A Framework for Developing an As-built Virtual Environment to Advance Training of Crane Operators

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ABSTRACT

Although hands-on practices are considered as the most effective training method for crane operators, they are always expensive and dangerous to be performed in the real world. As an alternative, virtual reality and simulator technology provide a close-to-reality experience in lifting operation while minimizing costs and hazards. However, the virtual environment in current training systems are static and designed ahead of time rather than representing an as-built construction site with its dynamic construction resource (workers, equipment, materials). Such drawback greatly limits the effectiveness of virtual training systems. To advance virtual training for crane operators, this research presents a framework towards constructing as-built virtual training environments by integrating Building Information Modeling (BIM) and real-time location tracking technology in a virtual environment. Implementing the proposed framework, a virtual training system for lifting tasks at an actual construction site was developed. The results of a pilot test show that such approach can effectively construct as-built work scenarios and potentially assess and improve operator proficiency in a virtual training environment.

INTRODUCTION

As one of the most expensive and frequently used kind of resources on construction sites, cranes play an importance role in construction activities. There are approximately 125,000 cranes in operation every day in the construction industry, responsible for major portion of lifting activities. A report (McCann and Gittleman 2009) from the Center for Construction Research and Training (CPWR) states that there were 632 crane-related deaths from 610 incidents in construction from 1992 to 2006, in which collisions and spatial conflicts have been identified as major causes that are responsible for 380 deaths. Similarly, as reported by Occupational Safety and Health Administration (OSHA), 40% of the deaths involving cranes on construction sites from 1984 to 1994 were related to spatial conflicts.

Crane operator proficiency is a major factor influencing crane safety. Neitzel et al. (2001) pointed out that crane operators have the most direct influence on the safety of crane operation, and thus they must have the technical and performance proficiency in operating cranes. In an assessment conducted by Shapira and Lyachin (2009) with 19 construction equipment and safety experts, operator proficiency
scores the highest degree of influence among 21 factors that will affect crane safety. At the same time, research has shown that the key to acquiring the necessary skills to control complex systems is hands-on and coached training (Cuqlock-Knopp et al. 1991). This approach, however, is difficult to implement in reality. On-site hands-on training will inevitably disrupt normal construction process, extend the construction time, and increase the expense on crane rental and fuel consumption. Moreover, it is too risky to expose an inexperienced operator to real hazards on site since any error operation may lead to serious consequence in schedule delay, budget increase, and most importantly injury and casualty. Because of the limited on-site hands-on practice, although all trainee operators have to take extensive and mandatory tests after the training, many of them who pass the tests find themselves either directly or indirectly involved in crane accidents.

To enhance the effectiveness and efficiency of current training programs of crane operators, this paper introduces a virtual reality (VR) based system that integrates BIM and real-time location tracking technology. A framework of developing an as-built interactive virtual training environment for crane operators was proposed and implemented in an actual building project. The results of a pilot test show that the proposed approach can effectively simulate the as-built work scenario for operator training purpose. Its potentials in improving the situational awareness and hazard identification were identified.

LITERATURE REVIEW

With the rapid development of computer graphic and interactive hardware, virtual reality technology provides a new opportunity to expedite the learning process and promote the learning effectiveness. Many efforts have been invested in the application of information technology especially of advanced virtual reality (VR) technologies in construction education (Issa et al. 1999, Bouchlaghem et al. 2002). More recently, Lin et al. (2011) developed a 3D video game that provides a virtual safety training environment where students walk through the site to identify potential hazards as a safety inspector. The results indicate such virtual training environment could increase their learning interests, motivate them to refresh their safety knowledge, and eventually enhance the learning effectiveness.

Emerging remote sensing technology greatly expended the sources of field information and the way they are collected on construction sites. Talmaki et al. (2013) presented a computing framework for monitoring and visualizing interactions between equipment and workers using sensor-based tracking and georeferenced model. The potential of visualizing field information in a virtual environment was further investigated by Teizer et al. (2013). They introduced an approach to assess and improve the training effectiveness of ironworker training by visualizing real-time location tracking data in an immersive 3D environment for worker performance review and assessment. The study indicates a great potential of integrating virtual technology in general worker training programs.

As an early effort in employing VR in construction heavy equipment operator training, Wakefield et al. (1996) developed an interactive VR excavator simulator for operator training. Taking advantage of the Internet as a communication tool, Bernold et al. (2003) developed a training system named the Internet-Based Backhoe Operator
Trainer (IBOT) that allows a trainee to practice with a stationary backhoe at remote training location. In the field of crane operator training particularly, Wilson et al. (1998) developed a Virtual Environment Crane Training Simulator (VECTS) for overhead crane operator training. It provides trainees with a 3D virtual environment for learning and practicing the skills needed for productive crane operation in the indoor factory environment. Kang and Miranda (2004) constructed a physics-based model of tower cranes to simulate their dynamic behaviors, which they proposed could be further developed for training program for crane operators or course material for university students. Immersive and efficient user interface of a virtual training system helps the user to build an effective communication with the virtual environment. As an effort towards this direction, Guo et al. (2012) proposed a training platform that allows multiple users collaborate with each other and interact with the virtual world to practice the tower crane dismantling task using Wii controllers.

Studies indicate the reliable transfer of skills can be acquired through virtual training to actual on-the-job tasks if the virtual training environment provided a high similarity between the virtual and real environments (Rose et al. 2000). Compared to training for normal workers, implementing virtual training for equipment operators requires authentic simulation of the controls and motions of the equipment in the virtual environment. Despite much research in adoption of VR technologies on building design and construction project level, their application is not very common on construction equipment operation training. One reason is that it is time-consuming and computational expensive to represent and reproduce as-built work environment in the virtual training environment. In addition, these tools are difficult to use and the visualization provided by them is not easy to customize with respect of intensive and dynamical characteristics of construction operations (Issa et al. 2003).

RESEARCH METHODOLOGY

A major objective of implementing virtual environment in operator safety training is to expose operators to potential hazards in a risk-free manner and help them develop timely and reasonable responses to these hazards. Compared to other types of construction equipment, cranes typically occupy relatively large workspaces. Therefore, on congested construction sites, the workspaces of cranes in many cases overlap with adjacent structure as well as the workspaces of workers and others equipment. Existence of such spatial conflicts requires not only proficient operation skills and knowledge, but also sharp observation and timely response to immediate dangers. In order to provide crane operators a better situational awareness of spatial conflict issues and let them respond the resulted collision hazards in a virtual world, this research proposes a framework towards building an as-built virtual training environment that allows multiple users manipulating virtual cranes via an interactive user interface. By monitoring the operations of virtual cranes and recording lifting trajectory and unsafe incidents in real-time, users’ performance can be potentially analyzed and evaluated based on pre-defined criteria. Figure 1 shows the framework of this research. Each part in the framework will be explained in the following sections.
Crane workspace simulation using as-built models and data

Given the fact that spatial conflicts are pervasive hazards in crane operations that could lead to tremendous losses by resulting collisions, the proposed approach needs to address the hazard of spatial conflicts in the virtual training environment. To accomplish this capability, three tasks need to be accomplished: 1) modeling crane controlling, 2) modeling as-built building structure, and 3) tracking and visualizing resource location data in real-time. The methods used in this research to complete these three tasks will be explained in following sections.

Crane modeling

In order to provide a close-to-reality experience when the user operates a virtual crane as they operate actual cranes in the real world, cranes in the virtual environment need to be modeled with actual geometry and configuration. To simplify the modeling effort while guarantee the modeling quality, the base models of
different types of cranes, such as tower crane and mobile crane, is downloaded from a 3D model website called Trimble 3D Warehouse. As another important aspect in virtual crane modeling, the manipulation of virtual cranes has to be simulated based on the actual principle of motions in crane operations.

Modeling of as-built building structure

Among all obstructions involved in crane operations, building structures warrant additional attention. Compared to the spatial conflicts with the workspace of equipment or workers on or near the ground, the proximity from crane parts to adjacent building structure exists in three-dimension in the workspace of cranes. Consequently, the spatial conflicts caused by building structure are more difficult for crane operators to identify. Building structure are also a main reason for blind spaces as they always block the eyesight from crane operator to the loads. As such an influential contributor in spatial conflicts in crane operations, building structure models in the virtual environment should accurately reflect the current structure settings and are able to update according to the construction schedule. To realize this functionality in the proposed virtual training environment, this study introduces a simple and fast approach to generate building as-built models using Building Information Modeling (BIM). Construction process can be visualized in BIM software by loading construction schedules. Then, 3D building model of a particular day can be extracted from BIM model and be modified based on a more detailed construction plan in a particular day. Following this approach, 3D building models can be quickly generated with minimum effort and are able to reflect the as-built conditions of the construction environment.

Tracking and visualizing resource location data

Construction resources such as workers, equipment, and material are dynamic obstructions in crane operation. Their workspaces often not only overlap with the workspace of cranes, but keep changing as they travel around on construction sites. The proposed virtual training environment is able to visualize location data of construction resources collected by Ultra-wide band (UWB) remote sensing system in real-time. A previous study by Cheng and Teizer (2013) revealed the potential of tracking data visualization in identifying safety hazards, facilitating the communication, and enhancing training effectiveness. Advanced from the previous research just visualizing the tracking data of workers to identify their unsafe behaviors, the tracking data of workers are visualized in the virtual training environment so that users is able to respond to the spatial conflicts between workers and loads in real-time. By defining a three-dimensional safety zone for each worker, the tracking data of each worker becomes a dynamic workspace in the virtual world.

User interface setup

For any virtual training program, effective human interaction is essential for users to understand the situation, experience training goal, and accelerate learning process. The framework proposed in this research adopted gamepad and spaceball through which users can control and operate virtual cranes and navigate the virtual construction sites. To simulate the actual crane manipulation, the buttons of a
gamepad were programmed to control different motion of movement of crane parts, such as the swinging of crane boom, translation of trolley, and lifting of crane hook. A spaceball was used for navigation and other functionalities such as switch cameras, show trajectory, and take snapshot.

Figure 2: Gamepad and Spaceball Configurations

Multi-user collaboration in spatial conflicted workspaces

Overlapping between the workspaces of different equipment is common on construction sites. To work safely and efficiently, it is important for both operators of these equipment to possess a situational awareness of the spatial conflicts due to their overlapping workspaces. By connecting and synchronizing the virtual environment on multiple computers over the internet, it can simulate the situation that multiple construction equipment work simultaneously in an overlapping workspace.

Performance monitoring and recording

Real-time alert for spatial conflict hazards

Focusing on spatial conflict issues in crane lifting operation, the proposed training environment defines two major incidents: proximity to obstructions, and swinging above workers on the ground. In the practice of crane lifting operation, operators have to avoid the proximity from loads to static obstructions lying on the lifting path, such as columns, walls, and equipment. According to OSHA, crane load is not allowed to swing overhead of workers on the ground. In the virtual training environment, a virtual safety zone of each obstruction is predefined. Virtual safety zones of different dimensions are assigned to each worker and building structure in respect of their dimensions.

Trajectory analysis and collision hazard identification

Lifting trajectory is recorded in real-time and stored in a .txt file for post-time analysis. As shown in Figure 4, the trajectory file contains x, y, z coordinates and time stamp information. To have a better understanding of the lifting process, the trajectory data was mapped back to the virtual environment. As to the safety performance, the system automatically identifies proximity and swing-above-worker incident. Information related to identified incidents such as which objects are involved in the incident, and where and when the incident takes place, are recorded in another .txt file as shown in Figure 3.
CASE STUDY

The proposed framework was implemented in a teaching building project on the campus of the Georgia Institute of Technology. A tower crane located in the middle of the west side of the building was responsible for most of the lifting tasks on the site. Ultra-wide Band (UWB) remote sensing technology was adopted for tracking locations of workers and materials, and the UWB system was set up on the second floor covering approximate 200 square feet, where six workers were working at. BIM model of the building was converted as 3DS model and imported into a virtual environment.

Construction equipment including dump trucks, dozers, excavators, and a mobile crane was modeled to simulate the as-built work scenario. A tower crane, as the main component of the training environment was modeled following the method introduced in section 3.1.1. Figure 4 shows the completed virtual environment for the case study. Two types of incidents, proximity to column and swing-above-worker, were modeled in the virtual environment. Proximity to columns incidents were detected by computing the distance between columns and loads. Swing-above-worker incidents were detected by computing the distance between workers and the projection of loads on the floor (Figure 5).
The purpose of this pilot test is to show that the development virtual training environment is capable of representing as-built work scenarios in crane lifting operations. Four as-built lifting scenarios with designed complexity levels were developed based on the real world scenarios. Those scenarios contain different types, quantities, and locations of obstructions (e.g., columns, workers), which make them distinct from each other in the level of operational complexity. Unfamiliarity with the controlling system and task requirements can greatly affect user performance. In order to minimize this problem, an instruction was given to the user explaining 1) the system setting and controller configurations, 2) the tasks they are asked to perform and hazards associated, and 3) the scoring mechanism of their performance. For each scenario, the duration of the lifting activity, the length of the lifting path, and incidents occur in all four lifting scenarios were computed in Matlab. Table 1 presents the results of data analysis. In the Incident row, P stands for the number of incidents due to proximity to static obstructions while S stands for the number of swing-above-worker incidents.

Table 1: Results of a Pilot Test

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong></td>
<td>61.1s</td>
<td>54.1s</td>
<td>62.3s</td>
<td>67.4s</td>
</tr>
<tr>
<td><strong>Length</strong></td>
<td>180.2m</td>
<td>190.8m</td>
<td>188.9m</td>
<td>193.6m</td>
</tr>
<tr>
<td><strong>Incident</strong></td>
<td>P: 0, S: 0</td>
<td>P: 0, S: 0</td>
<td>P: 1, S: 2</td>
<td>P: 1, S: 3</td>
</tr>
</tbody>
</table>

As the complexity level increased from scenario one to four, the user tended to spend more time for the task. At the meanwhile, the length of lifting trajectory also increased from 180.2 m in scenario one to 193.6 m in scenario four. As to the safety performance, no incident was detected in scenario one and two. As the numbers of columns and workers increased in scenario three and four, more incidents were detected. The occurrences of swing-above-worker incident are more than that of proximity to column incidents. Figure 6 shows the lifting trajectory recorded in each scenario. Red cylinders indicated the workers and columns involved in the incidents. The results of a pilot test revealed that the developed system could effectively represent the complexity of lifting tasks and potentially benefit the training of crane operators.
FUTURE WORK
Next stage to advance the proposed as-built virtual training environment will focus on automating the modeling process and exploring its effectiveness in improving performance of crane operators. The first step is to develop an assessment and analysis method for measuring and evaluating the productivity and safety performance of users. The second step is to propose a quantitative method to validate the effectiveness of the virtual training environment.

CONCLUSION
Although virtual environment has been widely adopted in construction design, planning, and education, its benefits in advancing the training of equipment operators at operation level remains further exploration. In this research, the need of an as-built virtual training environment was identified, and a framework towards developing such an environment was developed. The authors conducted a case study that implemented the proposed approach in developing a virtual training environment for an actual building construction site. The results show that the proposed approach can effectively simulate the as-built work scenario for operator training purpose. Its potential in improving the situational awareness and hazard identification were also identified. Overall, the study presented an incremental knowledge about the application of virtual reality technology in construction worker training, and indicated the direction and path for future research.

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REFERENCE