A multi-user virtual safety training system for tower crane dismantlement

ABSTRACT

Tower crane dismantling is one of the most dangerous activities in the construction industry. According to Smith and Corley (2009), tower crane erection and dismantlement causes 10% to 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 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 "Multi-user Virtual Safety training System" 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, 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 the working of the system and its practical application. The proposed system was evaluated by interviews with thirty construction experts with different backgrounds, divided into three groups according to their experience and trained by the traditional and virtual method 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 has great potential as a training platform generally.

KEYWORDS: Disassembly, dismantling, game-engine, safety, tower cranes, training, virtual reality,

BACKGROUND

Tower cranes are widely used in the construction industries of all developed countries. In the USA 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), for example, has reported an estimated 300 tower cranes to be in operation at one point in Miami during 2006. In Hong Kong, the Deputy for Labour of the Hong Kong Labour Department, Ting (2007), summarised an inspection conducted in July 2007 which 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 construction sites concerning 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 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 USA, an average of 82 workers were killed in crane accidents from 1997 to 2006 (Van Hampton, and Lewis, 2008). Smith and Corley (2009) also found that their erection and dismantling caused 10% to 12% of all crane fatalities. As crane accidents were responsible for 8% to 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% to 33% of all fatalities in construction and maintenance work. Another study, by Suruda et al. (1999), investigating fatal injuries in the USA involving cranes during 1984 to 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 to 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 at the location which should be 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 cranes operation. The Occupational Safety and Health branch of the Labour Department (2002) pointed out that dismantling a crane is more complicated than its erection due to space restrictions imposed by both the permanent and temporary structure around the crane. Tower crane dismantling is also a highly complex procedure, which 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 and 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 which allows the system to simulate the detail process of dismantling a tower crane and thus to provide virtual on-the-job training.

The 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
3. Improper operation, such as overloading

These three groups are also endorsed by MacCollum (1980) and Häkkinen (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 and the suggestion of worker training to be 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 (e.g., Goldenhar et al 2001). For tower cranes, this is even more important as lack of education and regular training of workers in the crane environment is one of the main causes of their associated accidents (Häkkinen 1993). Smith and Corley (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.

The current practice of training for operators and riggers

USA fatality investigations in 2005 found approximately 40 percent 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 for, in term 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 programme. The mentor passes his experience and skills to the mentee, which usually starts with the provision of guidelines to the mentee during the work on site. Of course, as the success of this system relies heavily on the quality of the mentors - a poor mentor can easily pass improper attitudes to the mentee. Unlikely the new regulations of 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 practice. Also, even after the mentees have received tuition during the work, they still have occasional difficulties in applying their skills and knowledge due to lack of sufficient practice. This situation has particularly hindered the development of mentees. In other industries, aviation for example, where safety is paramount, operatives 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, where 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 for operatives to develop the necessary skills in a non-hazardous 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 as early as the 1970s (e.g. Häkkinen, 1978). More recently, Shepherd et al. (2000) conducted a taxonomic analysis in USA crane fatalities, dividing more than 500 recorded crane related accidents into different types. Neitzel et al (2001) also reviewed crane safety in the USA 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 2009a; 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 of 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 advance programming skills and substantial time for development. As a result, the use of development kits is often unviable 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 (Allbeck and Badler 2002), limiting the ability of development kits to simulate particular behaviours.

Due to the difficulties in creating virtual environments by 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 behaviour 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 - the use of Microsoft Flight Simulator and 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 who have 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 and therefore representing a significant cost benefit. Lindheim and Swartout (2001) have also developed a new simulation technology which integrates game-engine technology with USA 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 USA 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 behaviour model testing and human 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). 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 (Refsland 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 BIM with a game application to develop real-time interactive architectural visualization. A similar approach was taken by ElNimr and Mohamed (2011), who aim to visualize simulated construction operations by game-engines. Juang et al. (2011) also try to simulate the physics of a forklift by 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 propose the use of 3D game environment for education purposes. The result shows 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 and Lepouras and Vassilakis (2005) have summarized previous effort in this area. Generally, they enhance the user’s motivation in learning. Chen et al.’s (2003) introduction 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

There are several game-engines 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 requires an advance programming process in order to make major change 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 as the user can build any kind of games (e.g. real-time strategy, role-playing game) in addition to FPS games. One of the most important issues for the authors to consider in this research was to build a platform for multi-users. As a result, *3DVIA Virtools* was selected as it is more effective in building multi-user platforms than other available game-engines.

MULTI-USER VIRTUAL SAFETY TRAINING SYSTEM (MVSTS)

Game engines are modified and adopted in different industries for various purposes. Some of the previous research have already identified game engines is suitable for safety management. For example, Lin et al. (2011) find that all interviewees agree the learning experience is facilitated by the game interaction. It is clear that the use of game engine can improve the learning process and thus enhance the safety performance of the trainees. In light of the situation, the authors suggest to use game engine to develop a training platform for tower crane dismantling. The use of game engine also allows the training to be carried out without physically prepare 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. These are (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 multi-user function of the game engine allows different users to login to the training platform simultaneously and to complete the training task corporately, which simulates the real construction process. For multi-user training, the system requires users to login with different roles, for example 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 contribution during the training. The trainees will benefit from the MVSTS and is expected to improve their safety performance for tower crane dismantling process.

The aim of the Multi-user Virtual Safety training System (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 in order to achieve training value:

1. Multi-user platform
2. Database
3. Knowledge and Rules

The combination of these functions forms the core of the system, which is shown in Figure 1. Trainees are connected to a shared virtual environment by the Multi-user platform. The Database stores the true values for all the pre-defined input of the trainees, while the Knowledge and Rules module validates the input of the trainees with the Database. The details of the functions are explained below:

Multi-user platform

In order 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 I.P. 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 labourers, 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, labourers 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 labourer 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 consists of one construction activity, so these are all minor tasks.

A small database is inserted into all minor tasks, which are pre-defined 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
   Since an attribute is given to trainees when they logged in, another attribute is given to the minor task to identify which trainees are responsible for the task.

Based on these simple attributes, the MVSTS can check if the trainees work at the right time, in the right place and to fulfil 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 below.

Real-time construction sequence verification

As already mentioned, the system assigns attributes to all the minor construction tasks. An example is shown in Figure 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 tasks within the third major construction task. The flow of the construction sequence is shown in Figure 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 Figure 4. Typically, the value of current task should not be smaller than that of previous task. This should be the same for both major and minor tasks. The concept here is to check the value differences between these tasks. Logically, the program is similar to the following[1]:

If “Previous Major Construction Task” – “Current Major Construction Task” <0,
or
“Previous Minor Construction Task” – “Current Minor Construction Task” <0,
V = “Current Major Construction Task”
N = “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 purpose. 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 trainees. Once an error is found, the system records the error in a log book (see Scoring System below).

Real-time verification of the trainees’ working location

The verification of the working location is carried out in two ways. The first is to check if the worker is present at the correct location. The second is to check if 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 Figure 5. Here, the worker on the left hand side collides with the 3D object while the one on the right hand side is free from collision. The system then records any errors in the database.

[1] Full details of the computer program are not discussed here.

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 according to instructions together in order to complete tasks safely. In order to check if trainees have performed tasks within their responsibilities, the system performs real-time verification of 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 Figure 2 and Figure 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) construction location and (3) the duty of the trainees. Once an incident is recorded by Knowledge and Rules 1 to 3, its detail 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 Figure 6. Here the first two rows identify the trainees' incorrect construction sequencing. The next two rows record the tasks that trainees performed which should be the responsibility of other trainees. The last row shows the errors in working location. In order to pass the training, the trainees should avoid making mistake. The trainees obtain the highest mark (32, as shown in figure 13) 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 which may lead to minor injury or damage to equipment, while serious mistakes refer to mistakes that may lead to serious injury or fatality. Trainees fail their training if they have made 2 minor mistakes or 1 serious mistake during their training process.

Input devices

In computing, input devices 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 nun chuck was used as the input device. The reason for selecting Nintendo Wii remote and nun chuck 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 movement

By controlling the nun chuck as in figure 7, 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 figure 8. 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 figure 9, hold the highlighted button of the controller and swing it as shown in figure 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. Here, as 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 nun chuck 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 Figure 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 which 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 Figure 12, which is an example of controlling workers' movement. Due to 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 pre-defined as shown in Figure 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' input. When the trainees failed to follow the pre-defined working sequence, the system recorded the mistake. For example, while removing the mast sections within the system, the bolts between two connected masts, and 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 location

This involves two situations:

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

An example is shown in Figure 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 which 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 rigger 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 all trainees fully understand the procedure. If rigger A completed rigger B's duty, it is possible that he misunderstand his duty and leave his responsible task 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 Figure 14. The reason for having a scoring system is to evaluate the trainees' performance during the training period. Each time the trainees make a mistake, the mistake was recorded and the score of the trainee responsible adjusted accordingly. The adjustment made is predefined and depends on the seriousness of the incident.

Feedback

In order to evaluate the effectiveness of the system, thirty 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 approximately three years to no 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 respectively included 10 construction workers with experienced in tower crane related operations and recently traditional tower crane dismantling training. Both groups A and B were trained by the proposed system. The selection of the evaluation method follows Schlickum et al. (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.

Afterward the tower crane training, all groups were invited to a short quiz session, which consisted of twenty 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 (group 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 (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 respectively for the three aspects. The results for Group C, with scores of 8.0, 8.2 and 8, were slightly better than Group A. Therefore, the result indicate that group B's performance is 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, while 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 experiment virtually with the walking path clearly enhanced the trainees' awareness of potential hazards on site.

In addition, the result of group 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, who were more experienced in tower crane operation.

Interviews were arranged separately for group 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 - 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 restriction 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 where 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. Firstly, the MVSTS provides a totally risk-free environment, which is almost impossible to do in real-life training courses. Secondly, the cost of MVSTS is reasonably affordable in comparison with creating a mock-up environment equivalent in real-world training. Thirdly, MVSTS is particular useful as a training platform in advance of traditional on-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. In order 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 utilising an existing game-engine approach. The integration of game-engines and safety training provides a close-to-reality 3D environment for trainees to learn and practice their knowledge. This system, termed the Multi-user Virtual Safety training System (MVSTS), 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 dismantling practice and develop new dismantling methods. In 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.

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Figures and Tables

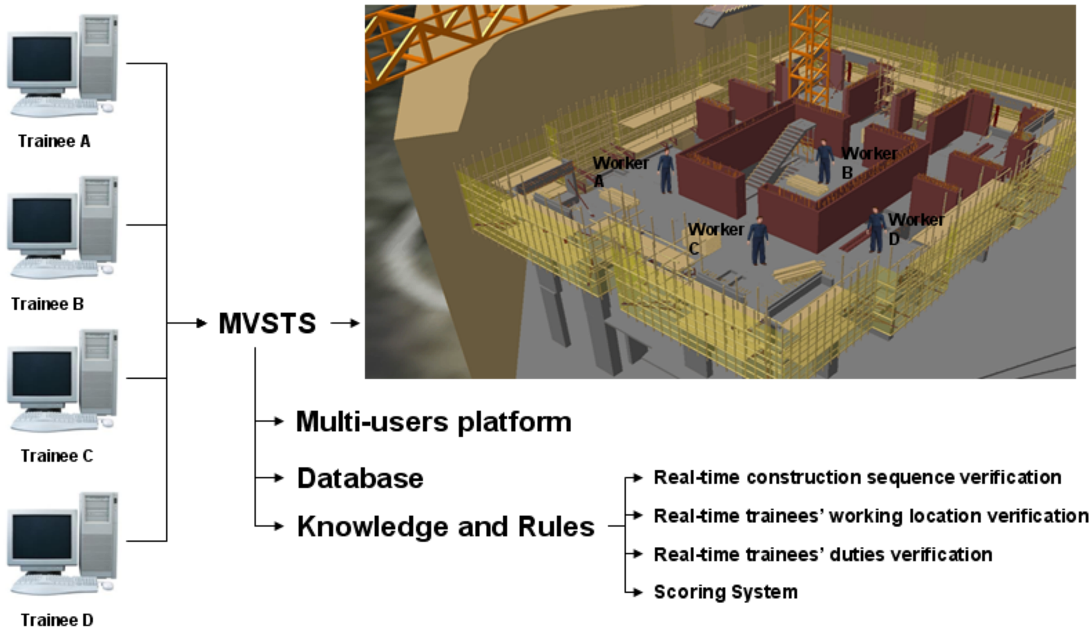

Figure 1. MVSTS system structure

0 : Major Construction Task	1 : Minor Construction Task	2 : Construction Location	3 : Restricted Location	4 : Responsible Trainee
3	5	Object 1	Object 2	Labourer

Figure 2. Example of the database for one of the minor construction tasks

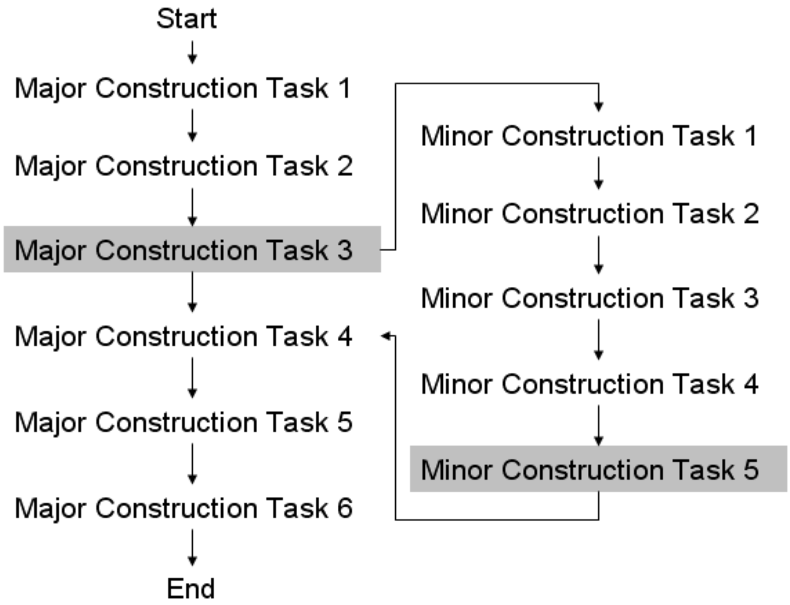

Figure 3. Typical construction sequence within the proposed system

0 : Previous Major Construction Task	1 : Current Major Construction Task	2 : Previous Minor Construction Task	3 : Current Minor Construction Task	4 : Trainee's duty	5 : Trainee's identity
3	3	4	2	Labourer	1

Figure 4. Example of a database for one of the labourers

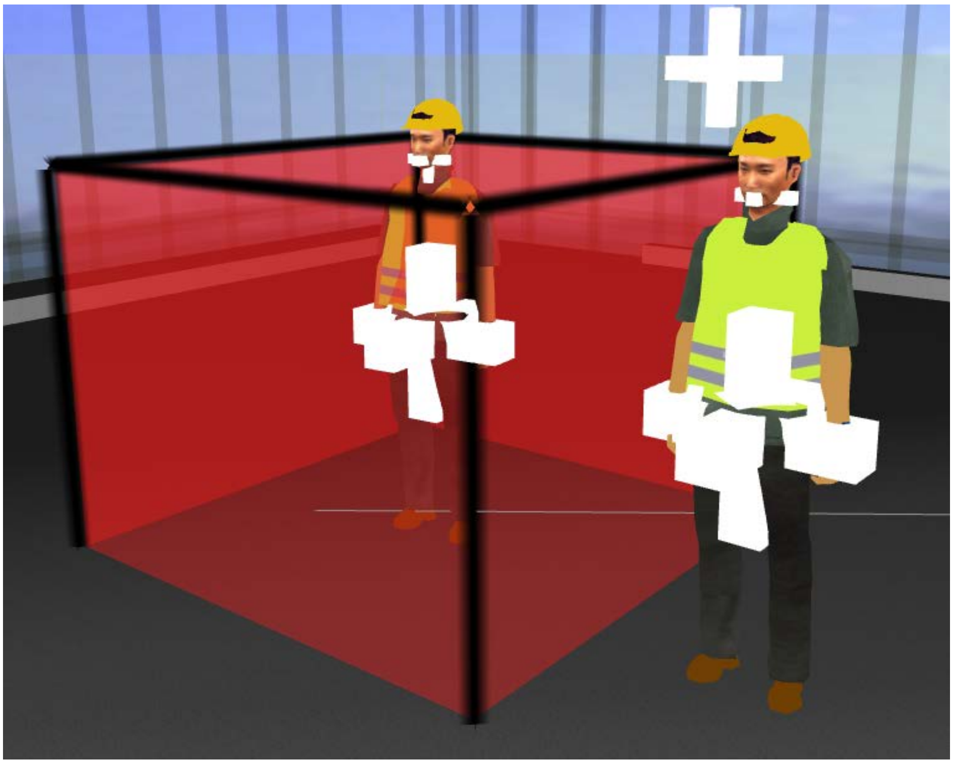

Figure 5. Example of a collided and collision-free worker

0 : Major Task	1 : Minor Task	2 : Related Trainee Identity	3 : Related Trainee duty	4 : Task's responsibility	5 : Incident type
3	5	1	Labourer	Labourer	1
3	6	2	Labourer	Labourer	1
4	1	1	Labourer	Crane Operator	2
4	3	3	Crane Operator	Labourer	2
5	1	1	Labourer	Labourer	3

Figure 6. Database of the Scoring System

Figure 7. Control of movement

Figure 8. Control of view angle

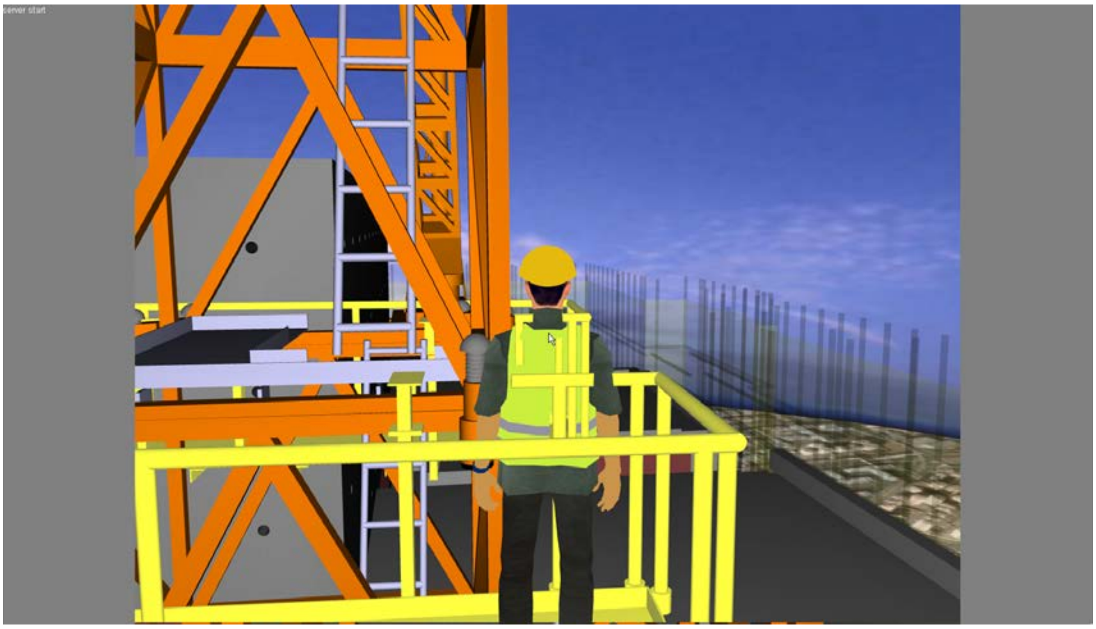

Figure 9. A worker stands next to the bolt before its installation or removal

Figure 10. Control of the bolt installation or removal process

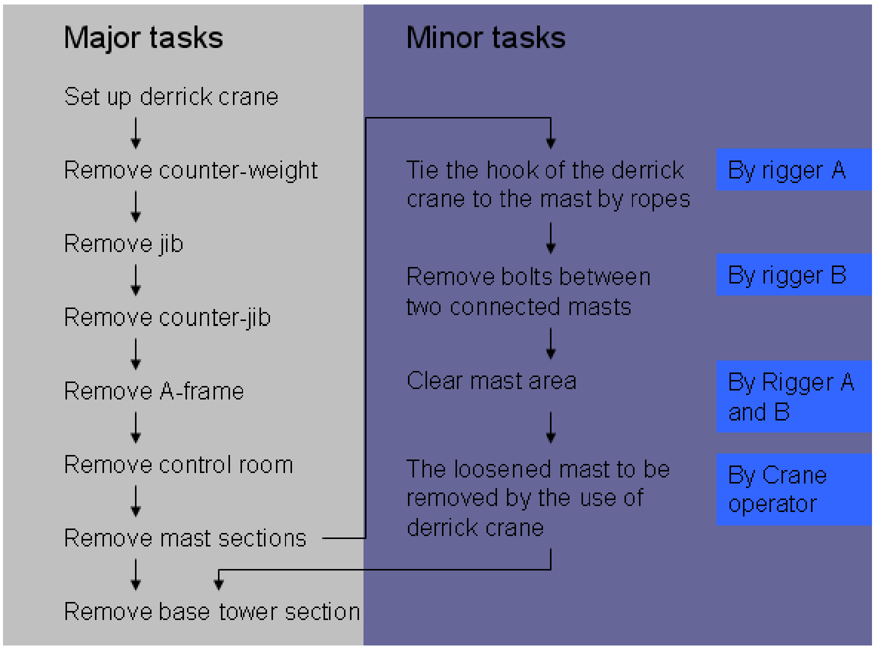

Figure 11. Classification of major and minor tasks

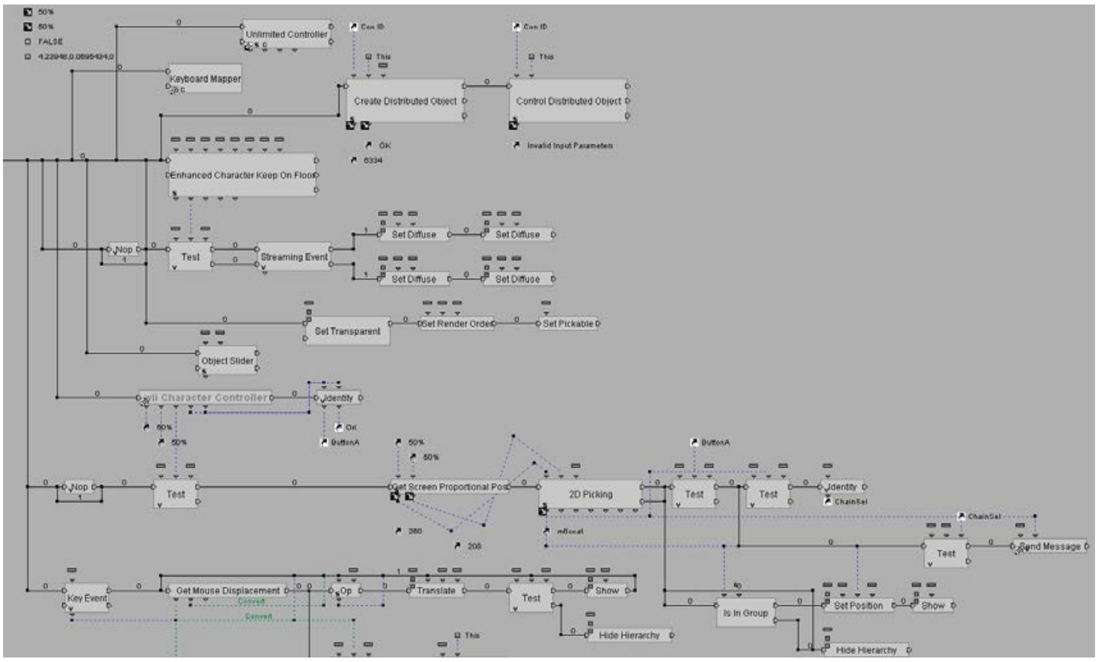

Figure 12. The script for controlling the movement of virtual workers

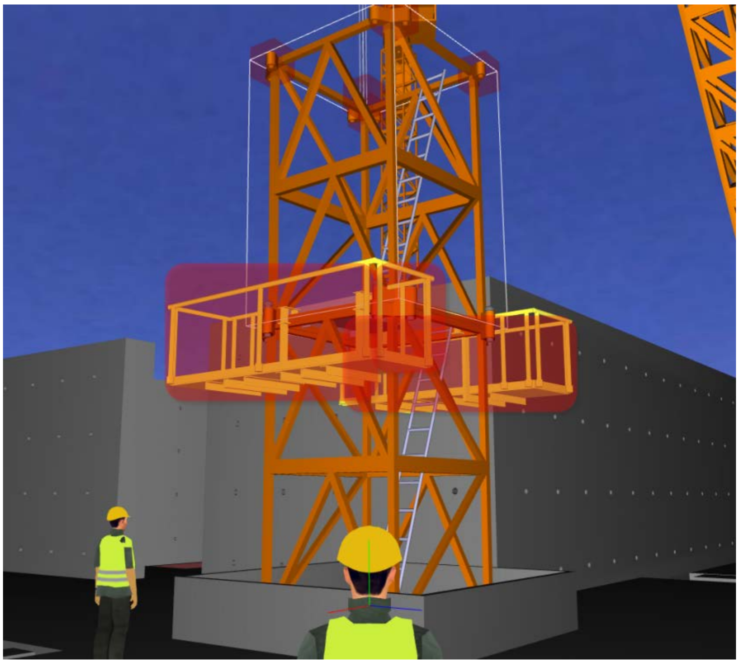

Figure 13. An avoided working area

Trainee Identity :	1		
Trainee's duty:	Rigger		
Incident record:			
incident number:	Incident type:	Major task	Minor task
1	1	5	3
incident number:	Incident type:	Major task	Minor task
2	1	5	4
incident number:	Incident type:	Major task	Minor task
3	2	5	3
incident number:	Incident type:	Major task	Minor task
4	3	5	3
Total Score:	28/32		
Result:	Pass		

Figure 14. Example of a scoring report

	Average of Group A	Average of Group B	Average of Group C
Scoring & Result Max = 30	24.2 *(2.441)	26.1 *(2.427)	24.3 *(2.283)
Working Location related Max =10	8.1 *(0.830)	8.8 *(0.980)	8.0 *(0.894)
Working Sequence related Max =10	7.8 *(0.872)	8.7 *(0.781)	8.2 *(0.872)
Working duty related Max =10	8.3 *(0.900)	8.6 *(1.02)	8.1 *(0.943)

*(Standard Deviation)

Table 1. The average score for the MVSTS case study