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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