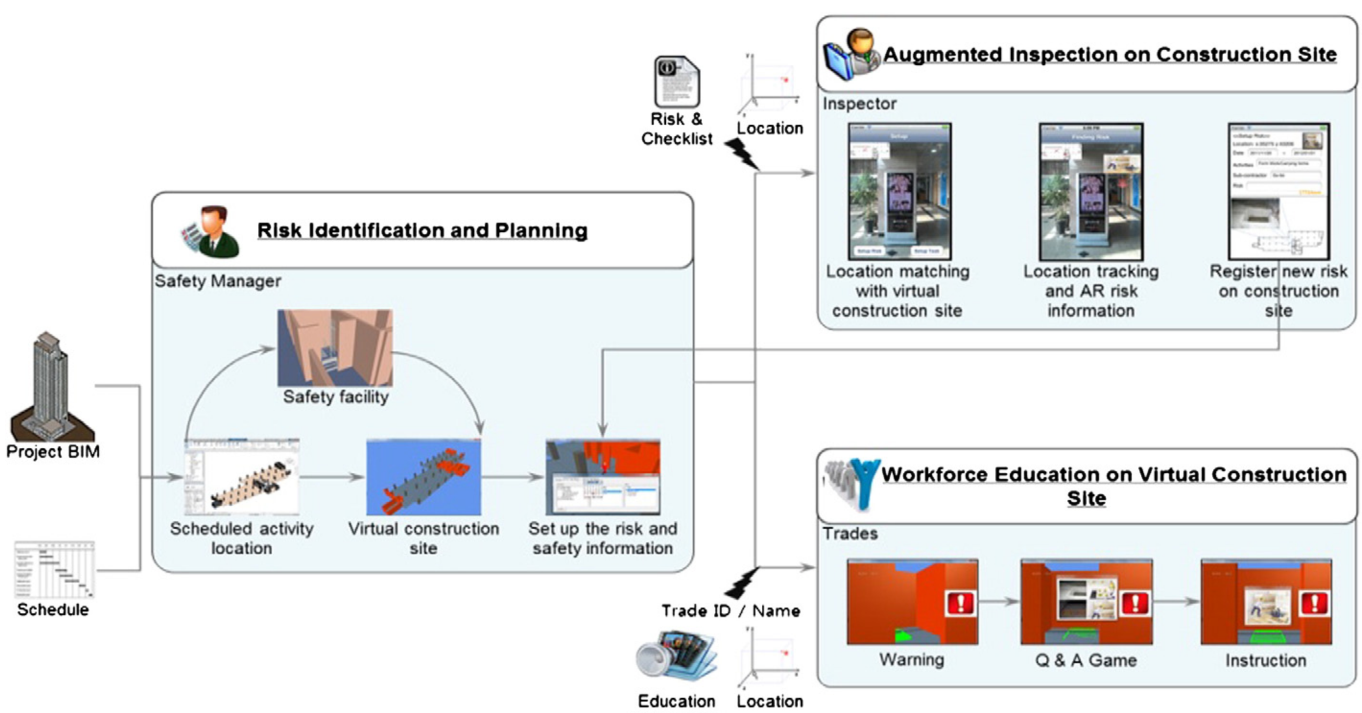

Fig. 2. An application process and information flow of SMVS.

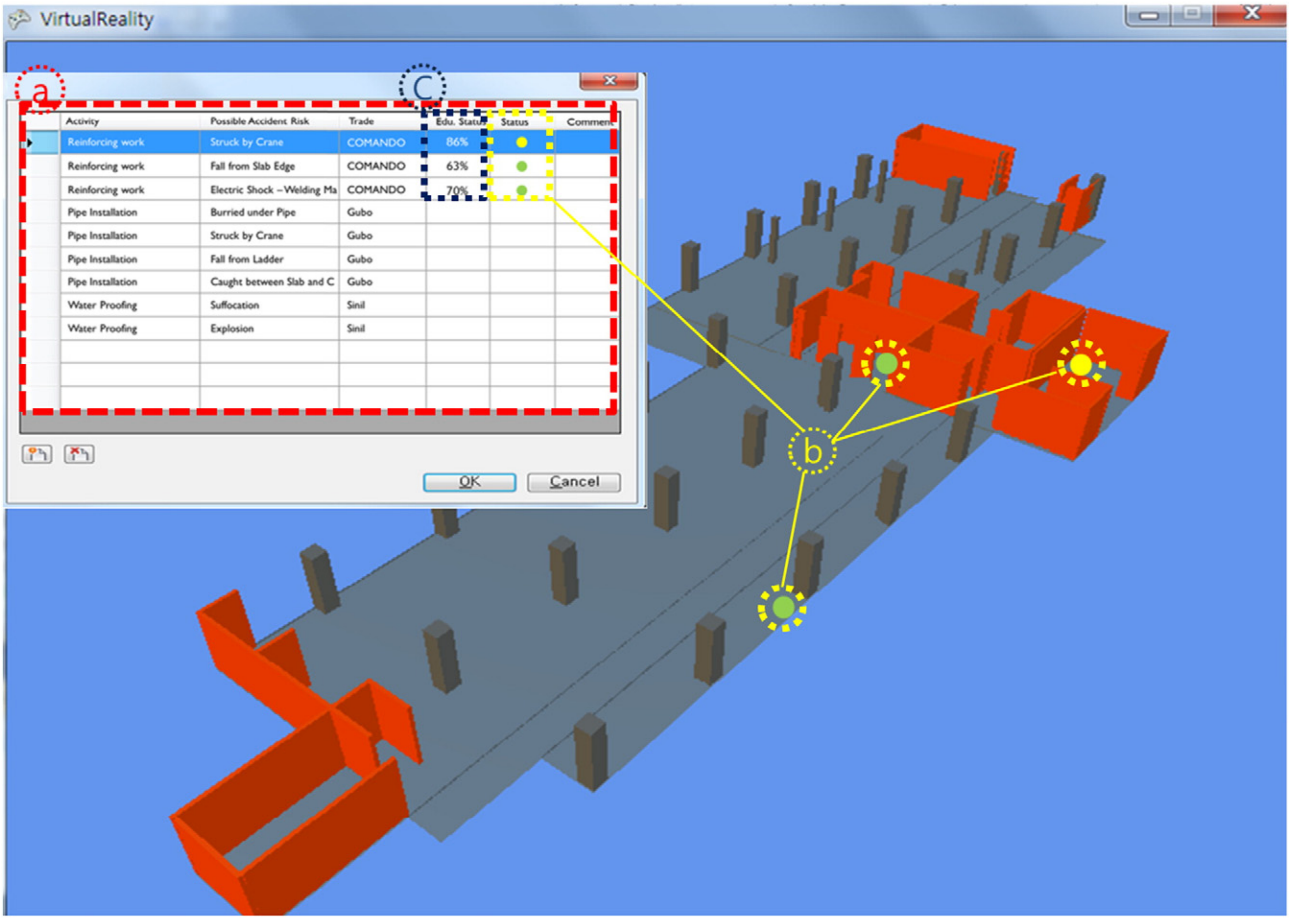

Fig. 3. Determined risk list. a. Accident risks from SID, b. assigned risks and its status, c. education status.

the education module is calculated as the average value of total worker's percentage of correct answers during the education. If this value is low, the trade has low safety knowledge. Therefore, the trade is more intensive observation or education. When the inspector goes to the real construction site for regular inspection work, he matches a random point extracted from the virtual site model with his location in the real site by sensor networking between AP and mobile utility of inspector. Then the location tracking system (LTS) calculates the relative distance between inspector and risks on the virtual construction site. Depending on the distance and device direction, TOI delivers and displays relative safety information and checklist on the inspector's mobile device during site inspection. This augmented information gives the manager a chance to capture the overall safety status in the construction site. From the location of the manager or trades they could see the brief information of risks through their mobile device display (Fig. 6). After the inspector checks safety measures in the site, the situation is recorded and transmitted to the safety information database (SID). In addition, new safety risks that occurred due to improper work are informationized at the site for the use of future education and inspection, which allows trade workers to be educated and notified at a real-time basis.

4. Case study for the test of field applicability of SMVS

4.1. Prototype system setup

A safety management scenario for a real site accident case has been designed for the test of field applicability of a prototype SMVS. The XNA 4.0 Game Studio, Revit 2012 Architecture for BIM modeling, Xcode 4.2 simulator for iPhone AR applications, and 54 Mbps WAP network for location tracking have been employed for prototype development.

4.2. Introduction of the case scenario

The field safety accident case occurred during the formwork and reinforcement work of an educational building project. More than half of the workforces in the site were foreigners. Weekly safety management plan was set up, including daily safety inspection and weekly safety education for workers, which covered one-week long construction work in the site. During the week, assembling steel bars for walls at the 4th floor would be done and at the same time steel pipes that would support the 2nd floor had to be lifted to the 4th floor for slab formwork. In this work process, the workers faced two kinds of safety risks of 'struck by vertical reinforcement of wall' and 'improper work of lifting supports through pipe shaft opening of the building.' The safety risk of 'struck by wall reinforcement' was predicted and identified in the safety meeting. However, since the pipe shaft opening was planned to be covered with concrete mortar, it was not considered to be dangerous at the safety meeting. This opening safety risk was then identified during the inspection and then the fences around the openings were installed. However, the workers removed the fences for their work convenience. Two days later, some new hired workers came in the construction site. Although they had been through a safety training program that morning, the workers could not recognize the opening on the site. As a result, one of the new workers was injured by falling down into the opening. With that in mind, the construction manager and the safety manager of the project wanted to have a new approach for field safety management using some advanced visualized technology.

4.3. Implementation of the prototype SMVS

The safety manager obtains a BIM site model related to the activity of formwork and reinforcement and then convert it to FBX file format to use the model in the SMVS environment. At the same time, the safety manager exports the coordination and property information of elements to the system. In this process, the schedule, activity and sub-contractors' ID are set up and also relative safety information of the activity is loaded to the system database. The database contains accident cases, educational materials, and checklist for inspection. Fig. 4 illustrates the BIM based site floor model made of Revit Architecture 2012 in the left, the right for the FBX converted virtual site model, and the middle for coordination input window.

The safety manager has a meeting with a reinforced concrete trade contractor to identify safety risks in the virtual site model with a worker avatar. Wall reinforcing work at the 4th floor is chosen as a hazard activity and an elevator space nearby walls is assigned as a related safety element. Then the safety manager picks the wall and inputs some constraints by checking the 4 day work duration and authorizing the trades to use this hazard situation for worker education. And then checklists for the wall reinforcing works such as 'bracing installation' and 'cover the cap over the top edge of rebar' are chosen for the use of field inspection and relative photos and videos showing accident scenes are selected for the education of this safety risk. Fig. 5 illustrates the virtual site model and the input window of the risk identification interface (RII) linked with the safety information database (SID) for the safety risk of the wall reinforcing work, which are designed for this prototype SMVS.

During the daily safety inspection, the inspector found a safety risk of pipe shaft opening in the site which is not identified at the safety planning phase. The risk should be registered to a new safety risk that needs to be notified, educated, and inspected. As mentioned earlier, the opening should be covered with concrete mortar plate, so a fence around the shaft opening is installed but it has been removed to lift supports for the 2nd floor to the 4th floor for workers' convenience. The registration process of this risk in the system is as follows: (1) the inspector's location of the site needs to be matched with that of the virtual site model through the AP sensor network; (2) the opening still cut photo, activity duration and name of trade contractor and relative education materials are registered at a real-time basis using the risk update interface (RUI); (3) with this registration, the trade contractor lead and workers can recognize and view the risk information via a smartphone or a tablet PC at a real-time basis. If an active RFID is applied to identify worker location, an immediate warning signal can be delivered to workers and a proactive accident control would be possible in the site as well. In addition, the updated safety risk can be immediately used for safety education of newcomers in the site.

The implemented mobile screen outputs of take operation interface (TOI) and risk update interface (RUI) of the prototype SMVS are illustrated in Fig. 6. The left screen shows the location matching, the middle shows the risk registration process using RUI and the right shows the TOI screen showing augmented safety information after registration.

A question and answer game (QAG) has been developed for regular safety education at the site. Workers access the game using company or worker ID then the user identification interface (UII) automatically displays the necessary safety education game related to his work activity. The QAG for pipe shaft opening case was developed and tested, with which the worker navigates his virtual job site by controlling with mouse or keyboard or joystick. As he comes close to the opening area, a warning-sign pops up and his safety game mission is started. Workers select a what-to-do for the risk situation among multiple choice safety measures. If correct, the system calculates the score of the correct answer, and if the worker chooses a wrong answer, the system displays relative information about opening related accident cases as well as right preventive measures in order to improve workers' risk cognition. The game continues

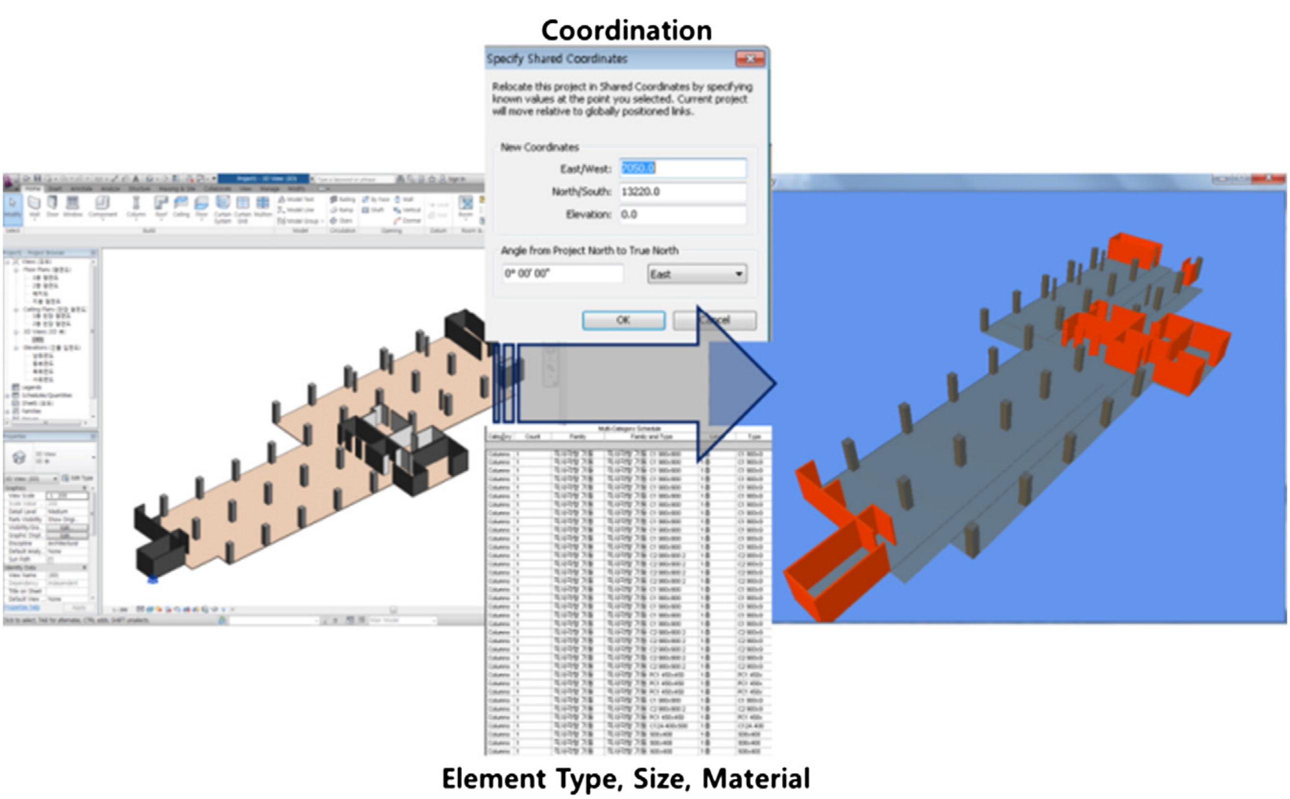

Fig. 4. Creating the virtual site model.

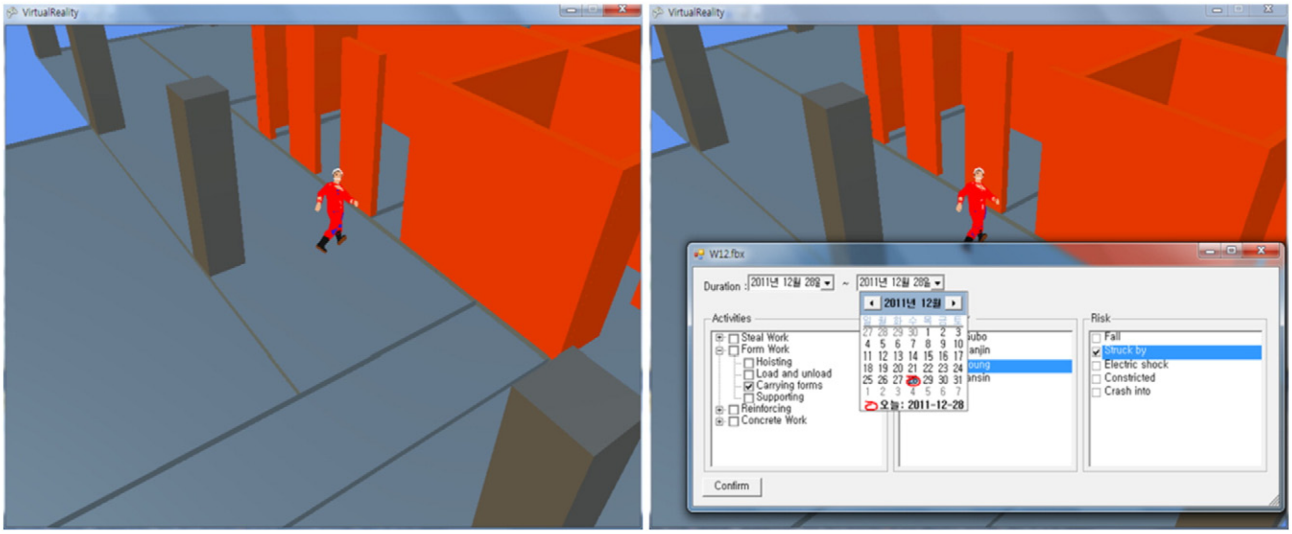

Fig. 5. Risk identification process using worker avatar.

until the worker finds the right answer. Fig. 7 illustrates the QAG screens of the prototype system implemented for the safety education of the pipe shaft opening case.

4.4. Test results

At this point of the study, the prototype system that reflects the system architecture of SMVS has been tested with a real accident case scenario in order to find its field application potentials. The practical applicability of SMVS has been ascertained and evaluated through interview. The interviewees were divided into four groups. The evaluation is subdivided into three parts: identifying risk before work execution, increasing comprehension of accident risk, and real-time communication. The summary of interview result is shown in Table 1.

These results indicate that the interviewees generally agree that the use of SMVS is applicable in field work and could effectively support communication in identifying unsafe working environments, unsafe action and dynamically making decision for unsafe status of construction site. The result can be explained through the effectiveness of the location tracking, visualization technique, and integrated system structure. It includes: 1) location based information utilization

Fig. 6. Augmented inspection.

and it provides much more realistic information, and improves comprehension, 2) application modules that reflect the interviewees working process and information, and explains why the interviewees were satisfied with the system.

However, some of the interviewees also expressed the opinion that they were unfamiliar with 3D information and that it was difficult to control the user's movement and view. Furthermore, to operate the system, information, time, and a temporary facility need to be integrated.

The use of SMVS, in contrast with the traditional safety communication method, provides a new communication platform for managers and workers. The managers and workers can get the information automatically after they connect to the system through a mobile device. The information can be utilized in a unified system for different safety management tasks. By utilizing the system, users can improve their safety knowledge and effective decision making.

Table 1
Summary of interview result.

	Average SMVS rating*		
	Identifying risk before work execution	Increasing information comprehension	Real-time communication
Construction workers (9)	3.89	3.33	3.89
Safety managers (11)	3.64	3.91	4.09
Construction managers (6)	3.67	3.83	3.83
Trade leads (5)	3.60	4.20	3.80

* The rating is scaled as follows: 1=Useless, 2=Ineffective, 3=Normal, 4=Effective, 5=Highly effective.

5. Summary and discussion

This study begins with an inquiry on how to apply some advanced visualization technologies to current safety management processes in the construction field that consists of safety planning, education, and inspection phases. An extensive literature review was conducted to investigate the application potentials of visualization technology as well as the necessity of interactive utilization of relative information during the safety management process. Then a system framework for a visualized safety management system (SMVS) was proposed, considering the integration of BIM, game engine, location tracking and AR technologies. A prototype SMVS was developed using the Microsoft XNA 4.0 Game Studio environment and its practical applicability was tested with a safety management process of a real accident case scenario. In addition, potentials and limitations of SMVS were discussed with field safety managers. The main findings and technical limitations of the study are summarized as follows:

1) In the previous visualization technology applications, it has been well proven that virtual 3D site models have a great potential to improve the identification of safety risks as well as worker's risk cognition and safety education. By integrating the 3D model, safety managers and workers can understand the exact environment of construction site. With the color point representation in 3D model, safety managers and sub-contractor leads find the location where the accident prevention measure is required before work execution. Also, based on the accident risks and site environment they could make a practical plan such as type of safety facilities, required education, working sequence adjustment, and safety patrol location. Meanwhile, 3D model based role-playing education immerses the worker in the situation. From the virtual reality, the worker could learn the exact risk in their job site. In addition, the mission not only clearly provides risks but also increases their immersion in education. In addition the record of education performance indicates which trades need more education or more supervision during their work.
2) However, the most important factor in the field safety management, effective communication with workers remains unsolved. It is found that the AP network-based location tracking with augmented reality for field safety could improve communication between workers and managers on a real-time basis. From the augmented risk information, the managers and workers recognize where and what the exact risks on construction site are in a short time. Also, they could easily comprehend the prevention measure with real construction site environment. It means that the time and labor which was spent for supervision could be decreased.
3) The system framework of SMVS reflecting a continuous safety management process would increase the interaction of various information required for safety planning, education, inspection, and time management of field safety manager could be reduced accordingly.
4) In developing the prototype system, it is confirmed that various visual safety information such as geometrical 3D models, photos, videos, and checklists can be easily integrated in a game development toolset such as Microsoft XNA without any data interoperability. However, the level of its interoperability with a virtual site model containing more detailed BIM element information and project schedule should be further examined.
5) More precise measurement of the WAP network-based location tracking using mobile device, in terms of sensor signal receiving, is required not only to provide an accurate real site location data but also to examine the tracking interruption in the case of multiple risk existence.

In conclusion, even though the potentials and practical applicability of the proposed SMVS framework has been ascertained with the evaluation of a simple prototype system, as future work, the system

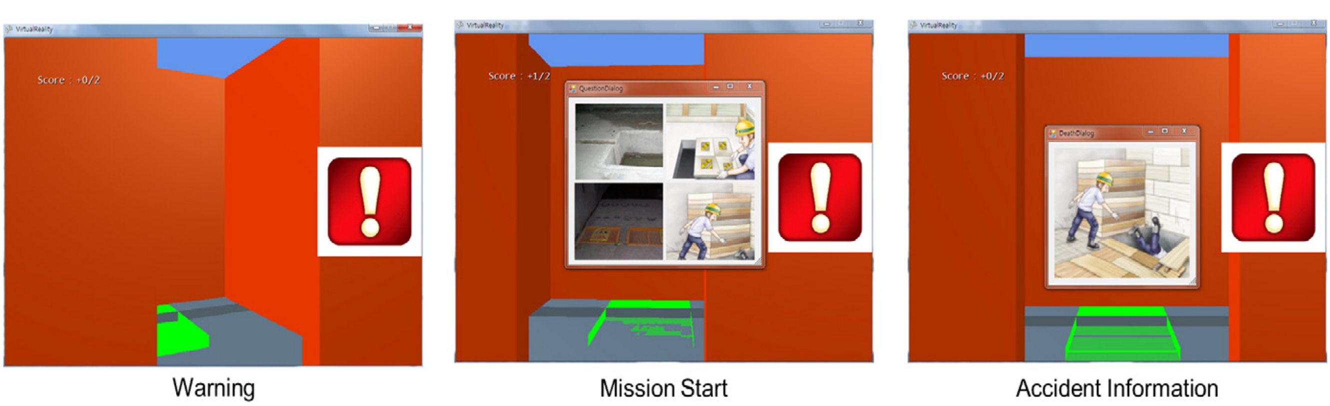

Fig. 7. Q&A game education.

applicability should be validated more technically in terms of the performance of field safety management such as accident prevention rate, managerial time, and cost–benefit analysis.

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References

[1] V. Bansal, M. Pal, Generating, evaluating, and visualizing construction schedule with geographic information systems, Journal of Computing in Civil Engineering 22 (4) (2008) 233–242.
[2] K. Chau, M. Anson, J. Zhang, Four-dimensional visualization of construction scheduling and site utilization, Journal of Construction Engineering Management 130 (2004) 598.
[3] Y. Chen, J.M. Kamara, A framework for using mobile computing for information management on construction sites, Automation in Construction 20 (7) (2011) 776–788.
[4] S.I. Choi, H. Kim, A study on the safety climate and worker's safe work behavior in construction site, Journal of Korean Society of Safety 21 (5) (2006) 60–71.
[5] R.M. Choudhry, D. Fang, S.M. Ahmed, Safety management in construction: best practices in Hong Kong, Journal of Professional Issues in Engineering Education and Practice 134 (1) (2008) 20–32.
[6] D.A. Bowman, A.A. Ray, M.S. Gutierrez, M. Mauldon, J.E. Dove, E. Westman, M. Setareh, Engineering in three dimensions: immersive virtual environments, interactivity, and 3D user interfaces for engineering applications, in: ASCE Proceedings of GeoCongress 2006, 2006.
[7] K.S. Eum, T.H. Woo, Developing experimental education program for safety considering psychological effect, Journal of Korea Safety Management & Science 11 (4) (2009) 15–24.
[8] M. Golparvar-Fard, F. Peña-Mora, C.A. Arboleda, S.H. Lee, Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs, Journal of Computing in Civil Engineering 23 (2009) 391.
[9] H. Guo, H. Li, G. Chan, M. Skitmore, Using game technologies to improve the safety of construction plant operations, Accident Analysis and Prevention 48 (2011) 204–213.
[10] B. Hadikusumo, S. Rowlinson, Integration of virtually real construction model and design-for-safety-process database, Automation in Construction 11 (5) (2002) 501–509.
[11] S.U. Han, F. Peña-Mora, M. Golparvar-Fard, S. Roh, Application of a visualization technique for safety management, International Workshop on Computing in Civil Engineering 2009, ASCE, 2009.
[12] J.S. Hong, A safety management activity model in construction sites through analysis of success factors, Han-Yang Univ., M. S. dissertation 2009.
[13] Y.S. Jeon, C.S. Park, A study on the framework of the continuous improvement model of construction process using construction failure information, Journal of Korea Institute of Construction Engineering and Project Management 6 (1) (2005) 195–204.
[14] T. Keller, S.O. Tergan, Visualizing knowledge and information: an introduction, Knowledge and Information Visualization 3426 (2005) 1–23.
[15] D.W. Kim, Safety management system for a large construction project using real-time location system, Ph. D. dissertation (2011).
[16] E.J. Kim, K.R. Kim, D.W. Shin, Improvement for safety education considering individual personality in the construction site, Journal of Korea Institute of Construction Engineering and Project Management 9 (3) (2008) 175–184.
[17] Y.J. Kim, A study on effect analysis that employment permit system affects construction field, Han-Yang Univ. M. S. dissertation (2005).
[18] M. Kiviniemi, K. Sulankivi, K. Kahkonen, T. Makela, M.L. Merivirta, BIM-based Safety Management and Communication for Building Construction, VTT Technical Research Centre of Finland, 2011.
[19] H.T. Kung, D. Vlah, in: Efficient Location Tracking Using Sensor Networks, IEEE, vol. 3, 2003, pp. 1954–1961, vol. 1953.
[20] B.S. Kwon, A study on the improvement of current construction safety management system, University of Incheon M. S. dissertation (2009)
[21] J.S. Lee, J.S. Hong, J.J. Kim, A self-control safety management activity model in construction sites through analysis of success factors, Journal of Korea Institute of Building Construction 8 (5) (2008) 110–117.
[22] S. Lee, Ö. Akin, Augmented reality-based computational fieldwork support for equipment operations and maintenance, Automation in Construction 20 (4) (2011) 338–352.
[23] H. Li, G. Chan, M. Skitmore, Visualizing safety assessment by integrating the use of game technology, Automation in Construction 22 (2011) 498–505.
[24] H. Li, Z. Ma, Q. Shen, S. Kong, Virtual experiment of innovative construction operations, Automation in Construction 12 (5) (2003) 561–575.
[25] J.C. Maing, T.H. Kim, H.H. Cho, K.I. Kang, Performance indicators for safety management information system, in: 8th International Symposium on Architectural Interchanges in Asia, 2010.
[26] Y. Masumoto, Global positioning system, Google Patents (1993).
[27] Y. Mizuno, H. Kato, S. Nishida, in: Outdoor Augmented Reality for Direct Display of Hazard Information, IEEE, vol. 1, 2004, pp. 831–836, vol. 831.
[28] MOEL, Occupational Safety and Health Act (OSH Act), Ministry of Employment and Labor, 2011. http://moel.go.kr.
[29] OSHA, Occupational Safety and Health Administration, Washington D.C, 2005. www.osha.gov.
[30] E. Sawacha, S. Naoum, D. Fong, Factors affecting safety performance on construction sites, International Journal of Project Management 17 (5) (1999) 309–315.
[31] K. Sulankivi, K. Kähkönen, T. Mäkelä, M. Kiviniemi, 4D-BIM for construction safety planning, in: Proceedings of CIB W099 2010, 2010, pp. 117–128.
[32] G.M. Waehrer, X.S. Dong, T. Miller, E. Haile, Y. Men, Costs of occupational injuries in construction in the United States, Accident Analysis and Prevention 39 (6) (2007) 1258–1266.
[33] X. Wang, Improving human–machine interfaces for construction equipment operations with mixed and augmented reality, Robotics and Automation in Construction (2008) 211–224.
[34] J.M. Wilson, Safety management: problems encountered and recommended solutions, Journal of Construction Engineering Management 126 (1) (2000) 77–79.
[35] H. Xie, M.E. Tudoreanu, W. Shi, Development of a virtual reality safety-training system for construction workers, in: 6th International Conference on Construction Applications of Virtual Reality, 2006, pp. 3–4.
[36] Y.M. Yim, Y.S. Hwang, Y.H. Choi, Case analysis of injured people for the reduction of industry disasters, Journal of Korea Industrial and Systems Engineering (2005) 236–243.