# A Multi-player Virtual Reality-based Education Platform for Construction Safety

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**Abstract:**

Construction is one of the industries with the highest fatality and injuries rate around the world. Studies indicated that human error is one of the key contributors of construction accidents. Although human error is inevitable, construction workers can acquire a range of skills and knowledge to improve the ability to identify and assess risk through training and experience. However, researchers have raised questions about the effectiveness of the existing construction safety training since the industry still remains among the most dangerous to work in. Recent advancement in virtual reality (VR) has offered us with the opportunities for providing a more effective approach for safety training. However, the existing research and applications on VR mainly focused on single user applications with static environments, which cannot fully address the challenges posed by the dynamic and teamwork characteristics of construction projects. In this paper, the authors presented a framework supporting the safety knowledge integration, building information utilization, and multi-user interaction. In the framework, a trainee's performance can be monitored in real-time and stored in the database to support the training performance analysis. A prototype multi-player VR-based education platform is developed following the proposed framework using Oculus Rift, Unity 5, C# and BIM application. The education platform presented in this paper provides an effective approach for safety training in an immersive environment to simulate the interactions among workers/equipment as well as provides informative and timely feedback for trainee.

**Keywords:** Virtual Reality, Construction Safety Training, Falling Objectives, Interactive Playing

## 1. INTRODUCTION

The construction industry makes a vital contribution to about one-tenth of the world's GDP; however, construction is the most dangerous industry in which there are more than 60,000 fatal accidents occur each year around the world, with an average of one fatal accident in every ten minutes (ILO. 2005).Hong Kong's construction industry has a worse safety record compared with its neighboring countries such as Singapore and Japan. There are currently about 3000 construction accidents per year. In 2013, there were a total of 28 industrial fatalities; however, 22 of them occurred at construction sites, which accounted nearly 79% of all fatalities. The construction industry is expected to continue to grow in 2015 due to the recent rise in public expenditure on infrastructure. However, the Construction Industry Council (CIC 2014) estimated that Hong Kong needs at least 10,000 additional construction workers to enter the construction industry, receive training, and be retrained every year until 2018. In addition to the growing demand for construction workers, Hong Kong is currently facing a shortage of qualified workers. There are about 320,000 registered construction workers in Hong Kong but only 70,000 are active. As a result, more emphasis has been given to adequate worker training in order to deal with high staff turnover rates and labor shortages as well as to meet the expected growth in Hong Kong's construction industry. Research has shown that inadequate or lack of safety training is one of the main causes for poor safety performance in the construction industry (Abdelhamid and Everett 2000) . Together, these factors contribute to the need for improving the effectiveness of construction safety education and training. However, the traditional construction safety education and training are unable to deliver trainees with the hands-on practice. Most instructors and trainers usually use pictures, charts, videos and lectures for educating and training. As has been observed by Edgar (1969), human only remember 10% of what we read, and 20% of we hear, but we retain up to 90% of what we learn through active participation.

Virtual reality has been widely recognized as a major technical advance to boost active participation and simulation for education. Currently, Virtual reality technology has been widely applied into fields such as aviation, military training and medicine (Bryne and Center 1993). Recently, researcher attempts to introduce virtual reality and gamming technologies for construction safety training (Fang et al. 2014; Guo et al. 2012; Juang et al. 2013). However, the existing applications of VR application in construction safety education have three major limitations:

1. Usually only one trainee is able to interact in the system while other trainees and trainer just watch from the big screen. However, construction are collaborative activities, which involved multi workers to work together (Fang and Teizer 2014).One worker's behavior might have serious impact on the others' safety

situation. Therefore, a system capable to support multi user interaction is needed.

2. Existing VR-based construction safety training applications only have few rule at specific location to tell whether the worker is behaving safety. Outside these limited areas, the trainee cannot get instant feedback from system. Therefore, a system capable to automatically and continuously evaluate the trainee's safety situation is preferred.
3. Existing VR-applications needs the trainer to record the trainee's performance manually on paper without supporting play-back function. A system which can capture the worker's unsafe behavior in the virtual environment and give summary data for the whole class would be a plus.

To provide a more effective construction safety immersive education platform, a new multi-user VR-based training platform should be proposed. The proposed platform should integrate a set of construction safety knowledge and can be scalable. In addition, multiple trainees should be able to interact in the same simulated environment and all their individual performance can be recorded for further analysis. In this paper, the authors proposed a system framework and deploy an education platform prototype.

The remaining of this paper is described as follow: In section 2, the framework of platform is described with each major component; In section 3, the framework is demonstrated using the scenario of a labor working near the crane load manipulated by a crane operator; In section 4, the economic and other aspects are discussed; In section 5, the works in this paper are summarized with future direction pointed out.

## 2. SYSTEM FRAMEWORK

Our system is divided into three sub-systems (figure 1), respectively:

2.1 Scene Generation Sub-System

The building information model can be imported into the system to create the basic environment where the trainees will play the educational game. At the initialization stage of our system, a list of all the equipment and the persons controlled by the computer will be initialized with pre-define movement Trajectory.

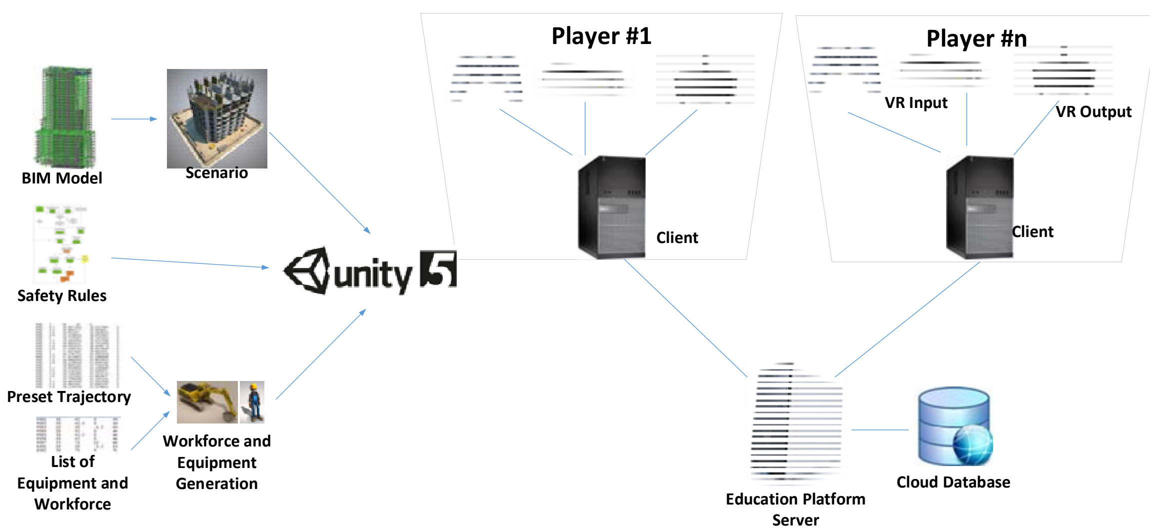


Figure 1. Framework of the System

Since BIM models are more commonly available on recent construction projects and the BIM model contains rich information, the BIM model can be used to create the realistic virtual reality environment (VRE) in the education platform with least additional efforts. The BIM model in Revit is first exported to FBX file and the AutoDesk materials are converted into standard material via AMC script. The FBX file can be imported into 3DMAX and integrated with AMC script. In 3DMax, the model is then exported again into FBX file, which is fed into Unity to build up the VRE for a specific project.

In our proposed platform, the VRE created based on BIM provides a construction jobsite environment with static building components where the worker's and equipment conduct their work. The workers and equipment are not included in the BIM model. In a real construction jobsite, many workers and moving equipment might work at the same time. The trainees might not role play all these actors at the concurrently. Therefore, some of the workers and equipment might need to be played by the computer/system. In our proposed system, a list of computer controlled workers and equipment is pre-defined with initial locations (x,y,z), trajectory. Those workers and equipment will be initialized in the VRE based on initial locations. The trajectories are used to simulate those entities' movements in the VRE.

### 2.2 Multi-User Immersive Interaction Sub-System

*Input from the Trainees.* For trainee controlled equipment, the moving direction (forward, backward, right turn, left turn, upward, downward, and etc.) of equipment can be captured from the keyboard or joystick. For the trainee acting as worker in the VRE, the input can be either captured from keyboard, joystick or vision-based devices (e.g., leap motion). The input on the keyboard or other devices is transmitted into Unity to continuously update the behavior and location of the worker and equipment. The trainee's head movement is captured from sensor mounted on VR display device (e.g., Oculus Rift, Samsung Gear VR, HTC Vive).

*Output Display for the Trainees.* As the location of the worker and his/her head movement is changing, the trainee's view will also be changed in the education platform developed by Unity. When compiling the education platform in Unity, the VR-based platform can be generated by setting the VR option. In this way, the trainee's view will be updated and displayed on VR display device in real time with the trainee's movement.

*Safety Rules and Evaluation Logics.* The safety rules can be elicited from regulations, codes, standards, and best practice in companies and presented in the form of decision flowchart following the standard procedure proposed by Luo (Luo et al. 2011). The decision flowchart of safety behavior judgement can be coded in Unity using C++. At each frame, the codes will evaluate each trainee's safety behavior based on the code.

This system infrastructure includes the clients and servers. There are two types of clients: desktop version and mobile version. In a desktop, a trainee walks and interacts in the virtual environment using leap motion and joystick, and get the real-time updated view on the Oculus Rift. Oculus Rift, joystick and leap motion are all connected on the client workstation. In contrast, a mobile version uses a smartphone (mounted on Samsung Gear VR) for data collection and processing. All the mobile and desktop sub-system are connected to a server to ensure that all the trainees are interacting in the same environment and the environment is updated based on all the users' inputs. The sub-system can use the safety-knowledge described in the scene generation sub-system to determine the safety situation of the trainees' safety situations based on their position, acceleration, velocity, and surrounding environments.

### 2.3 Performance Evaluation and Management Sub-system

All the trainees' behaviors, as well as the details of unsafe behavior, will be recorded in the cloud database. The safety training course's instructor is able to review how well a specific trainee performed in a simulated environment with his/her teammates. Also, the instructor can review the overall performance of a specific group (e.g., trainees from the same sub-contractor, trainee from the same trade, and etc.) to discover existing patterns. The discovered knowledge can assist the instructor to better prepare the contents of safety training course.
*Information Requirements for Performance Evaluation.* The first person-perspective video of each trainee is recorded and stored in server for later replay to support lessons learning. In addition, to provide data for the trainee's performance, a set of information (table 1) should be collected for each frame when playing in the education platform.

Table 1. Information Requirements for Performance Evaluation

| Data | Data Type | Example |
|---|---|---|
| Timestamp | Time | 2015-12-29 14:08:20.00 |
| Trainee's ID | String | HIPH2308 |
| Trainee's Role | String | Carpenter |
| Trainee's Behavior is Safe or Not | Boolean | Y |
| Trainee's Input | Array of Double*<br>*array of double is used to described the trainee's movement increment and directions | (90, 0, 0.5) |
| Trainee's Activity | String | Pouring concrete |
| Related Safety Rule(s) | String | WNCL1 (Working near crane load #1) |
| Education Scenario | String | Working Near Crane Load |

*Information Processing and Presentation for Performance Evaluation.* For each trainee in a specific training platform playing session, percentage of safety behavior and number of unsafe behavior is the key metric to evaluate his safety performance in the VRE.

$$\text{Safety Score} = \frac{Number\ of\ frames\ in\ which\ the\ woker'sbehavior\ is\ safety}{Total\ Number\ of\ frames\ in\ which\ the\ woker'sbehavior\ is\ safety} \times 100\% \quad (1)$$

In addition, number of unsafe behavior is also calculated based on the frames in the game. The pseudo code of calculating the number of unsafe behavior is defined below:

*i from 1 to total number of frames*

*if the worker's behavior is unsafe in i$^{th}$ frame*

*if the worker's behavior is safe in (i-1)$^{th}$ frame*

*number of unsafety behavior increases by 1*

In this pseudocode, violations of safety rule(s) in consecutive frames are considered as a same violation.

Those two key indicators can be calculated for an individual, a group of individuals, or just for a specific education scenario. Filters (e.g., activity, related safety rules, education scenario) can be applied in the data processing to provide more meaningful information for the trainers.

## 3. DEMONSTRATION

A multi-user construction jobsite safety training platform is developed to demonstrate the proposed framework described in section 2.

The BIM model of a public housing project in Hong Kong is imported into Unity via 3DMax and AMC Scripts. One excavator, two concrete trucks and two tower cranes were initiated at pre-defined locations in the created VRE. The moving paths of the excavator and concrete trucks are also given and coded into the Unity-based education platform.

Four education scenario were implemented in the prototype, including working near open edge, working near moving trucks, working near crane load, and entering jobsite for PPE pickup. The safety knowledge was extracted from Hong Kong construction safety regulations, and a main contractor's internal safety practice handbook and presented in decision flowchart (figure 2).

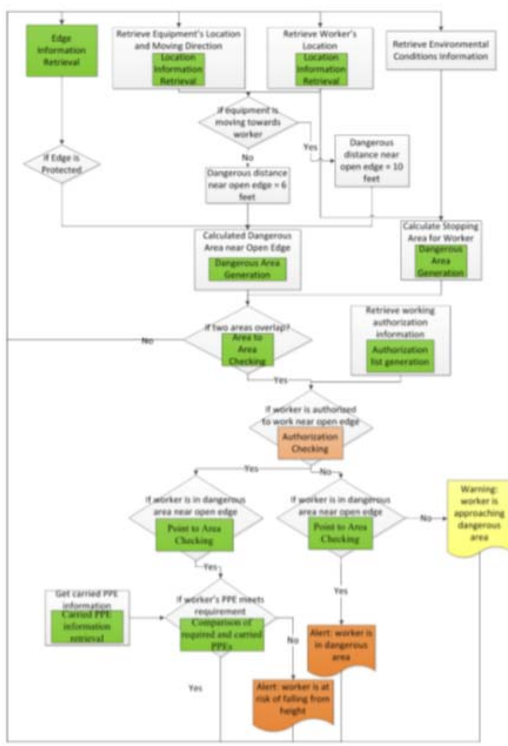


Figure 2. Safety Behavior Decision Flowchart

The education platform developed in Unity is then deployed on the computers (Core i-5, GTX960 4G, 8G RAM, 128G SSD-HDD) in the lab. When a user joins the education platform on a computer, he/she is asked to enter a user name and select his/her role (when all the cranes are occupied by other trainers, the crane operator option will not be listed on the role list). The user can then move in the simulated jobsite using keyboard. When the trainee's behavior violates any safety rule, a warning message will be displayed in his/her VR headset's screen (as shown in figure 3).

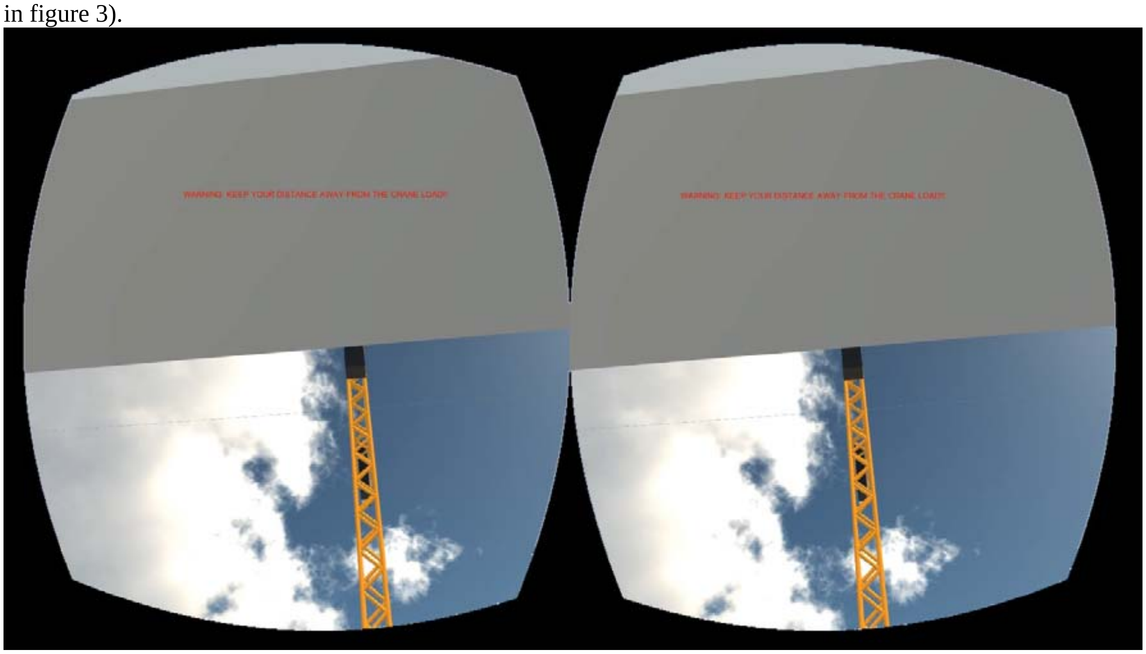


Figure 3. Warning Message shown on the VR Headset's Display

## 4. DISCUSSION

4.1 Cost Analysis of the proposed system

Table 2. Estimated Cost of the Education System

| Application Type | Component | Unit Price (HKD) | Qty Required |
|---|---|---|---|
| | Education Platform Server | 40,000 | 1 |
| Desktop Version | Workstation | 5,000 | N |
| | Oculus Rift | 2,700 | N |
| | Leap Motion | 775 | N |
| | Joystick | 100 | N |
| Mobile Version | Samsung Galaxy S6 | 6,000 | N |
| | Samsung Gear VR | 1,550 | N |
| | Joystick | 100 | N |
| Example | A classroom with 30 trainees (N=30) | | |
| | Desktop Version Education Platform: 0.30M HKD | | |
| | Mobile Version Education Platform: 0.27M HKD | | |

For a class with 30 trainees, the high performance server cost would be 40,000 HKD. If the platform adopts a desktop version, each set of devices of one trainee include a leap motion (775HKD), a joystick (100HKD), an oculus rift (2700HKD), and a workstation (5000HKD) with a sub-total of 8575HKD. So the investment for the whole class is 300,000HKD. If the platform adopts the mobile version, each set of devices is 7650HKD and the whole platform would cost 270,000HKD.

The return period would be 200 sessions of classes (assuming the admission fee for each training session is 100HKD and the administration fee <venue rental, instructor's salary and others> is 50% of the revenue).

4.2 Hardware for the Education Platform

The demonstrated prototype was deployed on Oculus Rift headset. However, oculus rift has quite strict system requirement on computer. According to Oculus official website, the minimum requirement would be NVIDIA GTX 970 / AMD R9 290 equivalent or greater GPU, Intel i5-4590 equivalent or greater CPU, 8GB+ RAM, Compatible HDMI 1.3 video output and 3x USB 3.0 ports plus 1x USB 2.0 port. The strict requirements (especially GPU requirement) makes the utilization of existing office computer impossible for many training center. Some VR headset alternatives might be appreciated for small to medium construction training centers.

4.3 User Interaction

Trainer's movement and behavior are captured using keyboard/joystick in our developed system. Motion capture might provide more rich information on trainee's input. For example, 26 nodes Xsens motion capture system deployed on the trainee can not only provide input of location and movement, but also provide the skeleton information on worker's behavior. The additional input can enrich the training scenario and create a more realistic training platform.

4.4 Limitations

Although there exist many benefits of head mounted display (HMD), there are some barriers for the wider adoption of VR in construction safety training: 1) Display technology. It was reported that discomfort and motion sickness can be experienced by the user when there is a gap between the user's perception of self-motion and the visual view. Higher resolution and higher refresh rate of the system might help to minimize this problem. 2) Connectivity and computing power. The wired HMD limits the user's working area since there needs a cable to transmit the large amount of data from computer to the HMD. Wireless connection free the user from restricting to a certain area, but the limited graphic processing power and data transmission capacity degrade the user's experience. Therefore, a wireless solution with new data compression techniques and powerful mobile HMD is needed.

## 5. CONCLUSIONS

The paper proposed a framework for integrating the safety knowledge and BIM to support multi-user interactive safety training. Three major sub-system was proposed in this paper. The current system includes the falling from height, PPE checking, working near the crane load, and collision with equipment. In this paper, working near the crane load is used as an example to demonstrate the implementation of the proposed platform. Some issues found during the implementation was discussed. The proposed education platform can help to advance the construction safety training to the next level because: it provides detailed, informative and timely feedback n on workforce's performance in simulated scenarios covering different topics. It can further enhance a trainee's understanding of their educational performance. The system embedded safety knowledge, the construction industry can benefit from providing and sharing better knowledge to all of the employees.

In the next stage of the project, the team will: 1) validate the performance by conducting experiments to ask the students and trainees to use the system for safety training and compare the performance with traditional safety training sessions; 2) decoupling the BIM model with the safety knowledge to enable the easy customization for different projects; 3) multi inputs from various devices other than keyboard.

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