Enhancing Learning and Teaching for Architectural Engineering Students uing Virtual Building Design and Construction

Cheng Zhang [1]& Bing Chen[2]

[1]Department of Civil Engineering, Xi'an Jiaotong-Liverpool University, Suzhou, China

[2]Department of Urban Planning and Design, Xi'an Jiaotong-Liverpool University, Suzhou, China

Correspondence: Cheng Zhang, Department of Civil Engineering, Xi'an Jiaotong-Liverpool University, 111 Ren'ai Road, Suzhou, China. Tel: 86-512-8816-1829. E-mail: cheng.zhang@xjtlu.edu.cn

Abstract

It is important for students in the built environment related disciplines to acquire subject-based knowledge and skills from reflecting on their experience. In return, the learning-by-doing approach has been widely adopted in the academic cluster of built environment. To further strengthen this, this paper proposes a Virtual Reality (VR) based learning and teaching tool. It creates a virtual 3D environment that helps architectural engineering students conceive their design ideas, plan the layout, design the structure, construct the products (buildings, communities, infrastructures, etc.), and directly interact with the products they designed. The objectives of this research are: (1) to build a VR design environment for students to experience corresponding impact from different scenarios, which will help the student understand and investigate different design theories and schemes; (2) to build a VR construction environment for students to investigate how the building is built and what safety issues should be noted when visiting a construction site; and (3) to provide a collaborative environment for students in the Built Environment domain for better communication through a complete building project featuring active and experiential learning. Unity is used to develop the package and VIVE, a VR package, is used to facilitate the immersive interaction between the virtual environment and the users. Students from the Built Environment cluster were invited to use the tool and give feedback using a questionnaire. Positive comments were given by the students showing that they were very interested in studying academic subjects through such a technical game. All of them wanted to play more rounds to improve their performance and to find answers to the questions they failed to answer correctly. Most of the students were willing to spend more time in finding answers after playing that game.

Keywords: learning and teaching, virtual reality, architectural engineering, building design and construction

1. Introduction

Active learning has been promoted to enhance the engaging of the students with materials, participating in the class, and collaborating with each other. The architectural engineering education aims to incorporate 'active learning' into all the teaching activities, which means students engaging with taught materials not passively listening. Among them, a CDIO concept is introduced based on a commonly shared premise that engineering graduates should be able to: Conceive – Design — Implement — Operate (CDIO), which is a complex value-added engineering system in a modern team-based engineering environment to create systems and products (CDIO, 2018). A good example in presented in (Millard and Jones, 2009), where the students design and construct cardboard bridges by 'hand-on' activities. Students learn the structural design through material strength testing, using structural analysis software packages, and testing their final products with designed load. Students enjoyed and learned more. However, the scale covered is limited to small truss bridges only. Large scale design activities should be provided to the students and a diverse of design projects should be incorporated into this practice.

In addition, in an integrated career environment, building engineers work collaboratively with other professionals such as urban planners and architects. It is essential for architectural engineering students to learn how to efficiently cooperate with students from other majors, especially within the built environment cluster. Meanwhile, urban planning students and architectural students are taught in a studio-based environment to understand the basic concepts of building design, 3D perception, model scale, etc. It is difficult for them to

challenge (or even fully understand) some design principles (e.g. how to create a pedestrian friendly working environment? And more importantly, why should it be designed like that? etc.) in such learning environment. A range of tools have been applied in order to solve this problem. For example, Computer-Aided Design tools (e.g. CAD/SketchUp models), physical models, case studies of best practice, etc. However, their effectiveness is still questionable, especially to beginners such as junior urban planning or architecture students.

Furthermore, to help the students understand better the construction of buildings, field trips to construction sites are usually arranged for students. By visiting a construction site, students have a realistic impression of how the building is transferred from design to reality by applying different construction methods. Their knowledge learned from the textbook is enhanced. However, finding suitable and convenient construction sites is not easy, which depends on the availability of appropriate sites and the teaching schedule. Proper time of visiting construction site is a constraint in terms of availability of the site being visited, and the readiness of proper knowledge engaged to the students. Moreover, not all the conditions are available at the time of visiting, for example, the site condition, construction stages, construction activities, safety concerns, etc. put constraints on explaining relevant knowledge to students.

Meanwhile, the Architecture, Engineering and Construction (AEC) industries are actively adopting information technology, such as, Building Information Modelling (BIM), Virtual Reality (VR) and Augmented Reality (AR) into practice, which results in improved communication, greater collaboration and productivity, better coordination of design drawings, faster delivery, reduced costs, and safer construction sites (Ahn, Cho, and Lee, 2013). University educators have also shown great interest in the use of VR and 3D in instructional design and assessment, as it is well recognized that computer technology can equip students to independently organize their learning processes. Educational studies have shown that VR, and computer games contribute to enhancing students' motivation and knowledge acquisition (Keenaghan and Horvath, 2014). Effectiveness in the learning and teaching of AEC has been driven by research showing that today's students represent the first generation to grow up with digital technology (Prensky, 2001). In addition, previous research also showed that the application of VR techniques could facilitate the communication across different stakeholders involved in a design project and thereby efficiently support participatory design or decision-making (Chen et al., 2012). However, it remains a challenge to integrate VR and 3D visualization into learning and teaching processes.

Based on above mentioned experience in the built environment cluster, a Virtual Reality (VR) based learning and teaching method is proposed in the present paper so as to improve the active learning capability by allowing students interact with their designed 'virtual built environment' directly and immersively. Architectural engineering students can learn from and work together with urban planning and architecture students to produce more realistic and better design. The VR-based environment can be used to help students understand the impact from different design scenarios. By using this learning and teaching tool, we expected that students learn more through these active and hands-on activities; emphasize more in problem formulation and solution.

2. Objectives

The ultimate goal of the present research is to extend the learning-by-doing approach into a virtual 3D environment. VR-based design and construction environment is developed to be used as a learning and teaching tool. The objectives of this paper are: (1) to build a VR design environment for students to experience corresponding impact from different design scenarios, so that design theories and schemes can be understood and investigated thoroughly; (2) to build a VR construction environment for students to investigate how the building is built and what safety issued should be considered on site; and (3) to investigate the effectiveness of such a learning and teaching tool in architectural engineering education.

3. Methodology

As shown in Figure 1, the VR environment is designed to comprise three main components which are Training, Design, and Construction. The Training part consists of variable developed functionalities, which enable the students to get familiar with the VR environment. Navigation and interactions are developed to enable the students to explore and change the VR environment freely and get instant feedbacks, such as Environmental Impact and User Experiences. The Design part allows the students to conceive their design ideas, plan the layout, design the structure, and directly interact with the environment. The Construction part provides the students an opportunity to explore a construction site by answering predefined domain-related questions and carrying out tasks assigned to them. In this VR environment, the students can experience the impact resulted from different design ideas, the consequences of spatial arrangement, the constructability of different structures, the safety issue on a construction site, etc. In addition, students can give comments on others work by reviewing the design done by other students, so that a collaborative design environment is created and different opinions can be visually

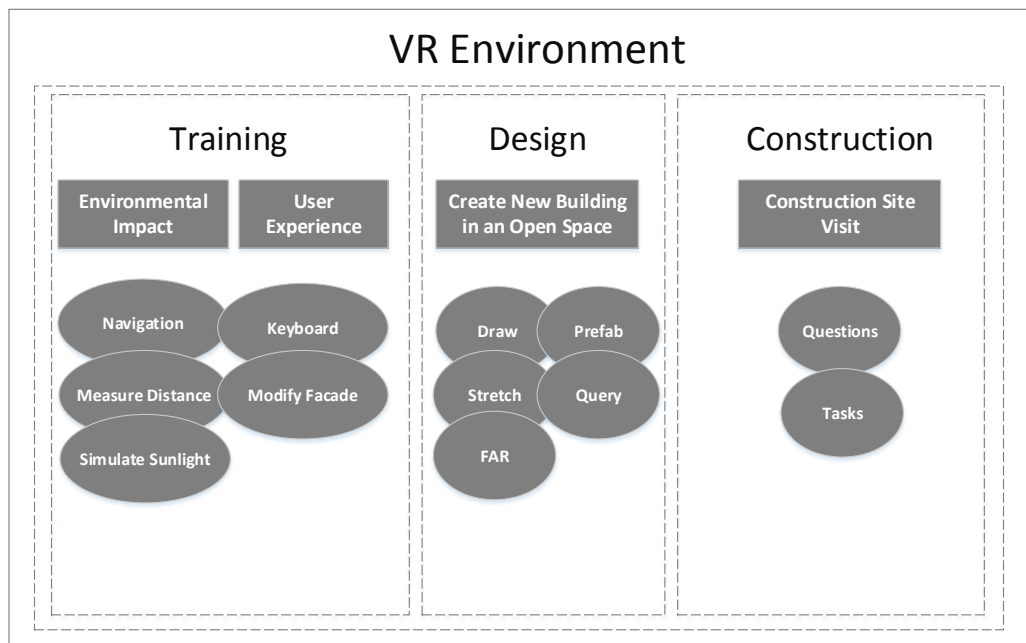reflected in the virtual environment for further discussion.

Figure 1. Framework of a VR building design and construction environment

3.1 Requirements Identification

First of all, requirements for the development were identified in terms of design and construction of a building project based on teaching experiences.

A range of issues need to be taken into account in design. To better understand design thinking and evaluate the strength and weakness of different design options, it is important to categorize these issues into a hierarchy system. Specifically, in a relatively large scale, urban designers need to consider city image (including Floor-Area Ratio and building height limit in a given district), urban morphology, road network for transportation, etc; in the medium scale, architects needs to consider, within the context of a relatively large scale, accessibility and moving routes, building typology, pedestrian friendly walking environment, etc; in the relatively small scale, indoor designers and structure engineers need to consider building structure, façade design, building materials, indoor comfort, etc.

The main requirements from construction point of view are: identify different structures, such as building elements, structural components, and construction methods. Apart from that, for exploring a construction site, safety is the essential factor that the students should bear in mind all the time; therefore, be aware of potential hazards that may occur on site is also important. Therefore, safety tasks are designed for students to carry out to figure out the potential dangerous and how to take corresponding measure.

It is important to note that these issues are inter-related in the design and construction process of a real-life project, which requires urban planners, architects, engineers to work closely in a collaborative manner. In other words, the education in the built environment domain should equip students with not only subject-based substantive knowledge and transformative skills, but also independence of thought and collaborative decision-making competency, action-oriented critical and systemic thinking, the ability to handle uncertainty and new problems arising in the design-build process (Chen 2015). The VR-aided tool is expected to support the revolution of education in the built environment domain. Therefore, room should be created for students to give in-time comments to other students' output from another point of view. Functionalities of communication should be developed in the platform to meet such requirements.

3.2 Modelling Existing Buildings

As part of the Design module, existing buildings are created to give the students spatial awareness in the virtual environment. Building models are created in a way that different components are created in corresponding layers with details by using SketchUp. These models are exported to Unity to form the virtual reality environment.

There are two file formats that commonly supported by Unity and SketchUp, which are '.obj' and '.fbx'. The former one stores Mesh and Textures into two separate documents, thus might cause material missing problem. Therefore, it is suggested to use the '.fbx' format, under which the model and its relevant materials are combined into one file. Besides, a 3D model covering a large area is created by using pictures taken by using a drone and reconstructed by using image processing. However, due to limited resolution, this model is only used for a top view and not for detailed design work. Figures 2(a) and 2(b) are examples of buildings in a university campus.
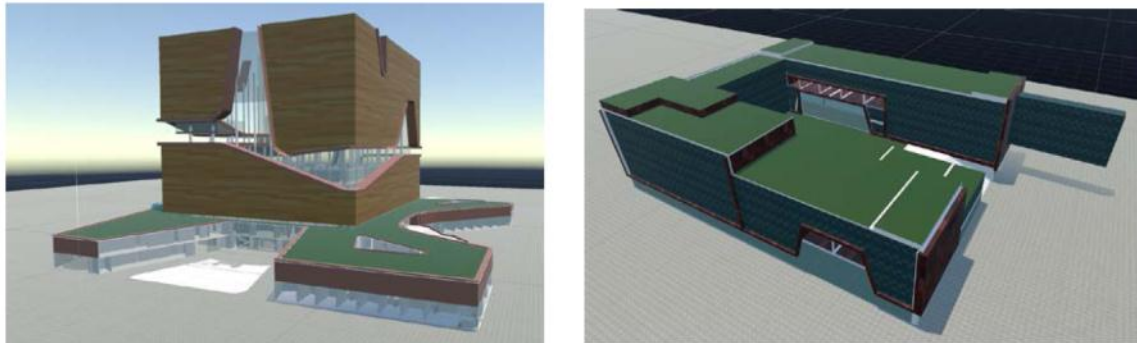
(a) Central Building   (b) Engineering Building

Figure 2. Sample Buildings in a University Campus

3.3 Developing functionalities for interaction with the model

A set of functionalities have been designed to facilitate the training and design purposes.

3.3.1 Navigation via Teleport

Teleport is chosen as the main navigation technique to prevent motion sickness and nausea that usually happen when transporting in virtual reality environment. By pressing the trackpad of the left controller, a curved raycast is shot out. The point where the ray hits the ground is considered as the desired destination. By releasing the trackpad, the user will be transported/moved to the position selected instantly, as shown in Figure 3.
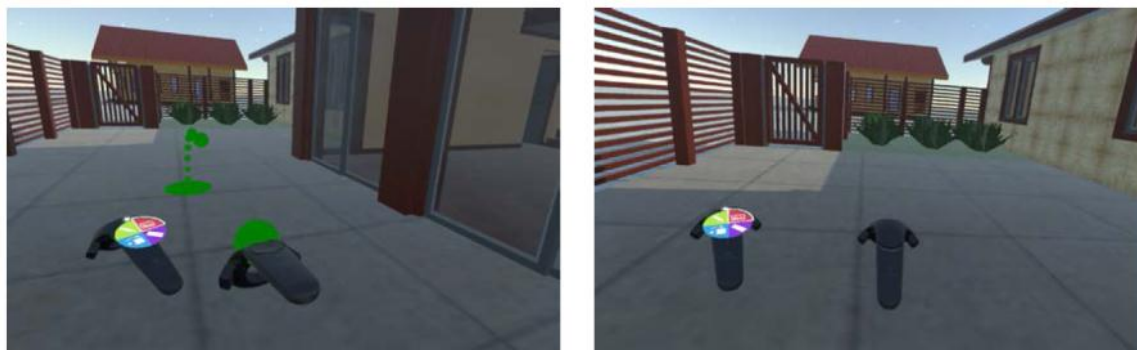
(a) Ready for Teleport   (b) After Teleport

Figure 3. Navigation using Teleport

3.3.2 Distance Measurement

By selecting this function, a straight ray will be casted from the controller. The distance between the point that the ray hits and the controller will be displayed, as shown in Figure 4. In reality, the human eye is not very good at estimating absolute values of distance and size; therefore, a distance measurement function is designed in the VR environment to give direct instructions to the students to design a building with reasonable dimensions.
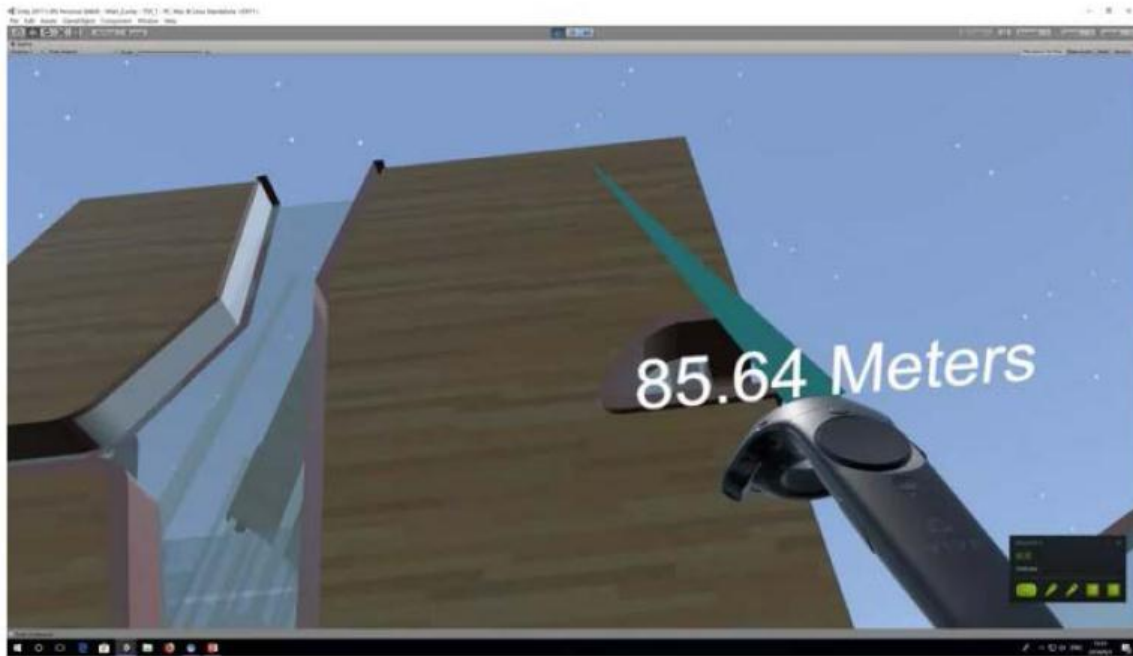
Figure 4. Measuring Distance

3.3.3 Virtual Keyboard

To enable giving in-time comments to other users, a virtual keyboard is developed by using the Raycast selection technique. A desired location can be selected to post the comment, for example, as shown in Figure 5, a comment is posted on the wall by leaving a message saying that the wall could be taller.

Figure 5. Input Comments by using a Virtual Keyboard

3.3.4 Modify Texture of Building Surfaces

To make the design more flexible, a function is designed to change the texture of a selected building surface. Upon selection, the target surface can be modified to some pre-defined material to give the user an instant view of different appearance of the building (Figure 6). It should be noted that the model needs to have layers pre-defined for each component when importing to Unity.
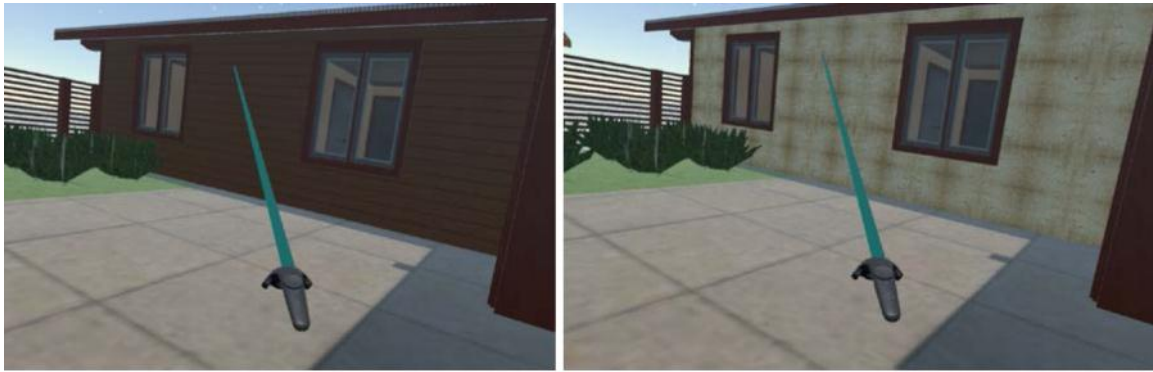
Figure 6. Modifying Texture of Building Surfaces

3.3.5 Sunlight simulation

This function is for experiencing the shadow caused by existing buildings by changing the position of the sun. By pressing the menu button on the controller, a simulated 'sun' will appear in the scene. By grabbing the sun and change the location freely, the shadow of the building can be shown instantly (Figure 7). Therefore, the effect from the newly designed building to the surrounding environment can be experienced implicitly.
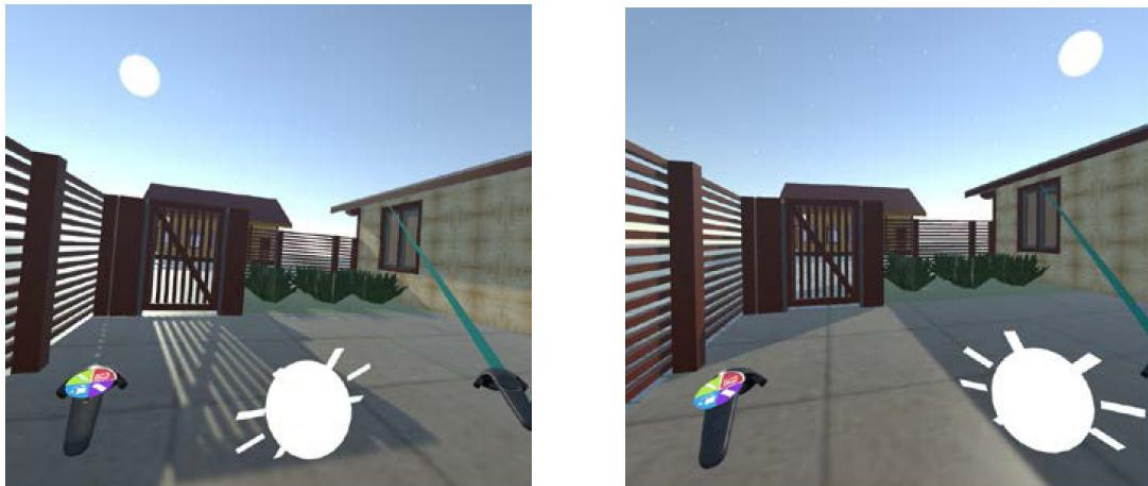

Figure 7. Shadow Effects

3.4 Design New Buildings

After the Training is properly done by the students, a design task is assigned by providing an open space surrounded by existing buildings. Corresponding functionalities are developed to enable the students to carry out the whole design process.

3.4.1 Creating New Objects

Since most of the buildings are in a shape of cubes, 'Draw' and 'Stretch' functions are developed to create building blocks. Rectangles will be drawn by selecting diagonal vertices on the ground and be stretched to a desired height to form a building block, as shown in Figure 8. This block is considered as a *Solid* shape in the VR environment and several further processing can be done.
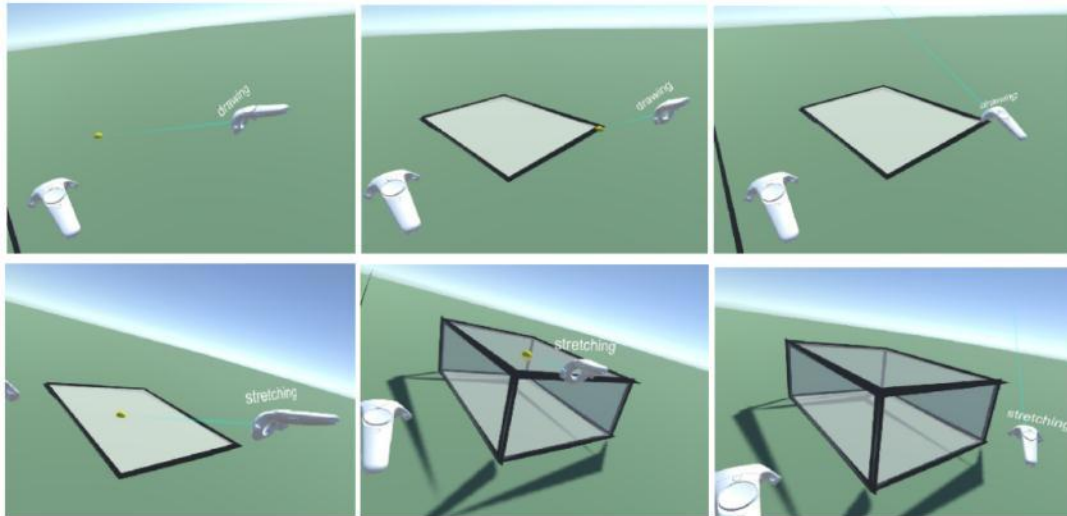
Figure 8. Steps of Creating a New Object

3.4.2 Editing Existing Objects

After the solid is created, all of its six surfaces can be stretched/compressed to make modifications. By selecting the target face and adjusting the distance of the selected face and its opposite one, the dimension of the box can be changed instantly. In addition, pre-defined models can be attached to existing blocks to meet the requirements of creating buildings with different floor areas by combing objects with different shapes. By switching to 'Prefab' mode, the pre-loaded model will appear on the surface where the ray hits. Thus, instead of rectangular boxes, combinations of different shapes can be created to give more flexibility to design buildings in irregular shapes.

3.4.3 Calculating the FAR

To help the students follow some design rules, the Floor-Area-Ratio (FAR) is calculated automatically when a new building is created, as shown in Figure 9. A default value of the floor height is set to automatically calculate the floor numbers when stretching the building block. Meanwhile, a 2D map is shown to indicate the location of the building.
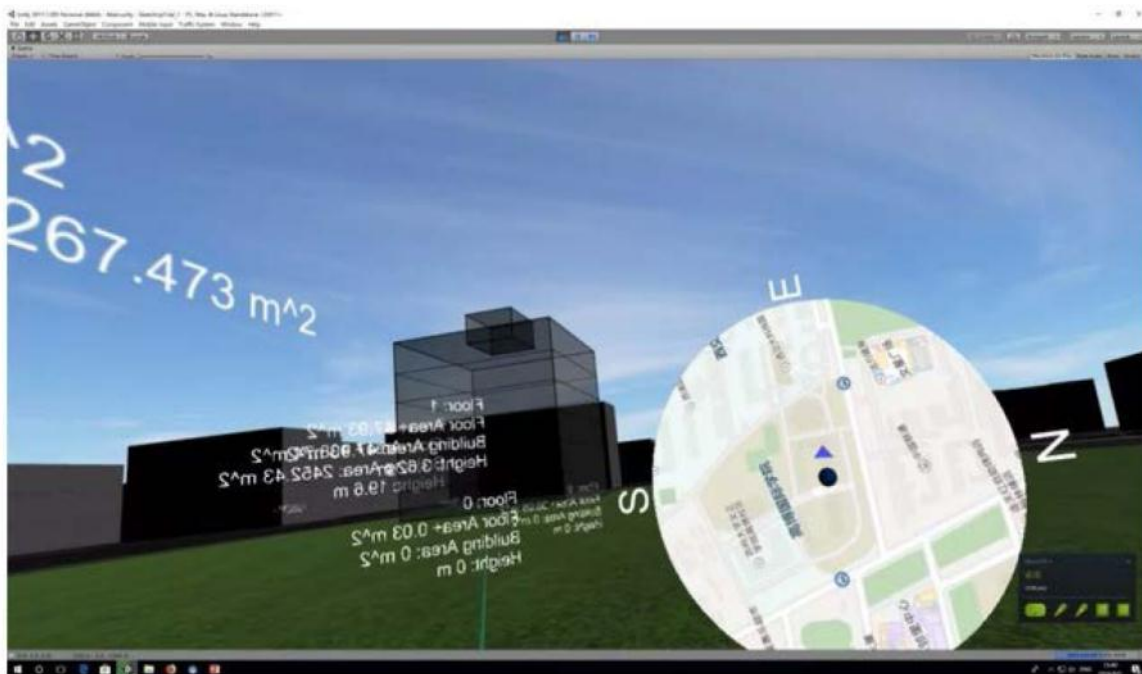

Figure 9. Creating new buildings in the open space

3.4.4 Querying functionalities to enable communications

User-based tag-searching and Building-based tag-searching are made available to communicate directly in the VR environment between different users. Since the current tool does not support multi-user mode, which means that only one user can use the tool at one time. The other users need to login using different ID and search for the design associated with others and leave comments to his/her design. Finally, comments from different users can be searched and summarized to the designer and make corresponding modifications. Database was created to store the information of the user and his/her design and enable query based on different conditions. Tables of dataset are shown in Figures 10(a) and 10(b).

名	类型	长度	小数点	允许空值 (
username	varchar	30	0	☐
gender	varchar	10	0	☑
age	varchar	5	0	☑
time	datetime	0	0	☑
isTeacher	double	3	0	☑

(a) User Table

名	类型	长度	小数点	允许空值
positionY	double	30	10	☑
positionX	double	30	10	☑
building	varchar	30	0	☑
user	varchar	50	0	☐
tag	varchar	100	0	☑
scale	double	10	5	☑
time	datetime	0	0	☑
positionZ	double	30	10	☑

(b) Operation Table

Figure 10. Database created for query

3.5 Game Development for Exploring Virtual Construction Site

Models that created in the Design step is used to create the construction site. In addition, objects common for a construction site are added to make the environment more realistic, as shown in Figure 11. A game engine is used to create the video game, which consists of a bunch of tools for advanced shading and shadows system, a skeletal animation system, a post processing system such as anti-aliasing and human computer interaction (HCI). Simulations of a real world can thus range from a vivid character, realistic lighting effects to an attractive scene.

The main components of the game engine architecture include a rendering engine, a physics engine and a core engine bounding two engines together and handling interactions between them. Rendering engine is responsible for visual effects with high reality degree and physics engine can further improve the simulation of the real world by applying physical formulas on the environment to provide realistic feedbacks for users' behavior. Details of developing the video game can be found in (Zhang et al., 2016; Zhang et al., 2017).
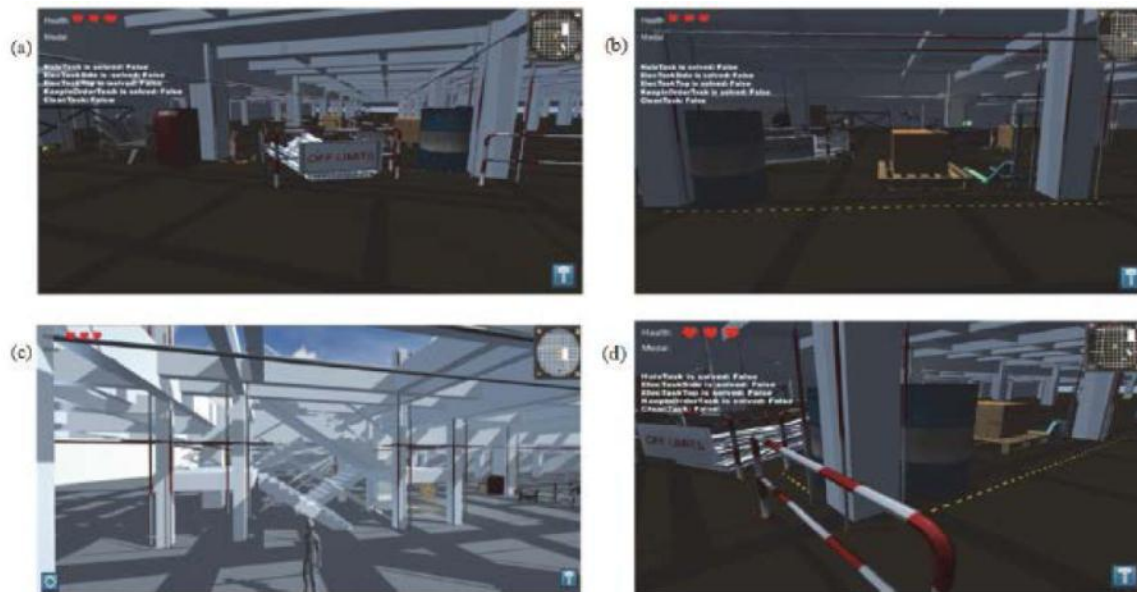
Figure 11. Designed Game for Construction Site Exploration

3.5.1 Domain-related Question Design

Domain-related questions are designed in terms of building structures, construction methods, construction safety management, and etc. to evaluate how well the students master the domain-related knowledge. For instance, in concrete construction, questions are designed according to the concrete material and relevant structures.

The question module provides chances to answer questions during the exploration. Signs are set up for spots where questions will pop up upon the user getting close to them. When a question is triggered, an answering panel interface will be displayed. Optional choices will be shown for the students to choose. Hints are available to help the students answer the questions.

3.5.2 Task Design

The function of the task module is similar to the question module, but is conducted in a more vivid way. Instead of choosing options from a list, the students are required to use tools or trigger some emergency to solve problem that they encountered. Two major types of tasks are designed as follows: Dominant task: If students can choose appropriate tools and put them in correct location, it means that the task has been accomplished successfully, otherwise, emergency may happen such as the avatar will fall down or getting an electric shot, and game is over. Recessive task: In some case, the user needs to trigger some action by themselves, for example, moving construction materials on site to designated locations.

For example, tasks are designed to emphasize the safety issues during construction. Uncovered openings or openings without fences are the biggest hazard on site; therefore, a task is designed to remind the students that there may be a risk when exploring the virtual construction site. As shown in Figure 12(a), an uncovered opening is designed somewhere in the scene, and the student is expected to install the fences provided in the ToolBox around the opening so as to solve the problem; otherwise, the avatar representing the student will lose one life once he/she falls into the uncovered opening. Figure 12(b) shows another type of hazard, which is electricity leakage, to remind the students of potential dangerous on site. The students are expected to find all potential safety risks and take appropriate measures so that the tasks can be accomplished.

(a) Uncovered Opening   (b) Electricity Leakage

Figure 12. Designed Hazards on the Virtual Construction Site

3.6 Testing

The prototype system is developed and students are invited to experience the VR Design and Construction Environment. Figure 13 shows a student is using the prototype and his design result of a group of buildings. Other design results are shown in Figure 14, where student created high-rise buildings and irregular structures.
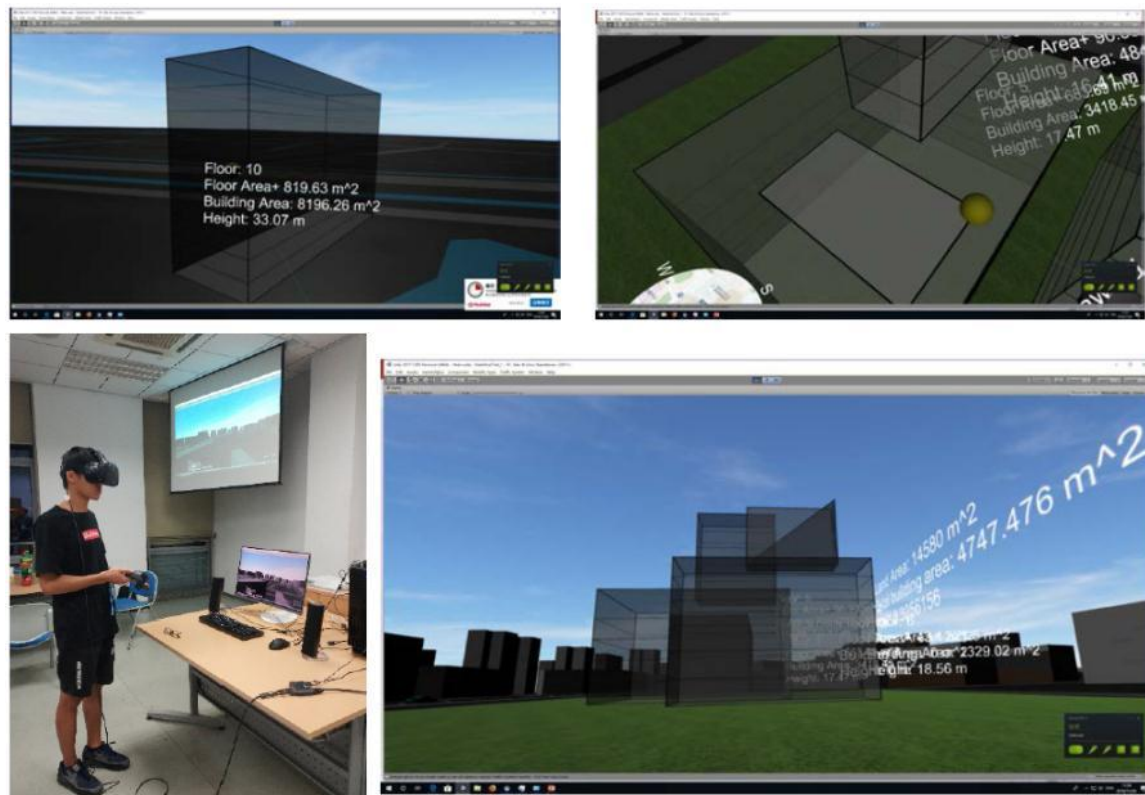

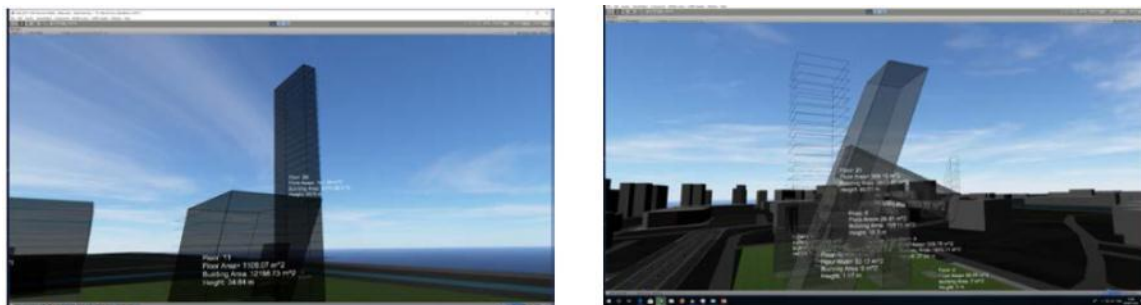Figure 13. An example of Design Result

Figure 14. Other examples of Design Result in the VR Environment

4. Result analysis

To explore whether students have learned from reflecting on the experience of using VR-aided took and participating in the relevant games, a questionnaire is designed to collect feedbacks from the students on their experience in using the VR-based learning and teaching tool. In total 31 students were invited to experience the VR tool, where the levels of the students are well distributed as 12.9% Year-1, 32.26% Year-2, 29.03% Year-3, 19.35% Year-4, and 6.45% MSc students. They are from the Built Environment Cluster with different domains, such as urban planning and design (22.5%), architecture (45.2%), and architectural engineering (32.3%). Among them, 45.16% of the students have experienced VR system before, where 50% of the experiences came from games, 21.43% came from Educational, and 21.43% from Design tools. A general feeling of good immersive experience is given by 74.19% students, while 51.61% of the students think this tool is impressive.

About 83.87% of the students gave positive feedback on a better understanding of the building layout by navigating in the virtual environment, and 80.65% of the students like the function of drawing and stretching a building block so as to preview his/her design more realistically. The ranking of the four major functionality for the design part is 1) sketching; 2) measuring; 3) navigation; and 4) material changing. More functionalities should be added based on the feedback. In addition, about half of the students, including Architectural Engineering and Architectural students, prefer to have some structural analysis functions to be added in the future so as to visually perceive the impact from various load condition applied to different structures.

Students from different domains have different understanding and expectation from the VR tool. For Architectural Engineering students, they feel more supportive in collaborative design by getting more understanding from urban and architectural design. For Architectural students, they put more focus on conceptual design and interior design, which results in requests for more façade materials and more shapes to be added in the future. While for urban planning students, they paid much attention to the Navigation inside and outside the buildings.

Some minor findings are: 1) some students felt dizzy when using the VR tool, and more interestingly, female students were more likely to have dizziness; 2) Although students had limited experience in using the VR platform, they mastered the operation very quickly and played in the platform without any difficulty after a short-time training.

Students also gave some suggestions on the tool, for example, 41.94% of the students want to explore more functions on structural analysis, and 32.26% of the students prefer more powerful sketching functionalities, which will be our future work of this research.

5. Conclusion

This paper proposed a VR-based learning and teaching tool to enhance the students' engagement, improve the collaboration across different disciplines in building design, and capture the students' interest in exploring engineering knowledge. It promotes critical thinking and reflection by putting the onus on students themselves to demonstrate how knowledge could be applied and tested in a more vivid way. By experiencing the platform of Training, Design and Construction, students are motivated and stimulated to learn actively and be eager to improve afterwards. Being able to show instant feedback from the VR environment undoubtedly attracted the students.

Feedback from the students showed that students have different focus and expectation to the functionalities provided in the platform. These differences were identified and analyzed to check the effectiveness of the VR-based learning and teaching tools. By analyzing the feedbacks collected through some questionnaires, some preliminary results showed that Architectural Engineering students were more supportive in collaborative design by getting more understanding from urban and architectural design.

To conclude, by using VR techniques to support learning and teaching in the built environment cluster, it can help students verify design theories in practice and, in return, improve their capability of applying, analysing, synthesizing, evaluating or even creating new design principles.

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