Multiuser Virtual Safety Training System for Tower Crane Dismantlement

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Abstract: Tower crane dismantling is one of the most dangerous activities in the construction industry. Tower crane erection and dismantlement causes 10–12% of the fatalities of all crane accidents. The nature of the task is such that off-the-job training is not practicable, and the knowledge and expertise needed has to be gained on the job. However, virtual trainers such as Microsoft Flight Simulator for airplane pilots and mission rehearsal exercise (MRE) for army personnel have been developed and are known to provide a highly successful means of overcoming the risks involved in such on-the-job learning and clearly have potential in construction situations. This paper describes the newly developed multiuser virtual safety training system (MVSTS) aimed at providing a similar learning environment for those involved in tower crane dismantlement. The proposed training system is developed by modifying an existing game engine. Within the close-to-reality virtual environment, trainees can participate in a virtual dismantling process. During the process, they learn the correct dismantling procedure and working location and to cooperate with other trainees by virtually dismantling the crane. The system allows the trainees to experience the complete procedure in a risk-free environment. A case study is provided to demonstrate how the system works and its practical application. The proposed system was evaluated by interviews with 30 construction experts with different backgrounds, divided into three groups according to their experience and trained by the traditional and virtual methods, respectively. The results indicate that the trainees of the proposed system generally learned better than those using the traditional method. The ratings also indicate that the system generally has great potential as a training platform. DOI: 10.1061/(ASCE)CP.1943-5487.0000170. © 2012 American Society of Civil Engineers.

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Background

Tower cranes are widely used in the construction industries of all developed countries. In the United States, for example, the demand for tower cranes is increasing and will continue to do so in the face of current levels of demand (Shapira et al. 2007); Shiffler (2006) has reported that an estimated 300 tower cranes were in operation at one point in Miami during 2006. In Hong Kong, the Deputy for Labour of the Hong Kong Labour Department, Ting (2007), summarized an inspection conducted in July 2007 that recorded a total of 215 tower cranes being used on 113 construction sites in Hong Kong, nearly two tower cranes for every construction site. Immediately after, a total of 123 warning letters were issued to contractors regarding the use of unsafe working practices involving tower crane operations, suggesting that much improvement is needed.

In fact, the use of tower cranes, including their erection, operation, raising, and dismantling, is one of the major causes of fatalities on construction sites in many countries (Beavers et al. 2006). In Hong Kong, a total of 12 tower crane accidents occurred during the period from 1998 to 2005, causing 14 fatalities (Occupational Safety and Health Council 2006), with approximately 50 workers dying in the past 40 years as a result of the unsafe use of tower cranes and related operations (Lee 2006). In the United States, an average of 82 workers were killed in crane accidents from 1997 to 2006 (Van Hampton and Lewis 2008). Smith and Corely (2009) also found that their erection and dismantling caused 10–12% of all crane fatalities. Because crane accidents were responsible for 8–16% of all construction fatalities, this is a considerable number. Even more significantly, it is also estimated by MacCollum (1993) that cranes are involved in 25–33% of all fatalities in construction and maintenance work. Another study, by Suruda et al. (1999), investigating fatal injuries in the United States involving cranes during 1984–1994, found assembly and dismantling to account for 58 deaths (12% of all fatalities in crane accidents). Similarly, crane accidents are attributed to approximately 12 and 17% of all fatalities or permanent disability in Finland and England, respectively (Suruda et al. 1999).

More recently, there have been five fatal accidents relating to tower crane use during 2002–2006 in Hong Kong, with three workers being killed in July 2007 alone (Ting 2007). One such accident in July 2007 caused two fatalities and five serious injuries. The accident happened during the dismantling process, with workers on the tower crane as it was climbing down. The investigation team reported that the workers may have been unfamiliar with...
the dismantling process and were working in a location that should have been restricted during the climb-down process. It is believed that the number of fatalities and injuries could have been reduced in this accident if the workers had been properly trained.

Dismantling is usually more hazardous than other tower crane operations. The Labour Department (2002) pointed out that dismantling a crane is more complicated than its erection because of space restrictions imposed by both the permanent and temporary structures around the crane. Tower crane dismantling is also a highly complex procedure that includes numerous inspections, cooperation between many operatives, the use of different tools and working at height. In addition, the operation also requires a high level of accuracy. Any variation in procedure or human error can result in a serious accident.

In this paper, a modified game engine is proposed for a new training system for dismantling tower cranes, which aims to provide a platform for the workers to receive adequate training before working on site. The training is carried out within a close-to-reality three-dimensional (3D) environment that allows the system to simulate the detail process of dismantling a tower crane and thus provides virtual on-the-job training.

Importance of Safety Training for Tower Crane Operations

Skinner et al. (2006) has examined the major causes of tower crane accidents on construction sites and classified these into three groups:
1. Failure of the tower crane structure;
2. Installation errors; and
3. Improper operation, such as overloading.

These three groups are also endorsed by MacCollum (1980) and Hääkkinen (1978). Some of these causes are obviously related to human errors, which could have been avoided if the operatives had been suitably trained before working with the cranes; the suggestion of worker training as the solution has been made by numerous researchers (Van Hampton and Lewis 2008; Smith and Corley 2009; Suruda et al. 1999).

In general, it is well known that the lack of structured training for providing skills and safety training to new workers is a hindrance to safety (Goldenhar et al. 2001). For tower cranes, this is even more important because a lack of education and regular training of workers in the crane environment is one of the main causes of their associated accidents (Hääkkinen 1993). Smith and Corely (2009) also point out that only a small portion of the tower crane rigger training class focuses on the assembly, climbing, and dismantling of cranes. Likewise, Beavers et al. (2006) agree that crane operators and riggers do not receive enough training and suggest that they all should be qualified before they work and that requalification should take place every three years. They also suggest that special trade crafts should attend crane safety training before they are allowed to work for crane-related operations instead of just through on-the-job experience, as is the traditional and current approach.

Current Practice of Training for Operators and Riggers

U.S. fatality investigations in 2005 found approximately 40% of employers to be rated as having inadequate or nonexistent training programs (Beavers et al. 2006). The situation is similar in Hong Kong, where Lee (2006) has pointed out that there are no safety training courses in tower crane dismantling provided by any of the local training institutions. The reason is that although the importance of tower crane training is acknowledged in the industry, off-the-job training opportunities for related workers are limited because, in terms of cost alone, it is usually impracticable to erect a tower crane and derrick boom merely for practice purposes. Therefore, the only way for trainees to practice is to work on site on real projects.

In Hong Kong, on-the-job training is carried out by training under a mentorship program. The mentor passes experience and skills to the mentee, usually starting with the provision of guidelines to the mentee during the work on site. Of course, because the success of this system relies heavily on the quality of the mentors, a poor mentor can easily pass improper attitudes to the mentee. Unlike the new regulations of the Occupational Safety and Health Administration (OSHA), the trainers are not required to undertake any form of certification process. There are also no regulations for the content of the training process. Thus, there is no assurance of good practices. Also, even after the mentees have received tuition during the work, they still have occasional difficulties in applying their skills and knowledge as a result of the lack of sufficient practice. This situation has particularly hindered the development of mentees. In other industries (e.g., aviation), in which safety is paramount, operators are required to undergo regular training to ensure their competence.

A further issue concerns the shortage of information on tower crane use. This is a particular problem in the disassembly or dismantling phase, in which construction operatives can only rely on the erecting–dismantling manuals produced by crane manufacturers (Lee 2006). Putting such information into practice is not a simple task, and mistakes are bound to happen. Clearly, what is needed is some facility in which operatives can develop the necessary skills in a nonhazardous situation. One means of doing this is in a virtual environment.

Previous Studies on Crane Operations

Crane accidents and their prevention have been studied by researchers since as early as the 1970s (Hääkkinen 1978). More recently, Shepherd et al. (2000) conducted a taxonomic analysis in U.S. crane fatalities, dividing more than 500 recorded crane-related accidents into different types. Neitzel et al. (2001) also reviewed crane safety in the United States and has provided some suggestions for improvement to the industry. Others have suggested controlling the safety performance of crane-related construction projects by measuring and analyzing the factors affecting site safety by different approaches (Shapira and Layachin 2009; Shapira and Simcha 2009b). Shapira et al. (2008), for example, suggests the use of a vision system to assist tower crane operations, which could eventually improve safety performance. Meanwhile, Kang et al. (2009) suggest the use of 3D simulation and visualization for simulating the erecting process of steel structures. They believe that the use of 3D simulation to rehearse the construction process in a virtual environment can help the crane operator to better understand the processes involved. However, despite this considerable amount of previous research into crane operations, little attention has been paid to the important issue of training.

Game-Engine Development and Applications

The virtual environment contains more information than a barely 3D environment. One important distinction is that it is possible to integrate user interaction (Smith and Hart 2006) in the form of collision detection, for example. Available virtual environment development toolkits have the potential to provide a subset of tools for building a complete virtual world. However, the use of virtual environment development toolkits have encountered numerous
difficulties. Building a realistic virtual environment is time-consuming, expensive, and complex (Laird 2002; Robillard et al. 2003). As Trenholme and Smith (2008) point out, the use of these virtual environment toolkits often requires advanced programming skills and substantial time for development. As a result, the use of development kits is often nonviable both in term of cost and time. In addition, it is hard for these tools to simulate embodied autonomous agents such as wind, fire, and smoke (Albeck and Badler 2002), limiting the ability of development kits to simulate particular behaviors.

Because of the difficulties in creating virtual environments by using development toolkits, Trenholme and Smith (2008) suggest the reuse computer game technology. According to Lewis and Jacobson (2002), game engines are a collection of modules of simulation code with no specification of the game’s behavior or environment. The engine usually includes modules to handle the input, output, and physics of the game world. These modules allow users to reuse programs, thus saving time and reducing the amount of programming work needed.

The use of game technology and game engines is a promising area of research. The first application of game technology in this area of research was in the aircraft industry, with the use of Microsoft Flight Simulator for teaching purposes, dating back to 1991 (Moroney and Moroney 1991). The simulator was designed as an instrument flight trainer, made available to individuals with a pilot’s certificate. Koonce and Bramble (1998) summarize the benefits of adopting PC-based flight training devices and point out that the use of this approach can dramatically save flying time in the actual aircraft, therefore representing a significant cost benefit. Lindheim and Swartout (2001) have also developed a new simulation technology that integrates game-engine technology with U.S. Army training in a project called mission rehearsal exercise (MRE). This aims to create a virtual reality training environment for soldiers. The soldiers can confront different pre defined dilemmas. They are required to make decisions in real time under stresses and various conflicts. The soldiers are then presented with the consequences of their decisions in the simulator. By gaining experience within the virtual environment, the soldiers are expected to be better prepared when they experience similar dilemmas in the real world.

The success story of the aircraft industry and U.S. Army has attracted the interest of several different industries. Visualization through a virtual environment is one of the generally investigated areas, and Trenholme and Smith (2008) have summarized the use of game technology for achieving visualization in different industries. For example, Bylund and Espinoza (2001) and O’Neill et al. (2007) suggest using game engines for context-aware system evaluation. An e-Tourism system was developed by Berger et al. (2007). Human simulations [human behavior model testing and human artificial intelligence (AI), human–robot interaction] by game engines were investigated by Silverman et al. (2006), Laird (2002), Laird et al. (2002), Lewis et al. (2007), and Wang et al. (2003). The visualization of information (Kot et al. 2005) and landscape (Herwig and Paar 2002) have also been achieved. Other game-engine applications, such as interactive storytelling (Cavazza et al. 2002), large-scale real-time ecosystem simulation (Refslund et al. 2002), phobia therapy (Bouchard et al. 2006; Robillard et al. 2003), photorealistic environment walk through (DeLeon and Berry 2000), psychological experimenting (Frey et al. 2007), serious game (Mac Namee et al. 2006), and virtual museums (Lepouras and Vassilakis 2005) have also been introduced. It is obvious, therefore, that game engines are widely adopted by different industries and have obtained considerable success.

More recently, the use of game engines was adopted by the construction industry, with Yan et al. (2011) suggesting the integrated use of building information modeling (BIM) with a game application to develop real-time interactive architectural visualization. A similar approach was taken by ElNimr and Mohamed (2011), who aimed to visualize simulated construction operations by using game engines. Juang et al. (2011) also tried to simulate the physics of a forklift by using a game engine, the simulation of a forklift providing a foundation to further develop equipment simulation by game engines in the near future. For construction safety, Lin et al. (2011) and Dickinson et al. (2011) both proposed the use of a 3D game environment for education purposes. The results show that students are interested in game environments, which motivates their interest in the topic.

The reason behind the success of game-engine applications can also be explained by their edutainment nature; Leopouras and Vassilakis (2005) have summarized previous efforts in this area. Generally, they enhance the user’s motivation in learning. The introduction, by Chen et al. (2003), of a new virtual environment for middle school students to learn from digitized museum resources reinforces this idea. Lepouras and Vassilakis (2005) also point out that game engines offer an affordable virtual reality for research purpose. They believe that game engines have offered a sophisticated, interactive environment with 3D graphics and immersion capabilities to the users.

Selection of Game Engine

Several game engines are available in the market. Doom 3 and Unreal Tournament 2004 provide powerful real-time rendering and interaction. But these first-person-shooter (FPS) game engines only allow the users to make simple modifications to the game engines and require an advance programming process to make major changes to the game environment. Other game engines, such as 3DVIA Virtools and Unity allow the user to build their own virtual world by using the built-in functions. These game engines give the user more flexibility and freedom because the user can build any kind of games (e.g., real-time strategy or role-playing game) in addition to FPS games. One of the most important issues considered in this research was to build a platform for multiusers. As a result, 3DVIA Virtools was selected because it is more effective in building multiuser platforms than other available game engines.

Multiuser Virtual Safety Training System

Game engines are modified and adopted in different industries for various purposes. Some of the previous research has already identified that game engines are suitable for safety management. For example, Lin et al. (2011) find that all interviewees agree that the learning experience is facilitated by the game interaction. It is clear that the use of game engines can improve the learning process and thus enhance the safety performance of the trainees. In light of the situation, this paper suggests that game engines should be used to develop a training platform for tower crane dismantling. The use of game engines also allows the training to be carried out without physically preparing a suitable environment (such as tower crane and related equipment), which is both time and cost effective. The proposed system provides a virtual environment for the users to experience the complete tower crane dismantling process. The dismantling process of the proposed system is structured and designed according to two sources: (1) The erecting–dismantling manual produced by one of the major crane manufacturers and (2) a method
of statement for crane dismantling from one of the major main construction contractors in Hong Kong. The multiuser function of the game engine allows different users to log in to the training platform simultaneously and to complete the training task at the same time, which simulates the real construction process. For multiuser training, the system requires users to log in with different roles (e.g., riggers and crane operators). The users then follow the instructions provided by the system until completion of the training. The system records the input and reports the performance of individual users at the end of training. The performance of the users is evaluated by their contributions during the training. The trainees will benefit from the multiuser virtual safety training system (MVSTS) and is expected to improve their safety performance for tower crane dismantling process.

The aim of the MVSTS is to explore the use of game engines in safety training for tower crane dismantlement. The trainees are expected to learn the working procedure, working location, and working duties of individuals inside the training system. The development of the system is based on an existing game engine, 3DVIA Virtools, a development and deployment platform from Dassault Systems. This can facilitate prototyping and robust development and is an innovative approach to interactive 3D content creation. It has a wide range of applications, including being widely used for design reviews, shopping experiences, simulation-based training, advergaming, and sales configurators.

The implementation of MVSTS includes the definition of functions. The system should be capable of delivering the following functions to achieve training value:
1. Multiuser platform,
2. Database, and

The combination of these functions forms the core of the system, which is shown in Fig. 1. Trainees are connected to a shared virtual environment by the multiuser platform. The database stores the true values for all the predefined input of the trainees, whereas the knowledge and rules module validates the input of the trainees with the database. The details of the functions are explained subsequently.

**Multiuser Platform**

To build a training system that can simulate the dynamic nature of a construction site, it is necessary to allow more than one trainee to connect to the system simultaneously. The platform was developed by comprehensive computer programming work. The 3DVIA Virtools development platform supports the use of the C++ language used in the platform development.

**Server Connection**

Once the system is started on any computer, it automatically searches for the server. The trainees can also manually connect to the server by providing a suitable internet protocol (IP) address. However, the platform is not only capable of connecting computers together, it is also capable of data synchronism between all the connected computers. The details of the synchronism are explained in the next paragraph.

**Assigning Attributes**

When the trainees sign in, MVSTS requires them to select their role during training, which can be laborers, safety officers, foremen, or machine operatives. For each role, their responsibility during the training period is stored in a database. The database provides an attribute to trainees, which indicates the role of the trainee within the process. Also, every construction activity within the system has another attribute. The attributes of construction activities are stored in the database. This attribute is used for verifying the duty of the trainee. For example, laborers have an attribute, \( L \), and all of their responsible construction activities are also given an attribute \( L \). When the trainees who are not assigned as laborers initiate a construction activity, the system checks the trainee’s role and compares it with the attribute of the construction activity.

**Synchronism**

The platform also synchronizes all connected computers when any of the trainees provide an input, including workers’ movements, construction activity, or machinery movement. This ensures that the virtual environments for all connected computers are always the same.

**Database**

It is necessary to explain the structure of the training tasks before describing the database. Within the training system, the complete construction process is divided into major construction tasks, and these major tasks are further subdivided into minor tasks. Each of the minor tasks is an independent task. The minor task should
consist of only one construction activity. The major tasks comprise a combination of numerous minor tasks. For example, the construction of a concrete wall includes formwork erecting, rebars fixing, concreting, and formwork dismantling. Hence, the construction of a concrete wall is defined as a major task within the system. The formwork erecting, rebars fixing, concreting, and formwork dismantling tasks are all independent tasks and consist of one construction activity, so these are all minor tasks.

A small database is inserted into all minor tasks, which are predefined in the training system. The database is simple and it includes only three attributes:

1. Time sequence: The correct construction sequence of all minor and major construction tasks is arranged and stored in the system.
2. Location: When the tasks require the trainee to work (or not to work) in a specific location, the data of the location is stored. It is usually represented by a 3D object.
3. Responsibility: Because an attribute is given to trainees when they log in, another attribute is given to the minor task to identify which trainees are responsible for the task.

On the basis of these simple attributes, the MVSTS can check whether the trainees work at the right time, in the right place, and to fulfill their required responsibilities.

**Knowledge and Rules**

The knowledge and rules are the functions that compare the input of the trainees with the database system. These comprise numerical comparisons, the details of which are briefly discussed as follows.

**Real-Time Construction Sequence Verification**

As previously mentioned, the system assigns attributes to all the minor construction tasks. An example is shown in Fig. 2. Here, an integer is given to the minor construction task, such as 5. The integer 5 indicates that it is the fifth minor construction task within the third major construction task. The flow of the construction sequence is shown in Fig. 3. When a trainee initiates a new construction task, the attribute of the new task is stored in the trainee database. The system compares the value of the original task with the new stored value, as shown in Fig. 4. Typically, the value of current task should not be smaller than that of the previous task. This should be the same for both the major and minor tasks. The concept is to check the value differences between these tasks.

Logically, the program is similar to the following:

- If “Previous Major Construction Task” — “Current Major Construction Task” < 0, or “Previous Minor Construction Task” — “Current Minor Construction Task” < 0,
- \[ V = \text{“Current Major Construction Task”} \]
- \[ N = \text{“Current Minor Construction Task”} \]

The program records the major and minor task numbers and puts them into the database of the main system for scoring purposes. The system checks the status of all the trainees in real time. When one of the trainees changes the value in his database, the system checks the database of all of the trainees. Once an error is found, the system records the error in a log book (see the section on the scoring system, mentioned subsequently).

**Real-Time Verification of the Trainees’ Working Locations**

The verification of the working location is carried out in two ways. The first is to check whether the worker is present at the correct location. The second is to check whether any other worker is at this location. Real-time collision checks are used to do this.
A 3D box is hidden and placed at the destination (correct location or restricted location). Once the trainees update their status, the system performs a real-time collision check. An example of a real-time collision check is shown in Fig. 5. Here, the worker on the left-hand side collides with the 3D object, whereas the one on the right-hand side is free from collision. The system then records any errors in the database. This includes the trainee’s identity, the current major task, the current minor task, and the construction location or restricted location (depending on the error).

**Real-Time Verification of Trainees’ Duties**
Discipline is vital in the construction industry. It is important for operatives to work together according to instructions to complete tasks safely. To check whether trainees have performed tasks within their responsibilities, the system performs a real-time verification of the trainees’ duties. This is done by comparing the database of performed tasks with the database of the trainee who initiates the tasks. As shown in Figs. 2 and 4, the data for “responsible trainee” and “trainee’s duty” are compared. If the data are found to be different, this is reported to the scoring system.

**Scoring System**
The scoring system records the incidents caused by the trainees. There are three forms of incident involved, which are related to (1) the construction sequence, (2) the construction location, and (3) the duty of the trainees. Once an incident is recorded by Knowledge and Rules 1–3, its details are recorded by the scoring system. Data are extracted from the database of both the construction activity and trainee, and the system creates a new array for capturing the related information. An example is shown in Fig. 6, in which the first two rows identify the trainees’ incorrect construction sequencing. The next two rows record the tasks that trainees performed that should be the responsibility of other trainees. The last row shows the errors in working location. To pass the training, the trainees should avoid making mistakes. The trainees obtain the highest mark (32, as shown in Fig. 7) only if they complete the training without making any mistakes. There are two types of mistakes, minor and serious. Minor mistakes are defined as mistakes that may lead to minor injury or damage to equipment, whereas serious mistakes refer to mistakes that may lead to serious injury or fatality. Trainees fail their training if they have made two minor mistakes or one serious mistake during their training process.

**Input Devices**
In computing, “input device” refers to the communication between user and information system. The keyboard and mouse are typical computer input devices. In this research, the Nintendo Wii remote and nunchuck was used as the input device. The reason for selecting the Nintendo Wii remote and nunchuck can be explained by its function to connect to the computer through Bluetooth and its accelerometers. The accelerometers allow users to give motion input, such as swinging their arms. A program was built to link the Wii remote to computers through Bluetooth technology.

**Control of the Virtual Worker’s Movements**
By controlling the nunchuck as shown in Fig. 8 (left side of the figure), the user can control the movement of the virtual worker to the location by controlling the direction of the highlighted button. Changing the viewpoint of the worker involves a similar procedure as moving the worker around the site. The only difference is that the user is required to press an additional button, as shown in Fig. 8 (right side of the figure). Another remote is used...
for carrying out different actions. For example, when the users are required to install or remove a bolt, they move the workers next to the bolt, as shown in Fig. 9, hold the highlighted button of the controller, and swing it, as shown in Fig. 10. Other actions are available but are not discussed in this paper.

**Manufacturing of Tower Cranes**

During the dismantling process, an extra tower crane, derrick crane, or mobile crane is often needed. In this paper, because the manufacturing of heavy machinery was not the main focus, the manufacturing of the assisting tower crane is simplified. The user is only allowed to perform slewing, trolley travelling, and hoisting. In a similar manner to moving around the site, the use of the Wii remote and nunchuck is used for controlling the crane.

**Case Study**

A case study was conducted for tower crane dismantling. The complete dismantling process was divided into major tasks and minor tasks, as shown in Fig. 11. The database of the construction activities was created after the completion of the related 3D models and construction process simulation. The virtual workers, roles, and database for the training process were then defined.

**Computing Detail for the Proposed System**

As mentioned earlier, the development of MVSTS is based on an existing game engine, Virtools. The game engine has built-in functions that enable users to develop games easily. For MVSTS, the virtual environment, simulation, and control interface are all built by a combination of these built-in functions. Developed commands can be as complex as in Fig. 12, which is an example of controlling workers’ movements. Because of the complexities involved, some of the commands are developed in C++, necessitating the employment of a professional computer engineer.

**Real-Time Construction Sequence Verification**

The construction sequence for the training process was predefined, as shown in Fig. 11. The major and minor tasks were also arranged accordingly. The construction sequence was defined according to the erecting–dismantling manual produced by one of the major crane manufacturers and a method statement for crane dismantling from one of the major main construction contractors in Hong Kong. Attributes were given to individual activities so that by comparing these attributes, the system can verify the users’ inputs. When the trainees failed to follow the predefined working sequence, the system recorded the mistake. For example, while removing the mast sections within the system, the bolts between two connected masts, a mistake is recorded unless it is not removed by Rigger B before Rigger A has tied the hook of the derrick crane to the mast by ropes.

**Real-Time Verification of the Trainees’ Working Locations**

Verification of the trainees’ working location in real time involves two situations:

1. The trainees must work in certain areas to avoid accidents; and
2. The trainees must avoid working in certain areas to avoid accidents.

An example is shown in Fig. 13. The working area to be avoided is highlighted. Two cubic boxes are placed and hidden at the temporary working platform. Before the crane operator starts the next task, all other trainees have to leave the highlighted area to avoid detection by the real-time collision check. Throughout the complete dismantling procedure, all prohibited areas and areas that are prohibited from time to time during the process apply the same rules. The trainees learn where to work by virtually working at the right location.
Real-Time Verification of the Trainees’ Duties

The minor tasks were assigned to Riggers A and B, respectively. If Rigger A accidentally completed the minor task “remove bolts between two connected masts” (which is the duty of Rigger B), the system recorded and reported the situation to the scoring system. The importance of verifying one’s duty is to ensure that all trainees fully understand the procedure. If Rigger A completed Rigger B’s duty, it is possible that he will misunderstand his duty and leave tasks for which he is responsible incomplete.

Scoring System

The scoring system collected information from all the different databases within the MVSTS. The information was stored within the system and printed in tabular form at the end of the training session. Each of the trainees received a report containing all the mistakes made by the trainee. An example of the report is shown in Fig. 7. The reason for having a scoring system is to evaluate the trainees’ performances during the training period. Each time the trainees make a mistake, the mistake was recorded, and the score of the trainee responsible was adjusted accordingly. The adjustment made is predefined and depends on the seriousness of the incident.

Feedback

To evaluate the effectiveness of the system, 30 construction operatives working as riggers during a tower crane dismantling process were invited to participate. The participants had different working experiences in erecting and dismantling tower cranes, from no experience to approximately three years’ experience. The riggers were then divided into three groups, named Groups A, B, and C. Group A included 10 construction workers with no experience in tower crane-related operations nor training in any tower crane-related course. Groups B and C included 10 construction workers with experienced in tower crane-related operations and recently traditional tower crane dismantling training, respectively. Both Groups A and B were trained by the proposed system. The selection of the evaluation method follows Schlickum and Hedman (2009) in their verification of the use of systematic video games in surgery. In their case, three groups of students with similar backgrounds were assigned different video game training regimes, and their performances were assessed afterwards.

After tower crane training, all groups were invited to participate in a short quiz session, which consisted of 20 multiple choices questions concerning the tower crane dismantling process. The maximum score for the quiz was 20, which indicated that correct answers had been given to all questions. The results for different groups are compared in Table 1. The performance of Group B was the best of all the groups. Group B scored 26.1 out of 30 on average (Groups A and C scored 24.2 and 24.3, respectively). The average scores of Group B were also the highest in all three different aspects related to working location, working sequence, and working duty, respectively.

Table 1. Average Score for the MVSTS Case Study

<table>
<thead>
<tr>
<th>Average score of Group A, B, and C</th>
<th>Average of Group A</th>
<th>Average of Group B</th>
<th>Average of Group C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scoring and result</td>
<td>24.2</td>
<td>26.1</td>
<td>24.3</td>
</tr>
<tr>
<td>Max. = 30</td>
<td>(2.44)²</td>
<td>(2.427)²</td>
<td>(2.283)²</td>
</tr>
<tr>
<td>Working location related</td>
<td>8.1</td>
<td>8.8</td>
<td>8.0</td>
</tr>
<tr>
<td>Max. = 10</td>
<td>(0.830)²</td>
<td>(0.980)²</td>
<td>(0.894)²</td>
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<tr>
<td>Working sequence related</td>
<td>7.8</td>
<td>8.7</td>
<td>8.2</td>
</tr>
<tr>
<td>Max. = 10</td>
<td>(0.872)²</td>
<td>(0.781)²</td>
<td>(0.872)²</td>
</tr>
<tr>
<td>Working duty related</td>
<td>8.3</td>
<td>8.6</td>
<td>8.1</td>
</tr>
<tr>
<td>Max. = 10</td>
<td>(0.900)²</td>
<td>(1.02)²</td>
<td>(0.943)²</td>
</tr>
</tbody>
</table>

(Standard deviation).

Fig. 12. The script for controlling the movement of virtual workers

Fig. 13. An example of avoided working area in highlighted color

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(8.8, 8.7, and 8.6 for working location, working sequence, and working duty, respectively). Group A obtained the lowest result, scoring 8.1, 7.8, and 8.3 for the three aspects, respectively. The results for Group C, with scores of 8.0, 8.2, and 8, were slightly better than Group A. Therefore, the resulted indicate that Group B’s performance was slightly better than Group C. Both the researchers and the members of Group B believe that the use of the proposed system is the reason for the differences in scores.

It is also believed that the use of the system provided valuable experience to Group B, whereas the game environment also motivated the members of Group B to learn during the training period. Group B scored particularly highly on location-related questions, prompting the conclusion that the use of the 3D environment improved the trainees’ understanding of the dismantling process. The experience of walking within the virtual environment and being able to experiment virtually with the walking path clearly enhanced the trainees’ awareness of potential hazards on site.

In addition, the result of Groups A and C are similar, and both the researchers and Group A members agree that the use of the system provided valuable experience for the Group A members. The virtual experience is one of the key reasons for their similar performance when compared with Group C, the members of which were more experienced in tower crane operation.

Interviews were arranged separately for Groups A and B to collect their opinions regarding the proposed training system. Four questions were asked during the interview to rate the traditional training method against the MVSTS, with a rating of 5 representing “highly effective” and a rating of 1 representing “not effective at all.” The average ratings were 4.1 (out of 5) for learning construction sequence, 4.0 for learning own weaknesses, 3.8 for learning working location and restrictions, and 3.5 for learning working cooperatively. These results indicate the MVSTS to be satisfactory, with the workers involved generally acknowledging that the system assisted them in learning the correct construction process. Compared with traditional training, the workers thought that the use of visualization improved their interest in training. They also stated that the use of visualization made the training content easier to understand. Moreover, they also agreed that the system’s final report helped them to identify their own weaknesses and areas in which further training is needed, something that is not possible with the traditional training process.

Through the case study, therefore, the MVSTS system proved to be useful for tower crane dismantlement training, and several advantages are apparent. First, the MVSTS provides a totally risk-free environment, which is almost impossible to do in real-life training courses. Second, the cost of MVSTS is reasonably affordable in comparison with creating a mock-up environment equivalent in real-world training. Third, MVSTS is particularly useful as a training platform in advance of traditional off-the-job training. The MVSTS provides valuable opportunities for the trainees to experience a close-to-reality training environment. Lastly, the use of MVSTS as a game environment can motivate the trainees to learn. Of the few shortcomings noted, one of the most important of these is that the development of MVSTS requires professional computer programming skills, which are not commonly found in the construction industry. To produce a close-to-reality environment, the development of the MVSTS is quite time consuming, especially that related to 3D modelling and texturing.

Conclusion

The research described in this project marks a major step toward the use of visualization skills in safety training. A new system of training for dismantling tower cranes is described by utilizing an existing game-engine approach. The integration of game engines and safety training provides a close-to-reality 3D environment in which trainees can learn and practice their knowledge. This system, termed the multiuser virtual safety training system, comprises four developed functions to allow trainees to learn comprehensive construction processes in a virtual and risk-free environment. A live case study is also described in which operatives undergo off-the-job training for the dismantlement process of a tower crane and which follow-up interviews indicated to be a significant improvement on the traditional approach. Feedback showed one of the main benefits to be the identification of the trainee’s weaknesses and opportunities for the development of further skills through off-the-job practice. The ability to allow the trainees to work corporately in a dynamic 3D environment clearly creates the opportunity for the workers to practice before the start of actual construction. The findings also indicate the use of MVSTS provides trainees with valuable experience, which can be almost as effective as real-life working experience. As the virtual environment of the system is not critical to the platform and can easily be changed in a short period of time for training users in a different virtual environment, such as a small construction site with limited space or a large construction site involving numerous cranes.

As far as future studies are concerned, further investigations for the use of existing game engines for tower cranes are suggested. One potential application is to investigate the use of game engines in current tower crane dismantlement practice and develop new dismantling methods. Demonstrating the capability of the game engine to produce a close-to-reality virtual environment illustrates the fact that game engines provide a perfect platform for physical-based simulation. The integration for the virtual environment and physical-based simulation can provide a platform for the designers to verify their proposals in a risk-free environment.

References

3DVIA Virtuools [Computer software], Dassault Systèmes, Paris.


