IEICE TRANS. INF. & SYST., VOL.E98–D, NO.12 DECEMBER 2015

PAPER

# A Novel Earthquake Education System Based on Virtual Reality

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**SUMMARY** An earthquake is a destructive natural disaster, which cannot be predicted accurately and causes devastating damage and losses. In fact, many of the damages can be prevented if people know what to do during and after earthquakes. Earthquake education is the most important method to raise public awareness and mitigate the damage caused by earthquakes. Generally, earthquake education consists of conducting traditional earthquake drills in schools or communities and experiencing an earthquake through the use of an earthquake simulator. However, these approaches are unrealistic or expensive to apply, especially in underdeveloped areas where earthquakes occur frequently. In this paper, an earthquake drill simulation system based on virtual reality (VR) technology is proposed. A User is immersed in a 3D virtual earthquake environment through a head mounted display and is able to control the avatar in a virtual scene via Kinect to respond to the simulated earthquake environment generated by SIGVerse, a simulation platform. It is a cost effective solution and is easy to deploy. The design and implementation of this VR system is proposed and a dormitory earthquake simulation is conducted. Results show that powerful earthquakes can be simulated successfully and the VR technology can be applied in the earthquake drills.
***key words:*** *earthquake drill, earthquake simulation platform, virtual reality, SIGVerse, Kinect, head mounted display*

## 1. Introduction

An earthquake is a destructive natural disaster that strikes suddenly and violently.Earthquakes occur about five million times all over the world each year. The damages caused by earthquakes are devastating. China is considered one of countries in the world most vulnerable to earthquakes. Statistics show that approximately 35% of the major earthquakes above magnitude 7 have occurred in China. Furthermore, half of the earthquake casualties in the world during the 20th century were in China, with over 59 million deaths. The most devastating earthquake in the past years was the Great Sichuan Earthquake (popularly known as the Wenchuan Earthquake), which had a magnitude of 8.0 and affected a population of 46.25 million in the province of Sichuan, Gansu and Shaanxi. According to the official statistics, 69,227 were killed and 17,923 went missing because of the disaster [1]. The earthquake destroyed almost 6.5 million homes, forced about 15 million people to evacuate and resulted in direct economic losses worth more than 845.1 billion RMB [2].

The tremendous damage and losses highlight the importance of the protection against earthquakes and mitigation of such disasters in China. However, the current earthquakes prediction system is not accurate enough to save lives. People have limited opportunity evacuated to safe places before an earthquake strikes. Thus, the only way to reduce damages and losses is through education and effective drills. The importance of disaster education, especially in relation to earthquakes, have been recognized in many studies since the last century [3]–[5]. With useful knowledge on seismic safety and effective practical training, people can be prepared to react appropriately during and after earthquakes. During the 2008 Great Sichuan Earthquake in China, none of the students at Sangzao Middle School were wounded or died because of the successful earthquake trainings conducted in the school every semester. This case stands out as an amazing example when many other schools suffered high casualties [6]. Therefore, an earthquake drill is the most important method to teach the public how to react and protect themselves if a strong earthquake were to occur.

Currently, most earthquake drills are not realistic enough. Generally, a drill starts after a specific alarm given by the organizers, and the students are organized to evacuate the classrooms as if a real earthquake were happening. However, no objects fall down, which is not as realistic as when an actual earthquake is happening. Thus, students are not provided with real earthquake experience. Furthermore, a stampede may break out easily and cause injuries during a drill because of the large number of participants. Therefore, a traditional earthquake drill is not a cost-effective and efficient approach to earthquake education.

Earthquake simulation is a promising alternative to traditional drills. Generally, an earthquake simulator is a shake house or a dynamic seat. A shake house (also known as an earthquake room) is built like a regular room with a solid structure and interior furnishings. This room is constructed based on a shake table, which simulates earthquake movement according to the magnitude and creates the ground movement phenomenon of the earthquake. In addition, other function modules, such as the sound system, can also be designed in this room to provide a vivid scene. Mean-

Manuscript received April 30, 2015.
Manuscript revised August 3, 2015.
Manuscript publicized September 16, 2015.
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DOI: 10.1587/transinf.2015EDP7165

while, a dynamics seat is developed, similar to the earthquake room, but the user sits in a chair to experience the vibration, and the earthquake scene is displayed on a screen. Although these two types of earthquake simulators enable users to experience real earthquakes, they are very expensive and not all the communities or schools can afford one. Thus, these simulators can be found only in earthquake museums or universities and can be accessed by a limited number of people, which do not include residents of underdeveloped areas.

In this paper, we propose an earthquake drill system based on virtual reality (VR) technology that can provide users with a 3D immersed virtual earthquake simulation environment with cloud computing technology and commercial off-the-shelf (COTS) portable devices. This system creates a 3D virtual environment and simulates the earthquake scenario on SIGVerse, which is a simulation platform developed by the National Institute of Informatics in Japan [7]. Users interact with the simulation platform via a body-sensing device. This way, the users can experience the earthquake simulation in real time and directly through body motions. Moreover, a head-mounted display (HMD) is employed to provide the visual feedback to users, and induce intuitive feelings toward the earthquake. This is a portable and cost-effective solution that can be adopted in the underdeveloped areas for earthquake evacuation drills.

The rest of the paper is organized as follows. We review the related studies on earthquakes and VR in Sect. 2. In Sect. 3, we present the system design. The implementation details are provided in Sect. 4. In Sect. 5, we present an experiment performed to prove the feasibility of the system, and we conclude the study in Sect. 6.

## 2. Related Works

### 2.1 Earthquake Simulation

Significant research effort has been directed toward developing earthquake simulation platforms in the field of earthquake engineering. The first earthquake simulations were designed by statically applying some horizontal inertial forces based on scaled peak ground accelerations to a mathematical model of a building [8]. With the development of computational technologies, dynamic simulations has been implemented based on a shake table, which is an experimental device that replicates the true nature earthquake input. The first shake table was devised in 1988 by John Milne and Fusakichi Omori from Japan. A hand-powered device which produce the simple oscillatory motion through a wheel-like mechanism [9]. At the beginning of the 20th century, a sophisticated shake table was built by F. J. Rogers at Stanford University to produce continuous and oscillatory disturbances through an electric motor [10]. As the interest and funding on shake tables improved, the Jacobsen-type shake table was developed. It could be stimulated in three ways: by combining of a pendulum and springs, by employing an eccentric-mass device that produces either horizontal or vertical motion, or by employing four synchronized electromagnetic vibrators that produces harmonic motion [11]. However, these systems provide inadequate representations of real earthquake motions. With the rapid development of control engineering, a modern shake table, which typically consists of a rectangle platform driven up to six degrees of freedom by servo-hydraulic actuators, has been built. Based on this control method, many large shake tables have been constructed, such as the CGS in Algeria [12] and the E-Defense in Japan [13]. Many shake tables are also employed as part of earthquake simulators, combined with solid construction as the earthquake simulation to demonstrate how we can protect ourselves during disasters. However, high cost and poor replicability make these simulators impossible to move and utilize around the country.

### 2.2 Virtual Reality

VR technology is an important branch of computer science and has been widely studied since the early 20th century [14]. This technology focuses on a computer-generated environment that can simulate the physical presence in real world, and immerses users in virtual environment by using many special devices to recreate the sensory experience, including virtual taste, sight, smell, sound and touch. Compared with traditional human-computer interaction, virtual reality has three characteristics: immersion, interaction and imagination [15]. Based on these features, VR has been applied to various fields successfully, such as military, medical [16], and education [17]. Considering that virtual reality can provide a vivid sense of a disaster without any real damage, it has been widely employed in safety-related training and education, such as mining, fire [18], and other emergencies [3]. Research and patents also have been proposed for earthquake simulation, such as that presented in [19]. However, in most of the simulation systems, people can only watch the disaster happening around them, while some of them provide simple interaction through the mouse and keyboard, which is not realistic enough. In our study, a novel earthquake drill system is designed for the user to interact with the environment directly. With a immersed HMD and body-motion sensor, a realistic experience is provided and the training efficiency can be improved significantly.

## 3. System Design

The system architecture is shown in Fig. 1. The earthquake simulation system is designed in a client-server architecture which enables the participation of multiple users from various clients via the network in the virtual training without moving the computing center. The system consists of the simulation engine, physical environment modeling, earthquake power simulator, and human computer interaction (HCI) modules. The earthquake simulation environment is established on the server side to avoid heavy computation tasks on the client and make the system portable. The simulation engine is deployed on the server side. The entire 3D

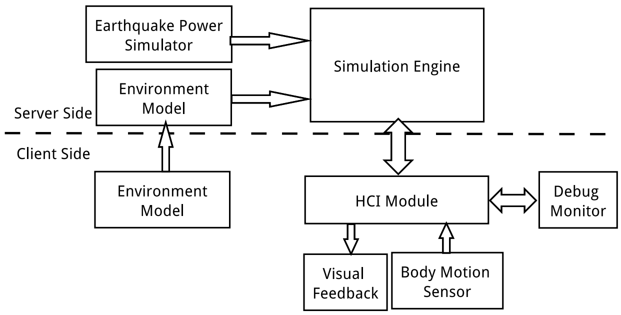


**Fig. 1** System architecture of the simulation system

modeling of the training surroundings is constructed by the environment modeling module to generate a virtual environment. A physics engine is also integrated into the simulation system. With the physics engine, the physical and dynamics properties of objects can be considered in the calculation to simulate the realistic movement of the different objects during an earthquake. In addition, physical interactions among objects, such as dynamic motion and object collision, can also be simulated in real time. The earthquake power simulator module is designed to generate the force applied to the object in the environment to simulate a certain earthquake magnitude.

The HCI module includes the body-motion sensor and immersive visualization modules. As a virtual drill system, the module should provide a vivid experience, which is one of the most important features. In most of the simulation systems, the situation is shown on the computer monitor, while the mouse and keyboard are employed for interaction. However, this kind of experience does not provide enough impact for the earthquake scenario simulation. In our drill system, the 3D visualization output of the entire simulation is implemented by the visual feedback module. An HMD is employed to show a visual feedback to the users in the first-person perspective scene, which provides users an immersive visualization and feeling. At the same time, the body-motion sensor module allows users to interact with the virtual environment directly. Instead of the mouse and keyboard, which will provide an unrealistic experience, this module employs motion sensor to collect data on human gestures, and then user motion is recognized by analysing the collected data, and the control information is extracted. A virtual avatar modeling on the server side follows the motion and gestures of the user in the real world and collects the feedback information.

## 4. System Implementation

Many COTS modules are employed to implement the whole system, such as SIGVerse for physical model simulation, Kinect for motion capture, and HMD for immersive display.

### 4.1 Simulation Engine

On the server side, SIGVerse acts as a simulator engine to model the 3D virtual environment and simulate the earthquake scenario. SIGVerse is a simulation platform that is based on client-server architecture with four main components, SIGServer, agent controller, SIGViewer and service provider. The SIGServer is the central server that handles the entire earthquake simulation. The dynamic calculation of the interaction among objects and physical characters is implemented by the opening dynamics engine (ODE) integrated in SIGVerse.

Generating 3D virtual scenes is the basis of the VR simulation system. A well-crafted 3D model can induce intuitive feelings from users. In this system, the format of the 3D virtual models of the training field are compatible with Autodesk Maya, and all these 3D model files are exported to VRML/X3D formats which can be parsed with the Xj3D that integrated in SIGVerse.

Service provider is an abstract layer for the data communication between the input/output hardware and the simulation system. The service provider extracts sensing information from specific devices and converts it according to the standard interface with the agent controller. With this, the agent controller can request the device as a service without knowing the sensing details. In this case, the motion-capture sensors and visual display devices can be easily supported in SIGVerse.

Agent controller implements the control algorithm that converts the external influence to object actions in the SIGVerse world. In SIGVerse, bodies such as humanoid avatar and moving objects that use perception and perform actions, are called “agents”. Each agent in the virtual environment can be controlled by a specified program or by an external input. In this system, the agent of the humanoid avatar is implemented as a controller connecting with the body-motion sensors, and the other agents of the physical objects are controlled by the earthquake power simulator.

### 4.2 Interaction between User and Simulation System

A humanoid avatar has been modeled by SIGVerse, and is presented as a chain of linked structures connected by joints. The avatar moves in the virtual world to simulate the motion of trainee. Kinect is employed as the motion input device to control the movement of the avatar in the virtual environment. With the RGB camera and depth sensor embedded in Kinect, skeletal tracking is available, and all joint data can be collected and transferred to the server in real time. The joint data can be easily mapped to the joint movements of the avatar. The movement model can be quickly generated with an initial calibration. The movement of the body, limbs and joints can be tracked as the inputs to the system. This process is a more natural user interaction mode for trainee, especially for elders, children, and people from underdeveloped areas who are not quite familiar with computers.

The service provider module provides a plug-in called SIGNIUerseTracker to support Kinect. This plug-in receives the data from Kinect, extracts specific skeleton data, and sends the data to the avatar controller on the server. All the skeleton data are sent as a string. In the avatar controller, the string is split into tokens, which are sequences of a certain joint data. The joints of the user can be directly mapped to the corresponding joints of avatar because the modeling structure of the avatar is the same as the skeleton tracking framework tracked by Kinect. This way, the avatar can replicate the motions and act the same as the user in the real world.

A motion gesture reorganization algorithm is implemented for the movement detection because of the limitation of the Kinect detection distance. Mapping the user's movement to the motion of the avatar directly is natural. However, in the drill system, a complex environment is simulated to be as large as a room or even a house, while the distance between Kinect and users is much shorter than the distance in which the avatar can move in the virtual environment. In our preliminary experiment, the users can easily move out of the detection area, which made us realize that the direct coordinate conversion from Kinect to SIGVerse is impractical. Therefore, a gesture recognition strategy is proposed and we try to make the gesture natural for the user in drill system.

Two semantic representations of actions are selected to control the movement of the avatar. For the movement in the system, marching in place is recognized as the command for the avatar to step forward, and speed is calculated from the frequency of right leg-lifting and the length of legs. This information can be extracted from the Kinect model. For the moving direction control, the motion of body turnaround is recognize as the direction change. However, as a Kinect design limitation, the accuracy of gesture recognition drops when the user stands side-to-face in front of the camera, and the model cannot determine whether the user is facing or against the camera. The accumulative errors highly affect the precision of control after several direction changes. Another gesture, the sweep of arm, is also recognized as a change in avatar direction to simplify the control. For example, when the user waves the right arm from left to right, the avatar turns 45 degrees clockwise. Based on these two actions, the user can easily control the direction of movement in the virtual environment.

The SIGViewer module in the system provides a GUI for users to execute the simulation and visualize the output of the virtual scene. An HMD is employed to provide users with a more intuitive feeling of the earthquake. HMD can track head orientation and movement through an accelerometer and a gyroscope, so that when a user's head rotates, the image of the virtual environment in the HMD rotates simultaneously. Through this mechanism, users can be immersed in the 3D virtual earthquake scenario and respond to the 3D view.

### 4.3 Earthquake Scenario Simulation Implementation

An earthquake is the result of a sudden release of energy in the Earth's crust that creates seismic waves. Generally, the types of seismic waves are divided into body waves and surface waves. Body waves, which travel through the interior of the Earth, include primary and secondary waves. Primary waves (P-waves) are compressional waves that are longitudinal in nature and arrive at seismograph stations first. Secondary waves (S-waves) are shear waves that are transverse in nature and arrive after P-waves. Compared with P-waves, S-waves cause more damage during an earthquake. However, surface waves, which travel in three dimensions, cause the most damage because the particle motion of surface waves is larger than that of the body waves.

The forces in different directions are applied on all the virtual objects in the simulation environment according to the waves.The P-waves are represented by the forces acting vertically and the S-waves are represented by the force acting horizontally. The magnitude of an earthquake depends on the intensity of the force.

In the world simulated by SIGVerse, the realistic physics movement and collision can be implemented by the ODE on the server, while the force can be added to the object dynamically online via the APIs provided by the agent controller module. As an important property of the object instance in the world, a dynamic library should be implemented based on the interface. During the simulation, a callback function is triggered periodically, providing a runtime interface to add force to the object instance. A list of forces to be applied to the object instances in the world is generated based on the power of the earthquake. Before the simulation starts, the detailed information on the forces are configured into the system, including the power, direction, start time, and end time.

The configuration of force is generated based on the seismic intensity of the earthquake. To the authors' knowledge, no precise quantitative model exists to describe the relation among the magnitude, distance to the epicenter and the force power applied to the objects during the earthquake. The scale of seismic intensity is employed to describe the power applied to the objects and the scenario of the disaster. However, no description of the timing sequence of the power exists. Therefore, the information on the force is generated based on the basis of earthquake intensity, scenario description report, and estimated power decay with time. In the experiment, the force in the simulation is determined based on the closely reproduced specific earthquake scenario.

## 5. Experiment and Evaluation

In this section, an experiment is conducted to prove the feasibility of the system. The SIGVerse-2.2.0 is deployed on a Dell Precision T3610 workstation, with Intel Xeon E5-1620, Quad Core HT, 3.7GHz, 4GB DRAM, NVIDIA Quadro K600, running ubuntu 12.04. The server is connected to a 100Mbps router with Ethernet cable. The SIGViewer is deployed on a laptop computer with Intel Core i5, 4G RAM, running Windows 7. The Kinect 1.0 for Windows from Microsoft and the VUZIX Wrap 1200 HMD is connect to the laptop with USB cable, and the screen of the laptop works as the debug monitor. As shown in Fig. 5, the perspective

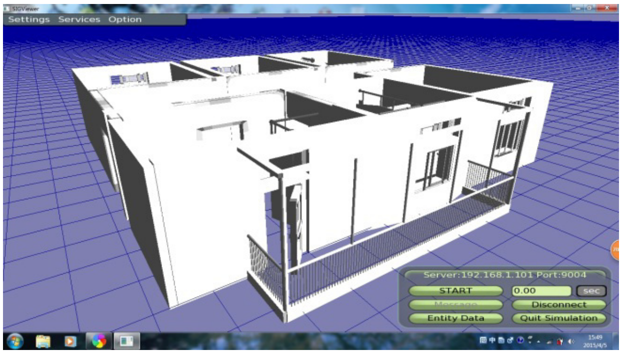


**Fig. 2** Model generated based on the dormitories

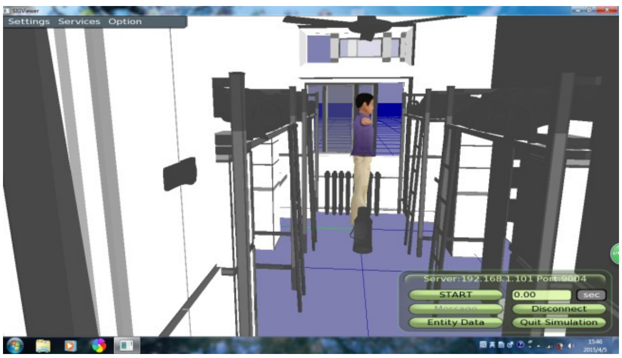


**Fig. 3** 3D view inside of the simulated dormitory

can be switched easily on debug monitor among first-person, third-person, and video signal from Kinect and two of them can be shown simultaneously on the monitor. In the practical application, the SIGVerse can run on the cloud server and only the Kinect, HMD, laptop computer, and network connection are required for the drill. These are all portable components and no complex instrument are required.

As shown in Fig. 2 in the earthquake simulation, the scene of the undergraduate students' dormitories in Nankai University is modelled in the virtual training environment. This virtual dormitory consists of four bedrooms, one parlor and one bathroom. In order to make user immersed in a real dormitory environment, 250 objects are integrated, including 18 kinds of objects from necessary things like beds and chairs to detailed small things like clasps and books. Figure 2 shows the entire 3D virtual environment of the dormitory and Fig. 3 shows the view of each room with an avatar. All the models are created in Autodesk Maya and then imported into SIGVerse.

The simulation world framework in SIGVerse is developed in XML format, which contains the definition of the virtual world and the agents connecting to the corresponding agent controllers. In this case, creating the agent file and the world file in XML format is essential. The agent file is written for each 3D model, including the moving object and humanoid avatar. It describes the basic configuration of an agent such as the physics shape of moving objects and joint nodes of the humanoid avatar. The world file is written for the virtual environment that consists of all agents.

**Fig. 4** User interaction with the system using an HMD


**Fig. 5** User perspective switch on debug monitor

It describes the configuration of the whole virtual environment and sets the dynamic properties for each agent, such as the initial position, size, and mass. Moreover, the world file attaches the agent controller to the corresponding agent in the virtual environment and specifies the programming language of each agent controller.

The user should stand 2m in front of Kinect to obtain the accurate motion-capture data. The dynamic properties of the parts of the objects in the No.1 dormitory are listed in Table 1. The forces are set to imitate the earthquake stroke in Chenyang Hope primary school in 2013, while the scenario is as described in the news report [20]. The earthquake was M7 with intensity level 9. Many experiment is conducted to determine the value of forces added to the objects to duplicate a similar scenario. The first several shake actions of the earthquake are simulated: beds begin to shake violently and most of the small objects without fixed points are thrown around. The configuration of the force applied to the object is hard-coded in the agent configuration files. In this environment, a powerful earthquake can be simulated.

The client connects to the software with the service name, host name, and port number, and then executes the simulation in the SIGVerse via the SIGViewer client. When the simulation starts, all the objects in the system begin to shake. Figure 6 shows the simulation of a virtual fan during an earthquake. When the simulation starts, the fan shakes back and forth every one second because of the change in the force direction. After one minute, the joint between the

**Table 1** Objects in No. 1 dormitory and detail properties

| object | Position(x,y,z) | Gravity (x,y,z) | collision | dynamics | mass | Force(x,y,z) 1st second | Force(x,y,z) 2nd second |
|---|---|---|---|---|---|---|---|
| fan | (10,20,0) | (0.0,-196.1,0.0) | true | true | 20 | (19500,0,-19500) | (-19500,0,19500) |
| Bed 1 | (20,7,8) | (0.0,-2942.1,0.0) | true | true | 300 | (19500,0,-19500) | (-19500,0,19500) |
| Bed 2 | (0,7,-8) | (0.0,-2942.1,0.0) | true | true | 300 | (19500,0,-19500) | (-19500,0,19500) |
| Bed 3 | (0,7,8) | (0.0,-2942.1,0.0) | true | true | 300 | (19500,0,-19500) | (-19500,0,19500) |
| Bed 4 | (20,7,-8) | (0.0,-2942.1,0.0) | true | true | 300 | (19500,0,-19500) | (-19500,0,19500) |
| Light | (25,22,0) | (0.0,-19.6,0.0) | true | true | 2 | (19500,0,-19500) | (-19500,0,19500) |
| Thermos bottle | (6,2,0) | (0.0,-49.0,0.0) | true | true | 5 | (19500,0,-19500) | (-19500,0,19500) |

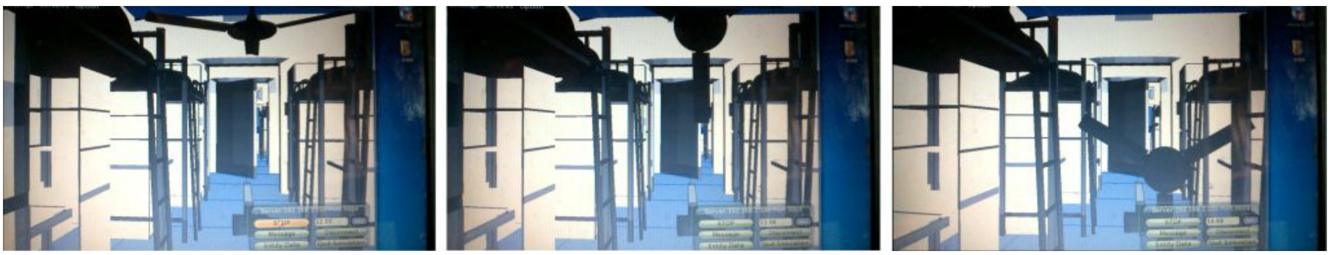

**Fig. 6** A fan dropped during the simulation experiment

**Table 2** Evaluation of the simulation system

| UI mode | ease of use | fidelity | precision | immersion |
|---|---|---|---|---|
| Mouse and keyboard | 4.06 | 3.88 | 4.25 | 3.69 |
| Kinect and HMD | 4.50 | 4.06 | 3.69 | 4.36 |

fan and the ceiling collapses and the fan falls down because of gravity. The entire visualization simulation is shown to the user through the HMD in real time, and the user can respond to the simulation by controlling the avatar. Figure 4 shows a user wearing HMD and interacting with the simulation system.

Sixteen volunteers are recruited to evaluate the effectiveness of the new interactive mode proposed, and to provide a mean opinion score after the experiment, where 5 means excellent and 1 means bad. The 16 volunteers includes 4 undergraduate students, 10 graduate students and 2 faculty from Nankai University. To make a comparison, another control agent is also implemented to control the avatar via the mouse and keyboard on the laptop. Every volunteer is requested to experience the simulation twice and score the ease of use, fidelity of the model, precision of control, and immersion after the experiment. The average of the scores is shown in Table 2. The result shows that the proposed system can provide an immersive and easy-to-use environment for the earthquake evacuation drill. The performance of the precision is not good enough because the direction and speed control via the motion sensor cannot be as accurate as that of the mouse and keyboard. The performance can be improved by providing the system with more initial data for recognition and more time for the user to become familiar with the new interaction mode.

## 6. Conclusion and Future Work

In this paper, we propose the design of a VR system for earthquake drills. The system architecture and implementation are as described in the proceeding section. This system is developed on SIGVerse to model the 3D virtual world and simulate an earthquake scenario. The natural user interface of Kinect and HMD are employed to ensure that users can easily master this system. The evaluation result shows that this system is an effective earthquake drill approach with portable devices. Currently, earthquake noise has not been implemented yet. In the future, a stereo generator can be integrated into the system to produce sound effects. Also a configuration generation mechanism based on the scale of the seismic intensity and object in the virtual environment will be designed for automatic scenario generation.

This system offers a new pattern for the earthquake training field, and it can be easily adapted to fire drills, emergencies handling of hazardous chemical substances, and other training fields.

## Acknowledgments

This project is supported by the National University Undergraduate Student Innovation Fund. Xiaoli Gong's work is partially supported by a grant from the Research Fund for the Doctoral Program of Higher Education of China (Granted No. 20130031120028) and Research Plan in Application Foundation and Advanced Technologies in Tianjin (Granted No. 14JCQNJC00700).

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