MULTIUSER IMMERSIVE VIRTUAL REALITY APPLICATION FOR REALTIME COLLABORATION IN DESIGN REVIEW PROCESS

BY

MR. SUNSENG TEA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (ENGINEERING AND TECHNOLOGY)
SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
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ENTITLED

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was approved as partial fulfillment of the requirements for
the degree of Master of Science (Engineering and Technology)

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ABSTRACT

Most project stakeholders have experienced problems understanding each other during a design review process of complex construction projects while staying remotely. In reality, the difficulty of sharing a common understanding during design review among remote project participants is a barrier to a successful project delivery. The recent advancement in visualization technology—Virtual Reality (VR) provides a practical solution to visualize and interact in the virtual environment of design, construction, and maintenance. However, the difficulty of bringing remote participants together in a virtual environment has impeded the implementation of VR technology in Architecture, Engineering and Construction (AEC) industry. The recent development of VR makes possible the solution for interactive visualization for design, construction, and maintenance. To fill the gap, this thesis presents a developed VR application for the realtime collaboration approach for remote users that enables clients and design professionals to clearly explore every aspect of their virtual project and facilitates interpersonal project communication in an interactive VR environment by using VR headsets. The primary aim of this research is to develop and test a VR application that provides not only a shared immersive environment but also realtime interaction between users in the virtual world. To successfully conduct this research study, a comparison was made between the immersive VR and the non-immersive VR experience among 44 students in terms of realtime collaboration in a building inspection task. Results indicated that the users of the developed immersive VR application outperformed those of the non-immersive platform as measured by the percentage of correctly identified design errors during the building inspection experiment. In practice, the developed application is expected to assist the project participants to create a shared immersive environment of their virtual project for an effective design review before construction work begins.

Keywords: Virtual Reality, Application, Realtime, Collaboration, Remote, Visualization, HTC Vive, Cloud computing

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Mr. Sunseng Tea

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LIST OF SYMBOLS/ABBREVIATIONS

Symbols/Abbreviations	Terms
AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
AR	Augmented Reality
AWS	Amazon Web Service
BIM	Building Information Modelling
CAD	Computer Aided Design
CAVE	CAVE Automatic Virtual Environment
CET	Civil Engineering and Technology
CONTEC	Construction and Maintenance Technology Research Center
FoV	Field of View
GUI	Graphical User Interface
HMD	Head Mounted Display
ICT	Information and Communication Technology
IDE	Integrated Development Environment
I_i	the average number of net identifications for the immersive group
I_n	the average number of net identifications for the non-immersive group
KMUTT	King Mongkut's University of Technology Thonburi
LCD	Liquid Crystal Display

NSTDA	National Science and Technology Development Agency
PC	Personal Computer
OP	Outperformance Percentage
PUN	Photon Unity Networking
RPC	Remote Procedure Call
SIIT	Sirindhorn International Institute of Technology
TU	Thammasat University
UI	User Interface
UNet	Unity Networking
VOIP	Voice Over Internet Protocol
VR	Virtual Reality

CHAPTER 1
INTRODUCTION

1.1 Research overview

The construction industry is one of the most flourishing sectors involving with planning, design, construction, and maintenance of real estate properties and public infrastructures. Furthermore, to deliver a construction project, there are participations from multidisciplinary stakeholders such as clients, project managers, architects, structural design teams, consultants, site engineers, and contractors. Generally, this fragmented industry cannot fulfil its goal without onsite and offsite intervention and cooperation from those project stakeholders who could limit or boost construction operation and development by using their specialism and experience in a collaborative manner (Fathi, Abedi, Rambat, Rawai & Zakiyudin, 2012). Recently, the construction projects are becoming more complex and modern due to demand and development of the owners and occupants in terms of their living standard, technologies and sustainability. Therefore, concerted actions are highly required to deal with the above-mentioned problem in order to achieve fast consensus decisions. Moreover, misunderstanding, misinterpretation and miscommunication induced by ineffective collaboration among project stakeholders often fails to track construction processes and to satisfy project requirements resulting in unprofitable and low-quality projects (Meng, 2012). As a result, Architecture, Engineering and Construction (AEC) industry has been seeking on innovative mediums and applications to increase effectiveness of current collaborative working environment. Meanwhile, digital technology in terms of visualization is developing to keep pace, and immersive VR is an appealing instance. The immersive VR has been commonly known as visualization technology that could totally immersing users into a digital content or a virtual space generated by computer via a VR headset (Mazuryk & Gervautz, 1996).

In the past, there was no integration of VR headset into the construction industry as assistance to this vastly complex sector. However, the utilization of immersive VR has been growing rapidly; thus, resulting in the advent of the significant technological working environment due to the collaboration between these two worlds. Immersive

VR system can assist construction tasks with its unique collaborative experiences by allowing not only shared visualizations of 3D models and human presence, but also verbal communication in the same virtual world between the design office and onsite engineers. Additionally, this advanced technology has been drawing the attention of many industries through investments to its innovative and practical solutions in digital visualization and collaboration between companies' employees in varieties of ways, contributing to cost-savings and better service for customers. For instance, employees and owners need to collaborate with each other while staying mobile throughout the workday as they maintain facilities or review design that they are not necessarily familiar with. Therefore, collaborative VR has the potential to support effective collaboration in construction by enabling them to interact with each other in a context-sensitive manner.

With the advent of this new technological trend, HTC Vive, which is an invention of the wearable VR headset with two controllers as both hands in the virtual space and two sensors as tracking tools of users' location and movement, can be utilized as a realtime collaboration tool in the construction industry. It offers users many functionalities and unique experiences such as the ability to completely disconnect from the reality, immerse into the lifelike environment generated by the computer, and provide real presences of the project participants through the human-human interaction; this could enable them to visualize the projects and collaborate on their virtual contents immediately and remotely. Moreover, the users could walk through the buildings, which have high level of realism to clearly view every buildings' component from different angles and discuss to reach the satisfaction of the owners before the start of the construction. Apart from that, it provides not only realtime, shared computer simulations to remote users, but also the transformation of how humans generate ideas and bring them to life.

1.2 Problem statement

Globally, there are often varieties of companies participating together in the highly fragmented construction industry, some coming with different purposes while sharing mutual interests in building construction and then moving on to another project. For example, in order to deliver one construction project from thousands of blueprints into a single actual building, there will be recruitment such as design professionals in preconstruction phase and construction professionals during the construction phase. Inevitably, fuss and difficulties occur rapidly and suddenly in every construction task, and project participants can lose track easily if they do not collaborate well. Additionally, construction stage—the most important stage, which requires much more attention and participation from multidisciplinary stakeholders, defines the final characteristics of the building's lifecycle, and the chance and cost of making changes or correcting design error go inverse dramatically. Consequently, collaboration plays a vital role in a successful construction project delivery due to the reduction of risk and uncertainty.

In present days, having plenary meetings, solving the problems and making decisions during conceptual design and construction stage are needed to be done offsite and onsite regularly and to some extent immediately for emergency cases. Hence, the need for strides of realtime collaboration is highly required as current construction projects are growing bigger and becoming more complex due to the demand in the standard of living. Current approach provided by architectural and structural teams during the design review meeting is just line-based or 3D drawings and to some extent projected on portable displays which is not so effective in locating the errors. Moreover, the owners have no basic knowledge on technical drawings, and the 3D models showed on the projector have lack of view and information because they are captured or rotated with predefined angle from the design teams. Therefore, the owners cannot navigate or sense the real environment of the building. Recently, the construction industry has continued seeking innovative methods and systems for more effective design review in a collaborative manner. In practice, the collaborative and technological environment serves as a quality enhancer, time saver as well as cost reducer in terms of productivity, efficiency, and convenience in teamwork encouragement, performance, and project completion time. As a result, a digital approach such as the immersive VR can be a key factor and problem solver for providing multidisciplinary stakeholders a unique immersive experience of their projects. Currently, the immersive VR is showing a great potential to deal with a variety of training (Sacks, Perlman & Barak, 2013), design and construction problems (Bashabsheh, Alzoubi & Ali, 2019) due to its practical solutions in digital visualization that facilitates more value-added activities especially remote design collaboration (Li, Roh & Ham, 2019). However, the adoption of advanced immersive VR applications for realtime collaboration in construction management and communication are still inadequate. Academically, there are still deficiencies in existing research, and the previous studies focused only on the single user improvement (Yan, Culp & Graf, 2011). Specifically, the existing collaboration practices are somehow time-consuming and extravagant in traveling to the site and the office, and sometimes create conflicts between multidisciplinary participants due to miscommunication, misunderstanding and misinterpretation of the projects.

Amidst all suggested approaches, a great concern to the study lies in the adoption of collaborative VR for assisting multidisciplinary project stakeholders with the ease of immersing into the same virtual project during conceptual design review. Design and construction tasks could be leveraged with the adoption of VR because it provides unique collaborative experiences via its immersion capability by enabling design teams and construction teams to co-review their projects before construction in a lifelike virtual environment; thus, benefits project revision and discussion. In addition to this, a multiuser immersive VR application helps visualize rich information imported from 3D modelling software for improving understandings and reducing misinterpretation caused by the complexity of modern projects among multidisciplinary stakeholders. Even though VR technology is advanced and well-established in effective project discussion and data communication, more work is still required for visualizing the project in a remotely collaborative manner.

1.3 Objectives of study

This study was conducted to achieve the following objectives:

1. To examine the current states and approaches in the design review process.
2. To introduce a digital or VR approach for realtime collaboration in the design review process in order to:
    a. reduce complexity and misunderstandings of the project participants during design review by providing a fully immersive environment of the project during the collaborative design review.

b. solve the issues of the geographically distributed and multidisciplinary working environment, that induce ineffective collaboration, by bringing remote stakeholders virtually together into the same project.

3. To investigate the applicability and performance of the developed approach whether it can be adopted and incorporated into the design review process through enhanced collaboration.

Figure 1.1 illustrates the overall concept of the developed application using VR approach for realtime collaboration in the design review process.

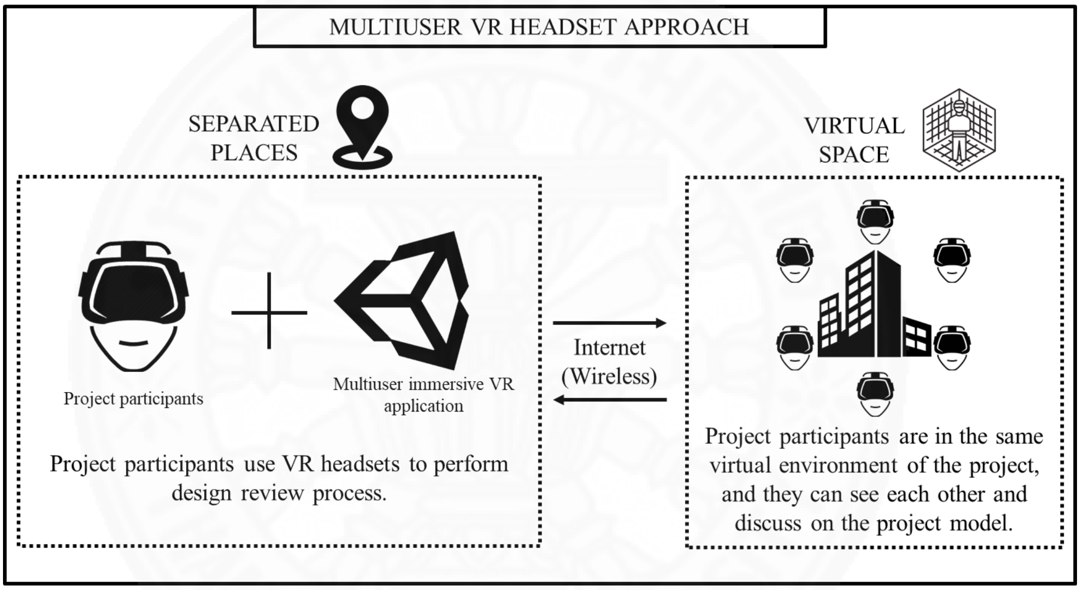


Figure 1.1 The concept of the developed application for realtime collaboration approach in the design review process.

1.4 Significance of study

The digital collaboration approach in the construction industry is a key element to the reduction in risk and uncertainty since the shared visualization and communication between project stakeholders in the distance can be done in realtime. As a result, the research on the VR application for realtime collaboration approach in the design review process primarily focused on the applicability and potential of advanced digital technology—multiuser VR-based application in terms of user-friendliness through the user interface (UI), productivity through functionalities, and efficiency through the capability of the developed application. The developed approach helps facilitate the realtime collaboration in current practices by providing faster access and realtime interactions on the projects between remote and local users. Furthermore, it promotes a faster completion of construction tasks by providing remote accessibility of the application, removing traveling time and slow decision making of the geographical dispersal working environment, reducing conflicts due to effective communication between multidisciplinary users and encouraging the collaboration of the fragmented construction. Accordingly, the developed approach plays a dominant role in assisting the project participants, who are working in the relevant civil engineering fields, with the efficiency of project discussion, project revision and project management via decision making in order to be professional and productive in construction supply chain. It makes them ready to adopt the cutting-edge technology of VR for the collaborative experience in the new digital era. Compared to previous collaborative practices without the aid of this technology, the developed multiuser VR application provides not only a shared immersive environment that allows the project participants to feel their projects before construction, but also realtime talking system for the effective remote discussion. With this technology, there appears to be good integration between project participants making it easy to immediately solve emergency problems and remove distance barriers contributing to effective collaboration.

1.5 Scope of study

This research mainly focused on development and implementation of a multiuser immersive VR application for realtime collaboration in the design review process. In order to prove the applicability of the developed application, a comparison was made between immersive VR and non-immersive VR experience in terms of realtime collaboration on building inspection task, and the experiment was focused on the performance enhancement of the design review before the building inspection task from the capability of bringing inspectors into the same immersive environment and allowing realtime interaction. In this research, the experiment was conducted using an inspection of a selected floor of SIIT Advanced Laboratory building (Civil Engineering Laboratory) to simulate the whole process of the design review, and only student subjects are included in the experiment not real professionals.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter presents the extensive and critical review of previous studies and literatures pertinent to VR technologies, VR applications in AEC, cloud computing technology and project communication. This chapter was conducted as one of the research tasks to ensure not only originality and rationale of this study but also the latest development and issues in VR applications for the realtime collaboration in the AEC industry.

2.2 General background of VR

Advancements are becoming more frequent, and with the recent popularity of technology in this generation, a lot of investment is being made. Nowadays, computer graphics is one of those investment and used in many domains of human life. At the end of the 20th century, graphics workstation becomes an indispensable tool for an architect, engineer, or interior designer due to its versatility. In the edge of revolution of computer chip, technology brings faster and faster computers to the market that contributes to price reduction, and these machines are equipped with better and faster graphics boards (Mazuryk & Gervautz, 1996). Consequently, it becomes possible even for an average user, to move into the world of computer graphics. This fascination with a new reality often starts with computer games and lasts forever. It allows to see the surrounding world in other dimension and to experience things that are not accessible in real life or even not yet created. Moreover, the world of three-dimensional graphics has neither borders nor constraints and can be created and manipulated by users as they wish – they can enhance it by a fourth dimension: the dimension of our imagination (Mazuryk & Gervautz, 1996). Humans, however, never satiate for the thirst of knowledge and innovation; therefore, they want to step into this world and interact with it – instead of just watching a picture on the monitor. The promise of being able to be inside another world might be resolved by VR. This technology which becomes overwhelmingly popular and fashionable in current decade. The very first idea of it was presented by Ivan Sutherland in 1965: “make that (virtual) world in the window look real, sound real, feel real, and respond realistically to the viewer’s actions” (Sutherland, 1965).

VR which may be called Virtual Environment, Artificial Reality, Cyberspace, Telepresence or Synthetic Reality, is a computer-created sensory experience that has the objective of creating a virtual world (entirely different from a real one or that replicates reality), having one immerse into it and giving one the capability of interacting with this world, while using specific devices to simulate an environment and stimulate one by feedback in order to make the experience as real as possible (Boas, 2013). In other words, it builds a digital reality using computer graphics, sounds, and images to reproduce electronic versions of real-life situations that replaces a user’s real-world one. VR is not a computer, but a technology that uses computerized clothing to synthesize reality. Figure 2.1 demonstrates a screenshot of an immersive VR experience in the third floor of SIIT Advanced Laboratory building using HTC Vive headset. Most current VR systems provide only visual experiences created by computer-assisted design (CAD) or other graphics/animation systems, but researchers are working on interface devices that add sound and touch. Undoubtedly, VR has attracted a lot of interest of people in last few years. Being a new paradigm of user interface, it offers great benefits in many application areas. It provides an easy, powerful, intuitive way of human-computer interaction since the user can watch and manipulate the simulated environment in the same way we act in the real world, without any need to learn how the complicated (and often clumsy) user interface works. Therefore, VR is widely used in the gaming and entertainment industries, as well as for various types of training. Depending on the final objective, VR may look very realistic or may resemble cartoon images. For example, many applications like flight simulators and surgical simulator are an integral part of training. Later, VR has been applied as a teleoperating and collaborative medium, and of course in the entertainment area. Specifically, VR applications have provided many potential benefits to the construction industry in terms of reducing the complexity of construction tasks and improving the collaborative tasks between the project participants. In general, the construction industry covers the significant practices of designing, planning, estimating, scheduling, constructing, repairing and demolishing of buildings and infrastructure. Besides, these practices are separated into 3 phases including preconstruction phase, construction phase, and postconstruction phase. Every phase has its own problems and difficulties occurring frequently that need immediate solutions since the cost of correcting the project is increasing whereas the chance of making changes keep decreasing. As a result, the construction industry is always hunting for effective and innovative solutions to deal with the current complexity in construction projects. Furthermore, the accessibility of information regarding design and construction are highly needed for effective management and cost reduction in every construction project. As a matter of fact, there is so much information and data in a construction project that the multidisciplinary stakeholders find it time-consuming and difficult to access in order to avoid replication and correction. Meanwhile, the user interface of the future is a screen that sits neither on the desk nor in the pocket, but the lifelike world itself — with a little help from technology. VR truly enhances and enriches our lives. The digitalization is moving to the adoption of VR due to the enhancement and facilitation of users' perspective in a new way of seeing, hearing and feeling. Consequently, VR plays a vital role in being a realtime collaboration approach by allowing users to collaboratively interact with digital contents in the virtual environment and in real time.

Figure 2.1 An immersive VR experience in the third floor of SIIT Advanced Laboratory building using HTC Vive headset.

2.3 Virtual reality development timeline

Historically, there were many milestones of research on digital technology from a small capability of the computing device to the advent of the VR system, and the timeline below is the development of VR system (Mazuryk & Gervautz, 1996):

- Sensorama (1960-1962): Morton Heilig created a multi-sensory simulator – the first approach to create a virtual reality system, which is a prerecorded film in color and stereo, augmented by all the features of an environment such as binaural sound, scent, wind and vibration experiences without interaction.
- The Ultimate Display (1965): Ivan Sutherland proposed the ultimate solution of virtual reality: an artificial world construction concept that included interactive graphics, force-feedback, sound, smell and taste.
- The Sword of Damocles (1968): Ivan Sutherland convert the concept of reality into a device considered as the first *Head Mounted Display* (HMD), with appropriate head tracking which supported a stereo view, and it was updated correctly according to the user's head position and orientation.
- GROPE (1971): The first prototype of a force-feedback system realized at the University of North Carolina (UNC).
- VIDEOPLACE (1975): Artificial Reality created by Myron Krueger –a conceptual environment, with no existence". In this system the silhouettes of the users grabbed by the cameras were projected on a large screen. The participants were able to interact one with the other due to the position tracking of image processing techniques in 2D screen's space.
- VCASS (1982): Visually Coupled Airborne Systems Simulator created by Thomas Furness at the US Air Force's Armstrong Medical Research Laboratories– by wearing HMD, an advanced flight simulator allowed the fighter pilot to augment out-the window view by the graphics describing targeting or optimal flight path information.
- VIVED (1984): VIrtual Visual Environment Display constructed at the NASA Ames with off-the-shelf technology a stereoscopic monochrome HMD.

- VPL (1985-1988): The VPL company manufactures the popular DataGlove and the Eyephone HMD – the first commercially available VR devices.
- BOOM (1989): BOOM commercialized by the Fake Space Labs is a small box containing two CRT monitors that can be viewed through the eye holes, and the user can grab the box, keep it by the eyes and move through the virtual world, as the mechanical arm measures the position and orientation of the box.
- UNC Walkthrough project: In the second half of 1980s at the University of North Carolina, an architectural walkthrough application was developed, and several VR devices were constructed to improve the quality of this system like: HMDs, optical trackers and the Pixel-Plane graphics engine.
- Virtual Wind Tunnel (1990): NASA Ames developed an application that allowed the observation and investigation of flow-fields with the help of BOOM and DataGlove.
- CAVE (1992): CAVE Automatic Virtual Environment is a virtual reality and scientific visualization system that projects stereoscopic images on the walls of room instead of using a HMD it (user must wear LCD shutter glasses), assuring superior quality and resolution of viewed images, and wider field of view in comparison to HMD based systems.
- Augmented Reality (AR): A technology that presents superimposition of virtual three-dimensional objects on real ones rather than completely replaces the real world. This is achieved by means of see-through HMD and was previously used to enrich fighter pilot’s view with additional flight information (VCASS).

2.4 Types of VR immersion

It is vital to be aware of different types of VR immersion before moving to the design and development of VR applications. VR can be generally classified into three different immersions depending on the VR apparatus as follows.

2.4.1 Fully immersive VR

Fully-immersive VR is the ultimate version of VR that lets the user totally immerse in computer generated world with the help of head mounted display (HMD) that supports a stereoscopic view of the scene accordingly to the user's position and orientation (Mazuryk & Gervautz, 1996). The system may be enhanced by audio, haptic and sensory interfaces, and it gives users the most realistic experience possible, complete with sight and sound. Furthermore, it comprises head-mounted displays, headphones, gloves, and maybe a treadmill or some kind of suspension apparatus that could provide high-resolution content with a wide field of view; so, whether flying or fighting, the users feel like they are really there. This type of VR is commonly used for gaming or other entertainment and training purposes in VR arcades since it gives a sense of presence that cannot be equaled by the other approaches. However, it tends to be the most demanding in terms of the computing power and level of technology (and consequently cost) required to achieve a satisfactory level of realism and development (Costello, 1997).

2.4.2 Semi-immersive VR

Semi-immersive VR is a relatively new implementation of VR technology and borrow considerably from technologies developed in the flight simulation field. This type of VR is mainly used for educational and training purposes and the experience is made possible with graphical computing and large projector systems. It comprises a relatively high-performance graphics computing system which can be coupled with either: a large screen monitor or a large screen projector system or multiple television projection systems (Costello, 1997). For example, in many ways, these projection systems are similar to the IMAX theatres. Using a wide field of view, these systems increase the feeling of immersion or presence experienced by the user. However, the quality of the projected image is an important consideration. Semi-immersive systems therefore provide a greater sense of presence than non-immersive systems and also a greater appreciation of scale. In addition, it provides users with a partially virtual environment to interact with, and this implementation provides the ability to share the virtual experience. This may have a considerable benefit in educational applications as it allows simultaneous experience of the virtual environment which is not available with head-mounted immersive systems. Additionally, stereographic imaging can be achieved, using some type of shuttered glasses in synchronization with the graphics system.

2.4.3 Non-immersive VR

Non-immersive VR, which is sometimes called Window on World (WoW) systems, is the least immersive implementation of VR techniques (Mazuryk & Gervautz, 1996). This is the simplest type of virtual reality applications since it involves a computer-generated environment in which an avatar is projected onto a conventional desktop monitor or wall without the support of any sensory output, and interaction with the virtual environment can exist by using traditional tools such as keyboards and mice. Furthermore, the non-immersive VR benefits users by not demanding any high performance hardware such as graphic card and being able to be implemented on high specification PC clones; thus, these systems can be regarded as the lowest cost VR solution which can be used for many applications (Costello, 1997). However, this low cost means that these systems will always be outperformed by more sophisticated implementations, providing almost no sense of immersion and being limited to a certain extent by current 2D interaction devices. The non-immersive VR is often forgotten as an actual type of VR because it is very common in our everyday lives. For example, the average video game is technically considered a non-immersive VR experience due to sitting in a physical space and interacting with a virtual one. These types of experiences have become more advanced in recent years with video games like Wii Sports, where the system detects your motion and translates it on screen.

2.5 Difference between VR and AR

VR and AR are two of the most disruptive and popular technologies nowadays which can change the way humans see, communicate, and interact with the world. Although they are similar, but they are not the same. It is very important to differentiate between VR and AR in terms of immersion, devices, and applications. Firstly, the main difference between these two technologies is the immersion they provide. VR generates a completely computer-generated world, everything the user sees is an artificial recreation, so the user loses contact with the real environment. On the other hand, AR enhances reality by adding digital information to it, so the user is still in contact with the real environment during the AR experience. This allows the user to interact with the augmented objects while being in contact with the real world. AR keeps the user in contact with the real world, that is what makes the biggest difference between the devices used. Additionally, immersion is not the only difference between these two technologies, the devices they use to deliver innovative experiences are also different between them. VR uses headsets, namely Oculus Rift, Google Cardboard, Sony, HTC Vive, PlayStation VR, and Samsung Gear VR, that immerse the user's vision and hearing into the virtual world, whereas AR is provided from a wider variety of devices: AR headsets (e.g. Microsoft Hololens), laptops, tablets, and smartphone. Last but not least, both technologies are applied to different industries with diverse use cases, different targeted users as well as market and business opportunities. The industry where they can grow the most is gaming and education. They both offer the chance to disrupt traditional methods, but their applications as solutions are different. VR can be used to immerse students and users into historical worlds or entertainment sites for example, making it a good solution for theoretical lessons and enjoyments. In contrast, the main feature of AR is the ability to interact with the augmented world; thus, it can provide students more practical lessons and insight about complicated lessons. For instance, students can use their phones to scan the pictures in the books to view digital contents of 3D model of pictures with explanations augmented on the book through the screen of their phones. As a result, students can learn and understand well by using AR benefits.

Ultimately, VR and AR both can be briefly summarized as follows:

Augmented Reality

- System overlays the digital contents into physical or real-world sense;
- Users can experience and interact in real world in real time;
- A mechanism needs to be established to merge virtual world with physical world; and
- Difficulty in registering virtual and physical environments.

Virtual Reality

- Completely immersive or computer-generated world or environment;

- System controls senses;
- A mechanism needs to be established to generate virtual environment; and
- Difficulty in creating fascinating VR environments.

2.6 Use cases of VR

Presently, VR has been well-known and promoted with certain smart devices. A variety of VR applications have been gradually developed and deployed in various industries and communicated across the globe to enhance the process and productivity and to improve the quality of human life. It has been shown that VR is still under the research and development process conducted by different companies, industries and institutes. In practice, VR enhances users' perspective of seeing the world in a new way through its power of immersion. The immersion of the computer-simulated information plays a vital in reducing the complexity over the difficult and costly tasks in training and design review by helping the trainees and the designer to perform the tasks as much as they can without spending on the training materials and easily to locate the design error. With the advent of the VR system, there are many sectors taking advantages of this technology such as:

- Industrial and manufacturing;
- Engineering;
- Training;
- Education;
- Medical fields;
- Museum;
- Military;
- 3D infrastructure visualization;
- Gaming industries and entertainment;
- Realtime collaboration;
- Marketing, advertising, news, and promotion;
- Navigation and path planning;
- Geospatial planning; and
- Urban planning.

2.7 Advantages and limitations of VR

As a matter of fact, VR provides an enhanced perception to help people experience seeing, hearing, interacting, and feeling their actual and existing environments in innovative and digital ways that can benefit their daily life. Indeed, this technology brings numerous benefits and simultaneously contains several aspects to be improved as discussed below.

2.7.1 Advantages of VR

VR has been known as an innovative approach of immersing users into a lifelike experience of pre-built project that are digitally generated. It allows users to sense and revise their real project before launch; thus, providing the users unique experience and impression of an illusion and interactions with the project in the virtual world. Indeed, this technology has numerous benefits such as:

- Collaborative experience for the geographically distributed working environment;
- Data communication;
- Work performance and productivity enhancement;
- Working environment encouragement;
- Fast accessibility of data;
- Knowledge, skills and information enrichment;
- Sharing remote experiences in real time between the users being at different places;
- Realizing gaming industries allowing the players to play and experience realistic games;
- Bringing the pre-built objects or pre-created things to existence; and
- Form of escapism.

2.7.2 Limitations of VR

Despite enormous potential practical applications, VR, in its current state, has drawbacks. It is still relatively expensive, and there is still a slight, but perceptible time lag between the user's body movements and their translation in cyberspace (i.e. latency)

(Morel, Bideau, Lardy & Kulpa, 2015). The equipment the user must wear, such as head gear, gloves, and other devices, needs refinement. At this early stage in the development of VR, no one knows what the long-term effect of using head-mounted displays might be on human eyes or what the possible psychological effect might be from spending too much time in cyberspace. Additionally, people using VR headset sometimes complain about chronic fatigue, a lack of initiative, drowsiness, irritability, or nausea after interacting with a virtual environment for a long time (Yu, Zhou, Wang & Zhao, 2019). We do not know how much each of these symptoms depends on the characteristics of the VR systems themselves, or on the characteristics of the individuals using the systems. As a result, Whether VR can be an effective tool for education, training, entertainments, etc. depends partly on one's definition of VR and partly on one's goal for the beneficial experience. It may not be worth the cost and utilization if the goal of the beneficial experience is simply to memorize facts. However, if the goal of the beneficial experience is to foster excitement about a subject, or to encourage productivity through exploration, or to give users a taste of what it is like to be anything they want, then VR may be worth the expense.

2.8 VR applications in AEC industry

Recently, VR has advanced more rapidly in the AEC sector than other industries, particularly in construction safety training (Li, Yi, Chi, Wang & Chan, 2018) due to the ability to not only totally immerse users into the lifelike experience but also allow navigating the model and interacting with 3D objects in order to make better sense of the project. With its advent, the AEC industry has started embracing this technology to increase efficiency throughout the project life cycle. Therefore, the collaboration of these two worlds is creating innovative ways of working for development. Given the growth of complex projects, efficient information and data management play a vital in reducing complexity and increase productivity of the project (James et al., 2011); hence, the AEC industry highly demands practical digital solutions to effectively control every single important information and data throughout the project life cycle. In practice, the main issue that induces the failure of fulfilling project requirements in the AEC sector is the deficiency in data communication and interpretation among the multidisciplinary stakeholders during design and construction;

thus, VR is having many potential benefits for tackling such setback and drawing an attention of both academic and commercial of research on the employment of this useful technology in the AEC industry. Recently, many researchers are trying to take advantages of this technology in order to leverage construction tasks for the greatest impacts in the AEC industry.

There is a variety of possible use cases in terms of architecture and engineering that can be taken into consideration for conducting research in order to facilitate design and construction process (Milovanovic, Moreau, Siret & Miguet, 2017). For example, a BIM-VR workflow could capture a photorealistic construction operation with the VR headset in preconstruction phase and during construction (Du, Zou, Shi & Zhao, 2018). Furthermore, with the capability of VR on headset, project stakeholder can see their project in real dimension and environment through a photorealistic digital content that is generated by computer simulation, so they are able to feel, sense and review their project before the start of construction. Construction education could be facilitated by providing a game-based safety training due to the advancement of human-computer interaction (Goedert & Rokooei, 2016). Besides, level of understanding and sophistication are enriched by an effective visualization medium in real practices of engineering and construction. At construction sites, VR could provide a lifelike representation of many necessary construction tasks, especially safety awareness due to its immersion. Construction site is a hazardous area where any worker could confront an unpredictable accident that leads to an injure or a fatality. As a result, VR ability to bring workers into a lifelike experience of those construction hazards that might occur due to the lack of attention and effective safety training has become one of the most important VR research topics (Eiris, Gheisari & Esmaeili, 2020) because the conventional safety training that has been used at the site is a lecture-based training focusing on discussions of previous experience or information received from occurred accidents, and those traditional approaches are sometimes ineffective (Hinze, Thurman & Wehle, 2013); this will result in reduction of fatalities and injuries of the workers (Li, Yi, Chi, Wang & Chan, 2018).

With advanced development of VR technology in the AEC industry, there are numerous advantageous applications to enrich the conventional approaches in current construction projects because VR changes the way construction stakeholders work via its facilitation to the construction tasks and visualization of the problems from preconstruction stage to completion of the projects.

2.9 VR applications for realtime collaboration approach

With the current advancement of technology pertinent to computational hardware, networking and the internet, researchers begin to develop multiuser functions in a VR environment due to more convenience. Many researchers are taking benefits of networking protocols in many industries, particularly in manufacturing, by implementing them in their applications or systems because they found that applying a multiuser feature in a VR context creates a capable tool to fulfil the need of realtime collaboration in current working environment. For example, Li, Roh and Ham (2019) presented a multiuser immersive VR training approach that allowed workers to have a cooperation on shipbuilding and installation in the virtual space of a computer simulation. Furthermore, Galambos et al. (2015) introduced a software framework to assist various methods of collaboration with the aid of VR technology as a communication media. Apart from that, the medical field has taken many advantages of the multiuser VR. For instance, Thielbar, Spencer, Tsoupikova, Ghassemi and Kamper (2020) integrated a multiuser VR approach to aid interactions between therapist and clients when they are remotely located. They also compared their approach with the single user VR platform, and the result indicated that participants tended to spend more time for training in the multiuser platform (Thielbar et al., 2020). Last but not least, Emmelkamp et al. (2002) and Schäfer, Koller, Diemer and Meixner (2015) applied the multiuser functions in VR to urge patients on the fight of acrophobia in the real world.

Although it is found that VR has the potential benefits for improving collaborative working environment, most of the previous research has been studied for training purpose in the manufacturing sector and the medical field. For example, most of manufacturing processes require workers to deal with some complicated operations, so it is important to create lifelike training environments of those difficult tasks or operations where remote experts could guide them in a remotely collaborative manner. Apart from that, VR could also be used to train patients about getting used to difficult situations of their illness. However, there are still some gaps on realtime collaboration in the immersive environment pertinent to design review in the AEC industry regardless of the great development on multiuser VR in other industries. Besides, the simplest level provided by the designer in the collaborative design review process is just a line-based paper or 3D drawings that are generated by computer-aided design software (e.g. BIM authoring tools), and to some extent projected on portable displays (Abdirad & Dossick, 2016). Nonetheless, reviewing the design on screens somehow cannot effectively locate errors due to current complex modern projects compared to the immersive VR (Paes, Arantes & Irizarry, 2017). Furthermore, it is found that efficiency of building inspection task could be improved through the capability of collaborative VR to bring inspectors together into the same virtual project (Eiris, Gheisari & Esmaeili, 2020). Therefore, the multiuser VR system could effectively deal with the above-mentioned collaboration issues in the AEC activities.

2.10 Cloud computing technology and project communication

Cloud computing is a service providing not only an enormous amount of virtual data storage but also a powerful computational capability to customers or users over a networked means (usually through the internet) according to their demand and usage (Liu, Hu, Huang & Peng, 2012; Voorsluys, Broberg & Buyya, 2011). Furthermore, it is composed of a group of computer assembly to form vast data centres which are geographically distributed by providers for efficient usage and connection (Sultan, 2010). Cloud computing is defined as a business concept covering a variety of technology such as virtualization and applications as Software as a Service (SaaS), platforms as Platform as Service (PaaS), and hardware as Infrastructure as a Service (IaaS) (Goscinski & Brock, 2010). Cloud applications have been employed in 3 domains of the AEC industry—construction management (Gong & Azambuja, 2013; Kumar, Cheng & McGibbney, 2010; Liang & Luo, 2013), design and engineering (Chen, Chen, Shen & Lee, 2015; Karamouz, Zahmatkesh & Saad, 2013; Latu et al., 2013) and BIM (Chuang, Lee & Wu, 2011; Redmond, Hore, Alshawi & West, 2012; Zhang & Issa, 2012). Specifically, the computational medium and project communication of the design, analysis, construction and management have been eased with the aid of cloud computing. For example, Petri, Beach, Rana and Rezgui (2017) presented how geographically distributed construction projects can be assisted with the aid of federated cloud—a medium to support collaboration of multiple stakeholders and organizations by creating shared environment. Furthermore, Senescu, Haymaker, Meža and Fischer (2014) improved common knowledge and collaboration of the project participants through a developed cloud application of progress communication system. Besides, BIM authoring tools have also incorporated cloud computing to advance BIM applications in terms of usability, collaboration, and interoperability. For instance, Redmond, Hore, Alshawi and West (2012) introduced a cloud-based medium for synchronizing data transfer amidst multidiscipline during preconstruction phase in order to ease the difficulty of relevant data storage and carriage for diverse construction processes. Additionally, Zhang and Issa (2012) studied various cloud BIM systems and cloud services such as Revit Cloud, Revit Server, Advance2000 and Amazon respectively; and came up with a framework as a decision making mean for cloud BIM applications based on specific use cases.

In spite of the accomplishments in VR and cloud computing technologies for enhancing productivity of the design, construction and operation, there is a requirement to investigate approaches by taking advantages of both technologies in order to provide better improvement of project collaboration to remote project participants. To bridge the gap, this research employs a public cloud computing service to capitalize multiuser VR in AEC activities.

CHAPTER 3
RESEARCH METHODOLOGY

This chapter chronologically presents how the study was successfully conducted in terms of research design and framework, research settings, research participants and research tools. Moreover, these above-mentioned elements could induce efficient research activities contributing to accomplishment of the research and significant research findings.

3.1 Research design and framework

To conduct the study, a research design and framework containing six research tasks was carried out to answer all above-mentioned research objectives and elaborated as below:

3.1.1 Task 1: review of existing research and literature

In this task, an extensive and critical review of literature was conducted to get an insight and find the gap in research regarding:

- The collaborative tasks of the construction project, their issues and currently used approaches, particularly both in the preconstruction phase and during construction.
- Potential benefits of integrating Information Communication Technology (ICT) field, namely cloud computing technology and VR system, with the collaborative tasks in the design review process.
- VR applications and development within the AEC industry, and how they help enhance work productivity, especially for the design review process.
- VR applications for realtime collaboration approaches within various industries, and how they could provide a better solution than the convention approaches.

The main purpose of this task is to ensure not only originality and rationale of the study, but also the latest development and issues of VR applications relevant to the research. Furthermore, it was mainly conducted to achieve the **first research objective** (to examine the current states and approaches in the design review process).

3.1.2 Task 2: proof of concept

The proof of concept was conducted to examine whether there is feasibility for the development of multiuser VR for realtime collaboration application and how it can be employed in geographically distributed and multidisciplinary working environment of the design review process. Specific research activities regarding the design and development of immersive and non-immersive VR applications in the Unity game engine were conducted in this task.

This task was conducted to achieve the **second research objective (**to introduce a digital or VR approach for realtime collaboration in the design review process). The outcomes of this task include working prototypes of VR applications for shared visualizations on both immersive and non-immersive platforms described as following:

1. A desktop VR application of multiplayer chat was created by using stand-alone server and Unity Networking protocol (UNet).
2. A sample of multiplayer desktop VR application was created by using UNet for sharing visualization via a server on AWS.
3. A multiplayer desktop VR application was created by using Photon Unity Networking (PUN) for testing with immersive VR application.
4. A final multiuser immersive VR application was created with 5 functionalities by using PUN:
    a. Shared immersive experience
    b. Realtime talking system (VOIP)
    c. Navigation feature
    d. Name tag of all connected users
    e. Laser gun tool from users' right hand

The prototypes which were integrated into the development of the final application are shared visualization applications that allow human-to-human interaction in the virtual world. The details of these working prototypes are discussed in Section 4.6 Application prototypes. Figure 3.1 shows one of the working prototype applications on the phase of testing the networking protocol for the immersive VR platform.

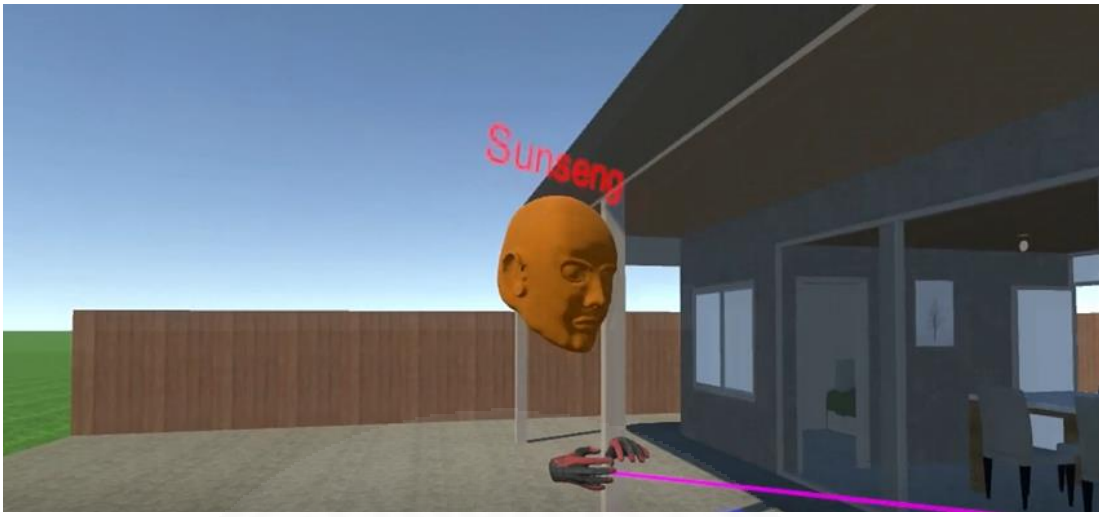


Figure 3.1 The immersive VR experience of remote user with the name tag and laser gun tool.

3.1.3 Task 3: multiuser VR application development for realtime collaboration approach

In order to overcome the deficiencies in current approaches and VR use cases in the AEC industry, particularly the inadequacy of VR application for a realtime collaboration approach, a multiuser immersive VR application that was specially developed with 5 functionalities including shared immersive environment, realtime talking system, navigation feature, name tag of connected users and laser from users' right hand for the collaborative design review was designed and developed. The developed application is a VR headset application implemented with the multiuser functions via cloud networking in order to provide a shared immersive experience for remote project participants. In this way, they can join concurrent scene of the photorealistic project rendered by the game engine. It connects the remote users and synchronizes their name, position, actions, movements, and verbal communication in the immersive environment through cloud networking in order to further enhance the quality of realtime collaboration in the design review process. Following the proof of concept, the application was developed for the collaborative design review of a selected part of a newly constructed SIIT Advanced Laboratory that represents typical collaborative design review. Figure 3.2 depicts the flowchart of the developed application. To achieve this, the following research activities were conducted:

- The 1st phase (shared immersive experience) was to generate networking scripts in order to allow all connected users to see each other; therefore, they could see each other's avatar and actions like the real presence in the physical environment.
- The 2nd phase (realtime talking system) was to attach the Photon Voice Recorder script to the avatar, so it enabled Voice over Internet Protocol (VOIP) in order to allow realtime verbal communication in the concurrent scene.
- The 3rd phase (navigation feature) was to develop the movement and camera scripts according to the SteamVR plugin in order to allow first person controller in VR mode to the remote users; therefore, they can move and turn to any location in the concurrent scene by using HTC Vive controllers.
- The 4th phase (laser gun tool) was to generate pointer scrip by using Remote Procedure Call (RPC) in order to let all connected users to point at where they want their partners to pay attention to.
- The 5th phase (name tag) was to create a canvas with an input field and a button by using RPC in order to allow users to input their name and click to join the shared virtual environment; thus; they know who is joining the scene with them.
- The 6th phase was to import the project model into the game engine in order to set up the virtual environment and build a final application for the collaborative design review.

This task was conducted to achieve the **second research objective**. It produced a complete multiuser immersive VR application equipped with the capability for the project participant to use as a realtime collaboration approach in the design review process and facilitate realtime collaboration on conceptual design review utilizing realtime interactions.

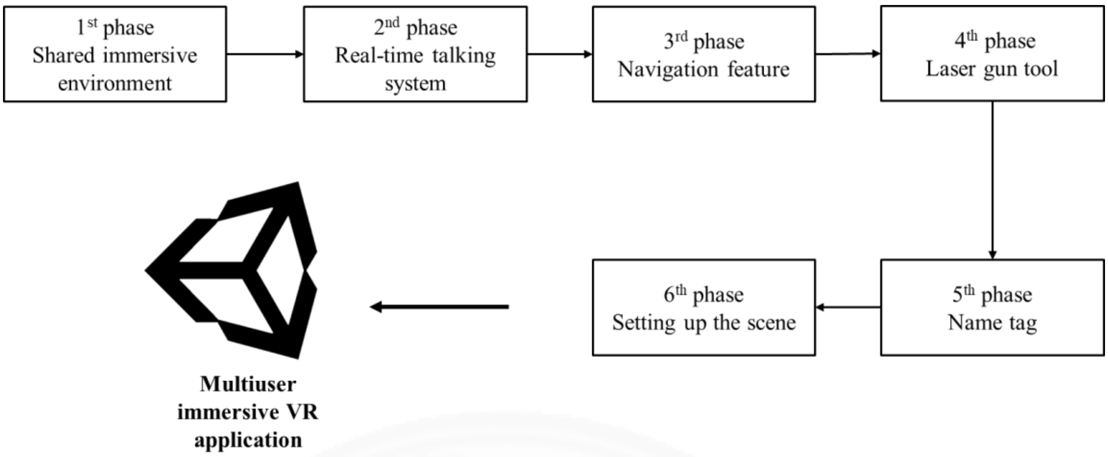


Figure 3.2 Flowchart of the multiuser immersive VR application development for realtime collaboration approach.

3.1.4 Task 4: pilot test

It is essential to better understand the existing states of practice and knowledge in collaborative design review carried out in the construction project. For this task, a pilot test was conducted with professionals who have working experience in the construction industry, particularly those with experience in the design review process, to get feedback through interviews since they could provide useful information as preliminary data relevant to the following topics:

- Current practices and issues in the collaborative design review process during both preconstruction and construction phase
- Current approaches used in the collaborative design review process in terms of technological support
- Potential benefit of the multiuser immersive VR application for the collaborative design review process
- Preferable functionalities regarding the developed application.

This task was conducted to achieve the **first and second research objective**. The outcomes of this task established a baseline understanding and fundamental concept guiding author to an appropriate start and effective development steps of the study. Figure 3.3 and Figure 3.4 show activities during the showcases and the interviews with the professionals.

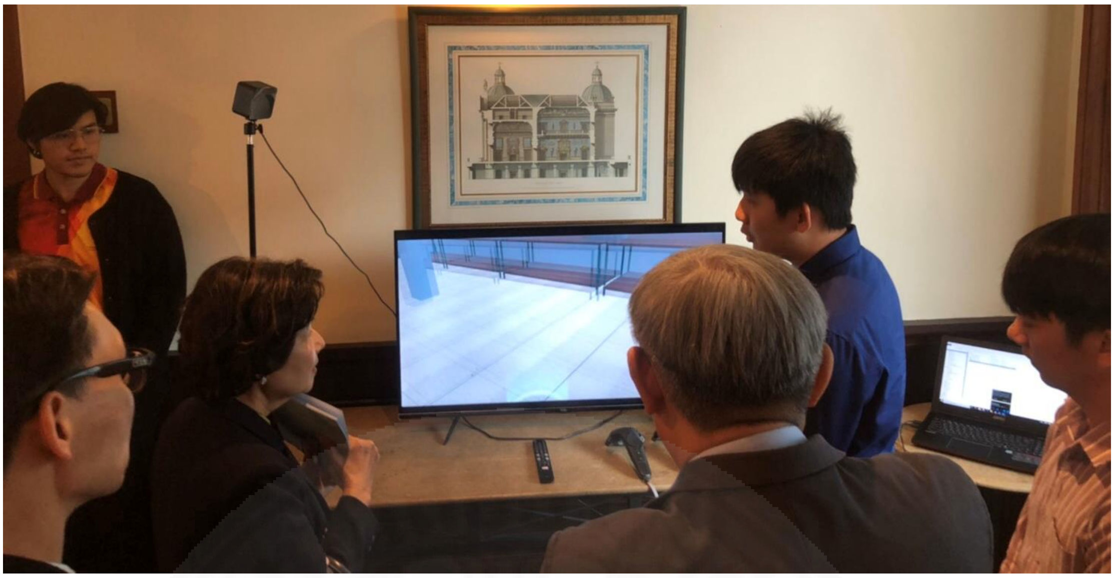


Figure 3.3 A showcase during a ceremony of receiving research grant for CONTEC.

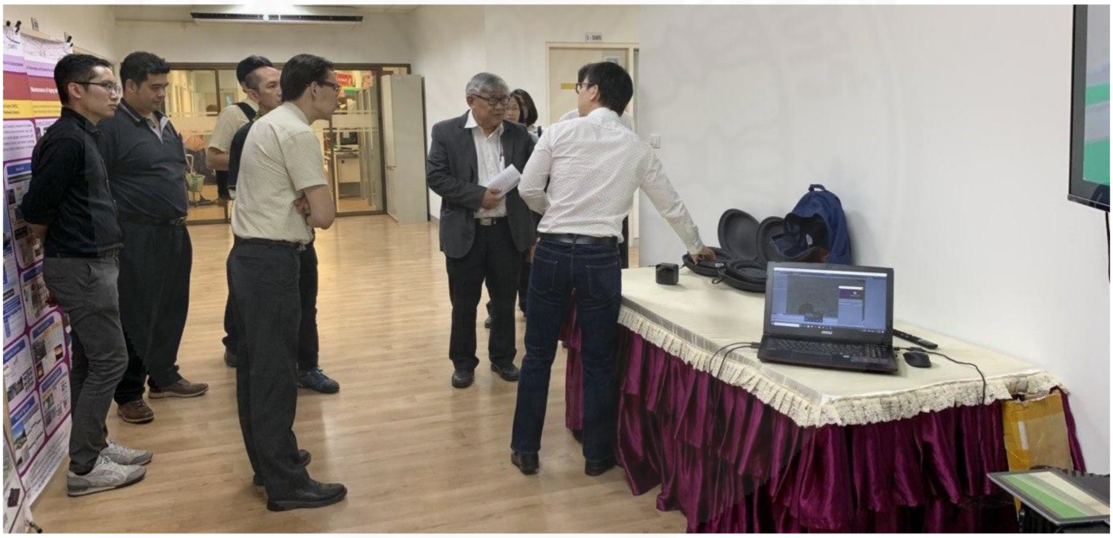


Figure 3.4 A showcase to NSTDA delegates.

Specifically, a pilot test was conducted with Asst. Prof. Dr. Rathavoot Ruthankoon, who is a lecturer at King Mongkut's University of Technology North Bangkok, Bangkok, Thailand, as well as a construction management professional with more than 10-year experience. He spent his valuable time to pay a visit to the school of Civil Engineering and Technology (CET), SIIT, TU for testing a demo application and providing feedback through an interview. The main reason that he was invited is because he is interested in VR research. Furthermore, he has been working as a representative of owners' projects; thus, he has been experienced in many construction projects and confronted many problems from the start to the end of the projects.

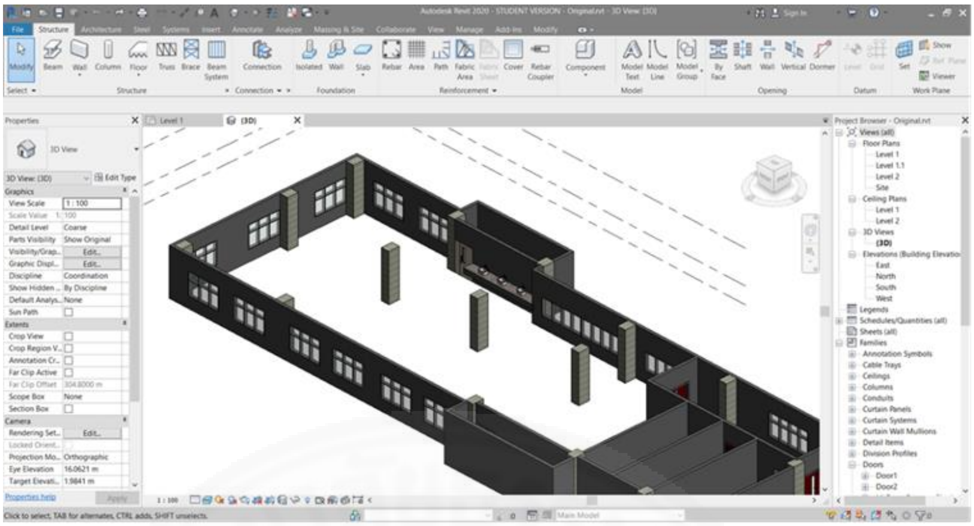
The demo application was tested by Asst. Prof. Dr. Rathavoot Ruthankoon and Assoc. Prof. Dr. Kriengsak Panuwatwanich, who is a head department of the school of CET, for 10 minutes inside the school of CET office. Figure 3.5 shows the activities during testing the demo application. Meanwhile, the demo application allowed a shared immersive experience, built-in realtime talking system, and navigation feature. After finishing the demo session, an interview session was conducted for about 30 minutes. Figure 3.6 shows the activities during the interview. In terms of the interview, when asked what the most frequent problems are occurring during the design review, Asst. Prof. Dr. Rathavoot Ruthankoon replied: "the project owners always change their mind regarding the architectural design, so it affects everything. And, the structural and mechanical engineers need to redesign again and again in terms of their discipline in order to follow with the architecture until the owners' satisfaction is reached". Furthermore, he explained about how the current design review process was performed: "we use SketchUp and BIM authoring tools for the design and review, but in my opinion, it really takes time to make everyone understand the same thing because we have to coordinate and communicate a lot. For example, if we discuss about one problem regarding the pump in the building, so we need to talk to the architects and engineers by calling for meeting. We usually do a process called drawing combination meeting, and we do it many times during drawing development in order to make changes according to the architects until the owners satisfy with the architectural design—the beauty of their buildings". He continued to state that "I totally guarantee that the developed application will give benefits. For example, my assistant takes many times to call everyone to send the drawings and make a consensus decision on just one problem since my current project is at Prachuap Khiri Khan province, the designers is at Chiang Mai province and the owner is in Bangkok (3 different locations and far from each other). Moreover, it takes so much time to arrange one face-to face design review meeting in Bangkok, and it is so difficult to make all disciplines come to a design consensus". Finally, he preferred the developed application since it was user-friendly and fast to launch without any installation. In terms of functionalities, he mentioned that the demo application provided sufficient functionalities for the collaborative design review process because the other functionalities were not highly required to check the preliminary design. As a result, his feedback regarding the developed application really benefited the research, and he believed that the developed application could provide more effective collaboration to the project participants in terms of the design review process and distant barrier.

Figure 3.5 A demo of the developed multiuser application tested by Asst. Prof. Dr. Rathavoot Ruthankoon and Assoc. Prof. Dr. Kriengsak Panuwatwanich.

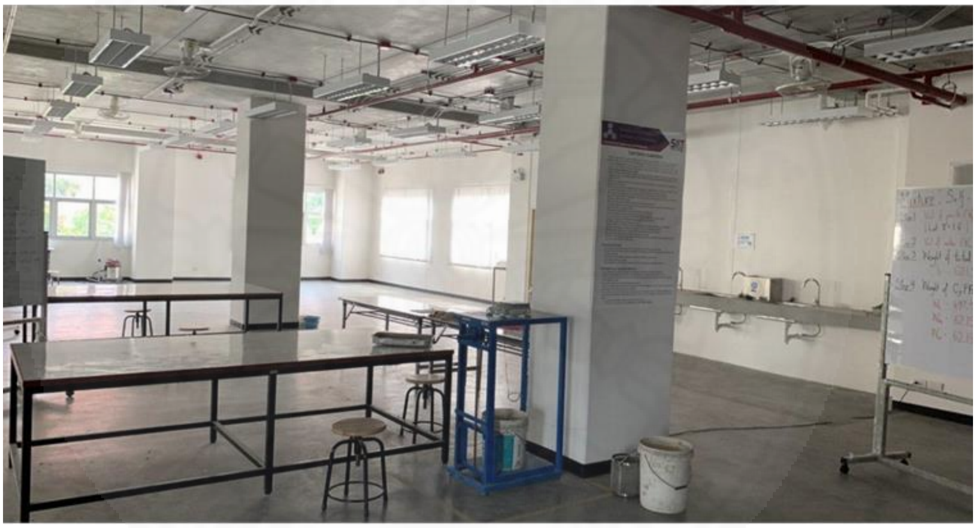
Figure 3.6 An interview with Asst. Prof. Dr. Rathavoot Ruthankoon after testing the demo application.

3.1.5 Task 5: testing and assessment of the developed application

This task was conducted to achieve the **third research objective** (to investigate the applicability and performance of the developed approach whether it can be adopted and incorporated into the design review process through enhanced collaboration). In order to prove the applicability of the developed application through enhanced collaboration due to human-human interaction in VR, the comparative advantage was tested between the immersive VR experience and the non-immersive VR experience in terms of realtime collaboration on building inspection task, and the experiment was focused on the performance enhancement of the design review before the building inspection task from the capability of bringing inspectors into the same immersive environment and allowing face-to-face conversation. There were 2 conditions being focused in the experiment including remoteness and realtime collaboration, so the two users of both groups have to stay at separate places and simultaneously perform the design review. In the experiment, there were 21 places intentionally changed in the virtual model of the Civil Engineering Laboratory in order to let the subjects collaboratively inspect the discrepancies after examining both the virtual model on both platforms (immersive and non-immersive) and the real site. The discrepancies were clustered into 3 categories including architectural discrepancies, structural discrepancies, and interior discrepancies. Table 3.1 shows discrepancy list for these three categories. Figure 3.8 shows the discrepancies on 2D drawings between a real drawing and an error drawing. Deliberately, the building inspection task was separated into 2 zones—zone A and B (as shown in Figure 3.8) for data analysis and results because the author wants to examine whether there is any difference between both results by comparing these 2 zones and combined results where zone A is more complex and bigger than zone B in terms of component quantity (doors, windows and columns), location of components and total area (about 465 square meters for zone A and 220 square meters for zone B). For example, there are totally 14 windows in Zone A, whereas zone B has only 7 windows. Therefore, both zones have different configurations, and it is more difficult and takes more ability to memorize and detect all the errors for zone A than zone B.



(a)



(b)

Figure 3.7 The non-immersive experience: (a) the virtual model of civil engineering lab and (b) the real site of civil engineering lab.

Table 3.1 The discrepancy list of the three categories.

Architectural Discrepancies		Structural Discrepancies		Interior Discrepancies	
1	Miss a window	10	Wrong type of column	20	Wrong window
2	Mistake door for window	11	Miss a column	21	Wrong window
3	Miss a door	12	Miss a column		
4	Miss a window	13	Wrong type of column		
5	Miss a door	14	Extra column		
6	Miss a washbasin	15	Extra column		
7	Miss a window	16	Miss a column		
8	Miss a window	17	Miss a column		
9	Miss a window	18	Extra column		
		19	Wrong position of column		

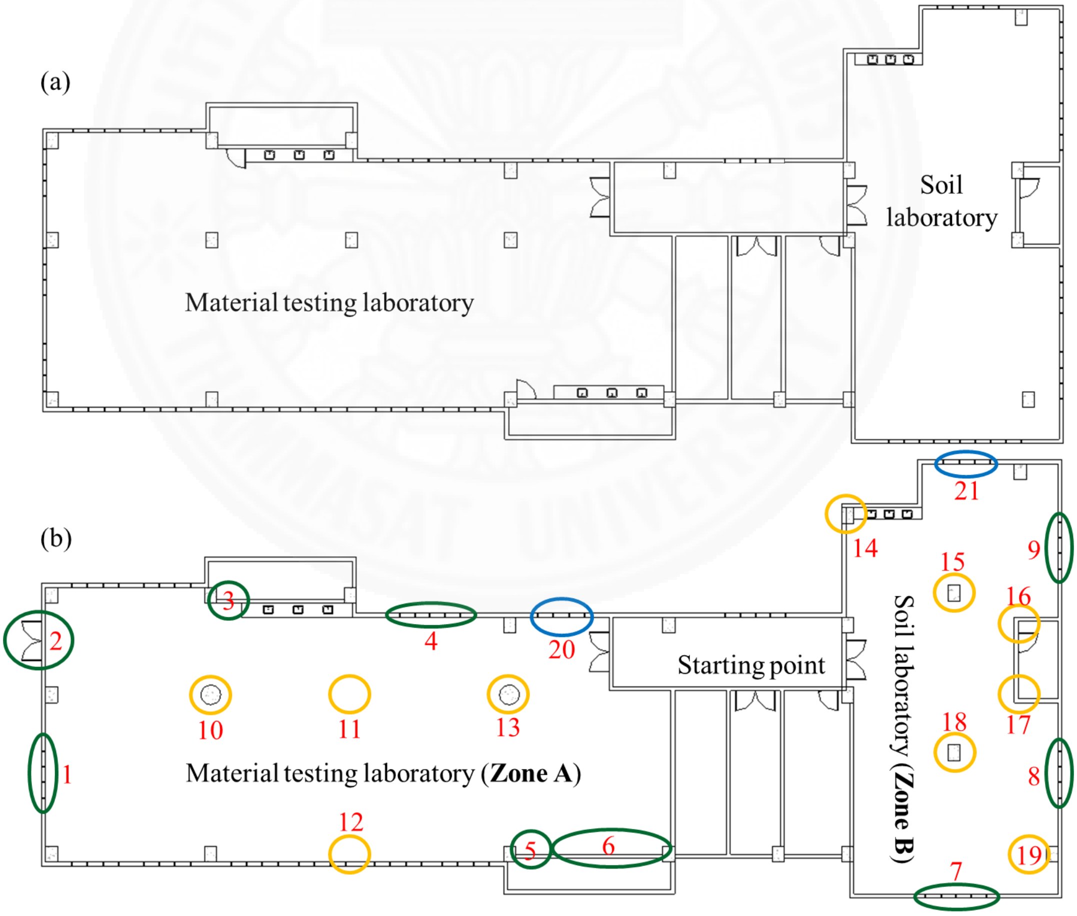


Figure 3.8 The 2D drawings of the Civil Engineering Laboratory: (a) the correct floorplan and (b) the error floorplan.

Figure 3.9 shows workflow of the building inspection experiment. There were 4 sessions in this building inspection experiment, and they are elaborated as follows:

1. Recruitment session: 44 undergraduate and graduate student were recruited through "request for volunteer", so the sampling could be classified as convenient sampling. Furthermore, the subjects were divided into two groups—the immersive group of two students (n=22), and the non-immersive group of two students (n=22).
2. Training session (10-15 minutes): all the students must familiarize themselves with the provided platform depending on which group they were assigned randomly (immersive or non-immersive). They were also given instructions regarding the tasks to be conducted and types of discrepancy they expect. They were allocated enough time to practice how to use both platforms.
    a. Immersive group was provided with a shared immersive environment, real presence of the connected partner including name tag, laser gun tool and navigation feature, and the built-in realtime talking system, so they can see each other, exchange information via face-to-face conversation and use the laser to point at where they want their partner to pay attention on. All operations were controlled by using HTC Vive controllers and headset.
    b. Non-immersive group was provided with Revit navigation tools to view the virtual model, the aid of Skype sharing screen feature and Skype built-in realtime talking system for communication. All operations were controlled by using a keyboard and mouse.
3. Review session (5 minutes): both groups had limited time (five minutes was limited for the review session as some participants may feel sickness—nausea, headache, dizziness and lightheaded, for 10 min or more in the VR environment based on the previous studies) to review and memorize the layout and details of the building. The training session and the review session were conducted in the Artificial Intelligence (AI) Laboratory of SIIT main building because it has separated rooms which allowed the subjects to remotely collaborate on the review. After reviewing the virtual model, both

groups had to walk from the AI Laboratory to the third floor of SIIT advanced Laboratory building which took about 1 to 2 minutes.

4. Building inspection session (15 minutes): after 5 minutes review session, both groups were immediately asked to go to the real site of the CET Laboratory located on the third floor of the building. The goal of both groups was to identify as many discrepancies as they could with the given time in a collaborative manner, based on memory from the review session (from what they saw in the virtual model), and they were allowed to communicate while inspecting the discrepancies in the real site, but without looking at the 3D model. Their performance was compared; therefore, the effective number of discrepancies they discovered was evaluated. Moreover, to prevent random guessing during the inspection, both groups were told that there was a point penalty if they identified an incorrect discrepancy. That is, their effective number of discrepancies will be deduced for every incorrect identification they make. As a result, the subjects will carefully identify what they are clear based on their memory.

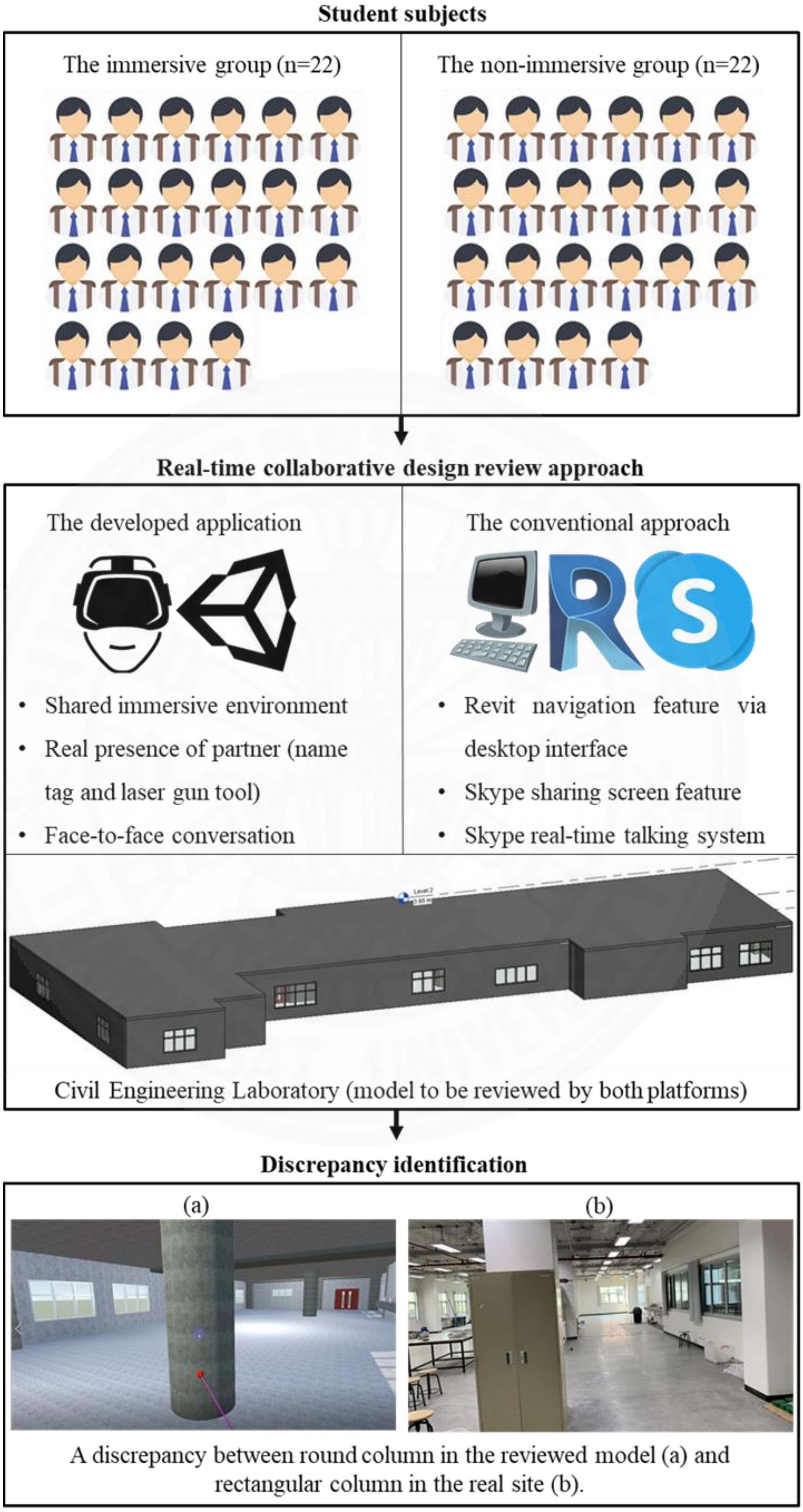


Figure 3.9 Workflow of testing and assessing the developed application in the building inspection experiment.

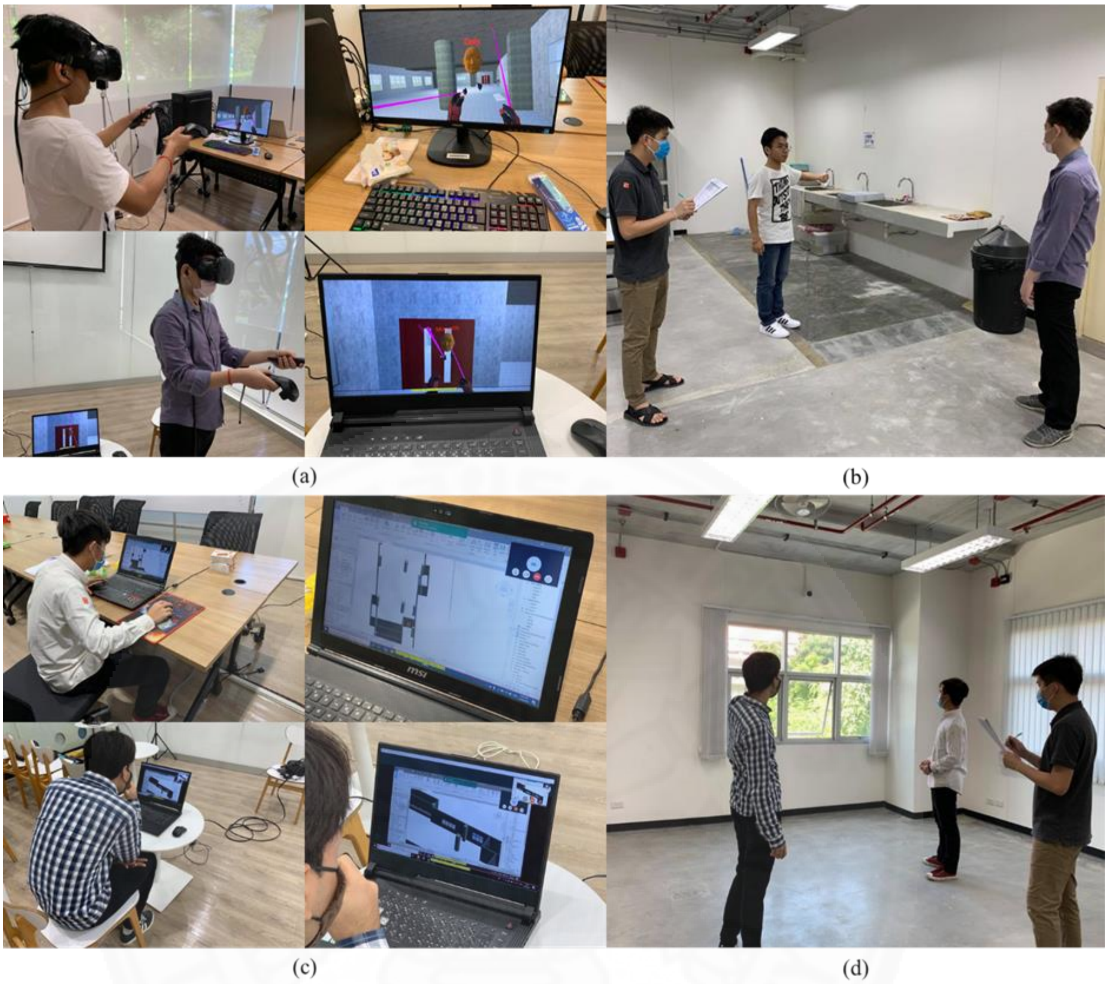


Figure 3.10 Building inspection experiment activities (a) the immersive group in review session; (b) the immersive group in building inspection session; (c) the non-immersive group in review session; (d) the non-immersive group in building inspection session.

3.1.6 Task 6: research results for research papers and a thesis

This task was conducted to achieve the **third research objective** and allowed the researchers to compile and communicate their relevant knowledge and the research results obtained from completing the previous tasks through a thesis or publications.

Figure 3.11 illustrates the summary of research procedures conducted in this research study.

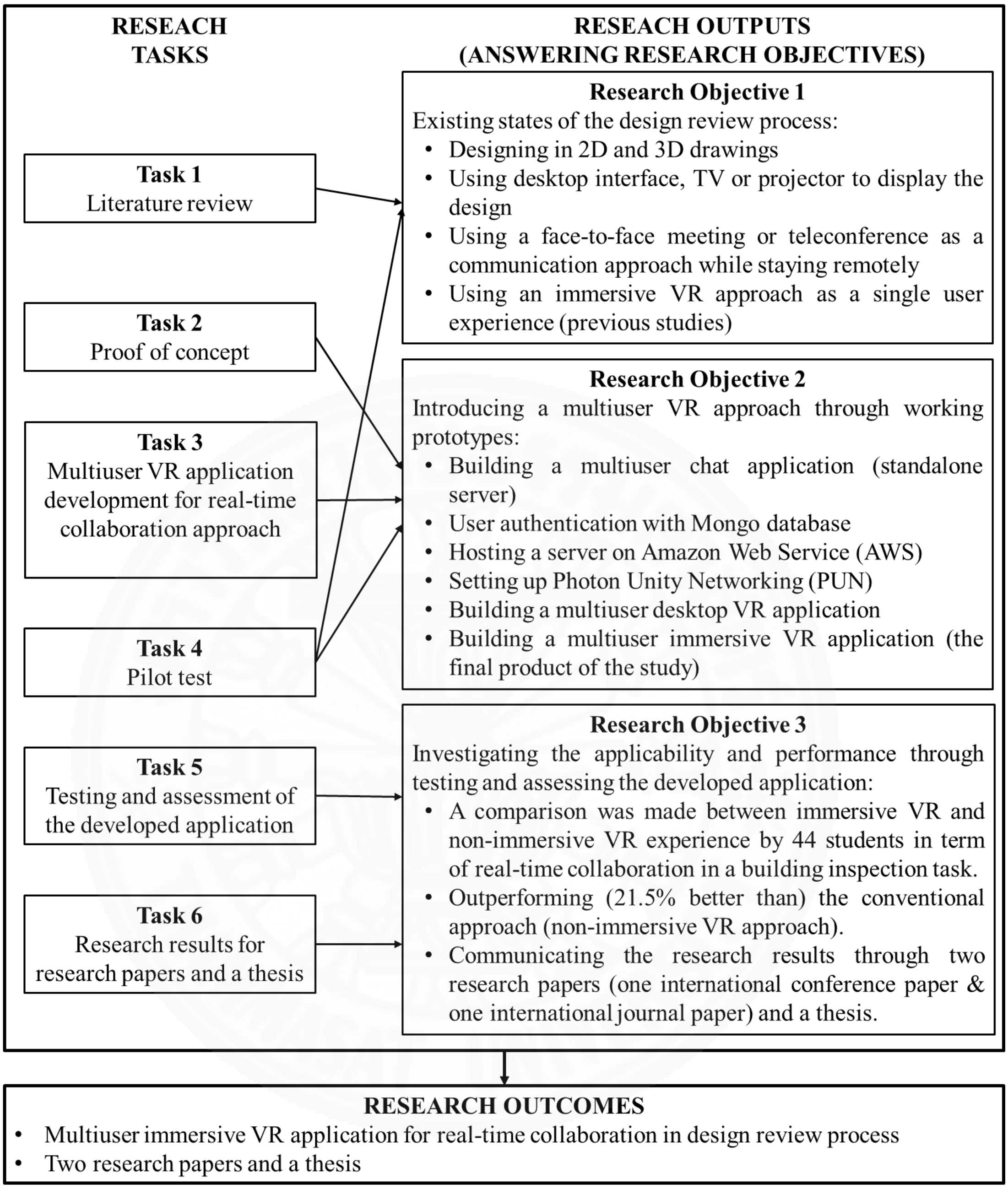


Figure 3.11 Summary of research procedures.

3.2 Research settings

The following settings were taken for conducting the research tasks in terms of the pilot test and the building inspection experiment (review session and inspection session) throughout the research period:

1. The pilot test was conducted at the school of CET office (on the third floor of the main building) located at the main campus of SIIT, Thammasat University (TU).
2. The review session of the building inspection experiment was conducted at the AI Laboratory (on the ground floor of the main building) located at the main campus of SIIT, TU.
3. The building inspection session was conducted at the SIIT Advanced Laboratory building (on the third floor) located at the main campus of SIIT, TU.

3.3 Research participants

In this research, there are two groups, which are professionals and students, being participants as described below:

1. At the early stage, Asst. Prof. Dr. Rathavoot Ruthankoon, who is a lecturer at King Mongkut's University of Technology North Bangkok, Bangkok, Thailand as well as a construction management professional, visited to the School of CET, SIIT, TU, for testing a demo application and providing feedback through an interview. He was also a representative of owners' projects, so he had experience in many construction projects and confronted many problems from the start to the end of the project.
2. Besides, a group of professionals from National Science and Technology Development Agency (NSTDA) was invited to join a meeting of updating the research progress. They paid a visit to the showcase of the developed application and gave constructive feedback.
3. More significantly, 44 undergraduate and graduate students, who are inexperienced participants from the school of CET, were recruited to test and assess the final version of the developed application. The main reason they were selected was because they did not have any background knowledge regarding technical drawings as the owner do, and the author wanted to have a controlled environment of the experiment.

3.4 Research tools for design and development of multiuser VR application

In order to conduct the study, defined design and development tools such as off-the-shelf head mounted display and computing hardware, student version simulating software and programming language were required to develop the application. Furthermore, the application was developed and employed for facilitating realtime collaboration in the design review process between multidisciplinary participants; thus, an open-source cloud computing service was also needed to generate a multiuser feature. In terms of computing hardware, a MSI laptop (GP62MVR 6RF Leopard Pro) and a ASUS laptop (ROG Strix G531GU-AL060T) with graphic cards of GeForce (NVIDIA) GTX 1060 (4GB) and 1660Ti (6GB) were employed for the development of the application, and HTC Vive were used as VR headsets. Besides, several pieces of software were utilized including Unity, Microsoft Visual Studio for coding C# programing language, AutoCAD, Revit and 3ds Max in order to create 3D assets, generate the application workflow and build a complete application (.exe extension file) for the developed application. The most important tool is the networking protocol, that enables all multiuser functions for the developed application. Photon Unity Networking (PUN) was used in the study because it is one of the most famous cloud-based networking libraries in the game industry since it is open-source and easy to implement. The Photon company provides not only the real time multiplayer library, but also voice communication library which are essential for the developed application. Figure 3.12 illustrates all the research tools that were used for the development of the application.

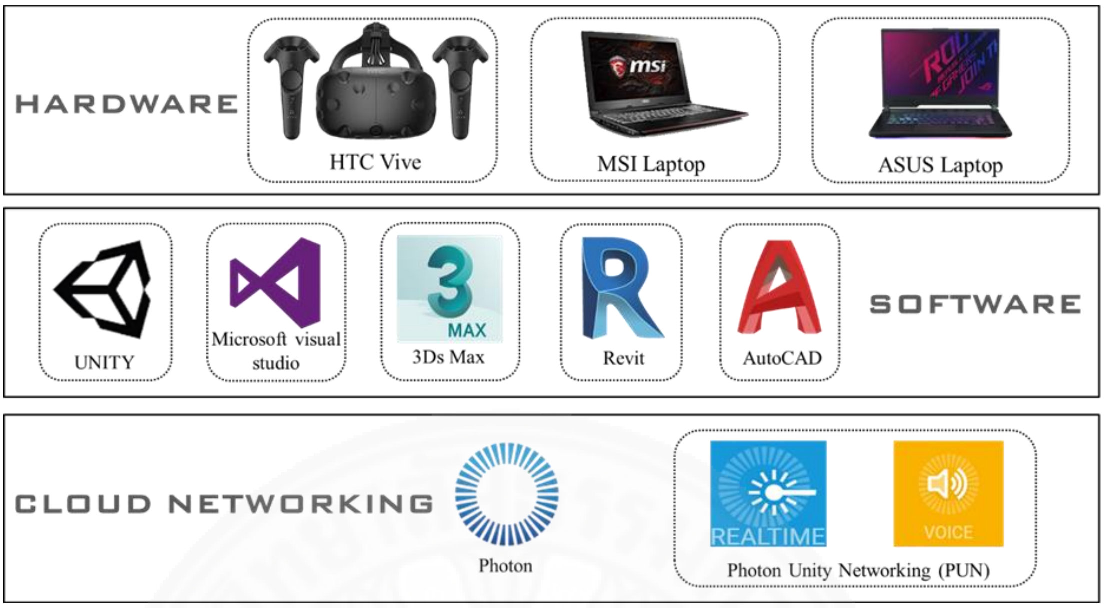


Figure 3.12 Research tools for the development of the application.

3.4.1 Software for VR prototype and application development

All VR prototypes and applications in this research were successfully designed and developed by utilizing certain student version software listed below.

3.4.1.1 Unity

The main reason of using Unity in this research is that it is a feature rich and fully integrated development engine providing out-of-the-box functionality for the creation of interactive 3D content. In particular, it is not just a cross-platform game engine for building 2D or 3D games, it is a complete platform that can be developed across mobile devices, desktops, VR or AR devices, consoles or Web. In other words, it technically supports a variety of platforms which allow developers to be able to design and develop a variety of applications. Unity is also highly recommended by many industries. Practically, it is currently used in many fields, namely architecture, art, children's applications, information management, education, entertainment, marketing, medical, military, physical installations, simulations, training, so on and so forth. In this research, all versions of the developed applications were designed, developed and built by Unity (shown in Figure 3.13) using two main platforms: desktop VR and immersive VR.

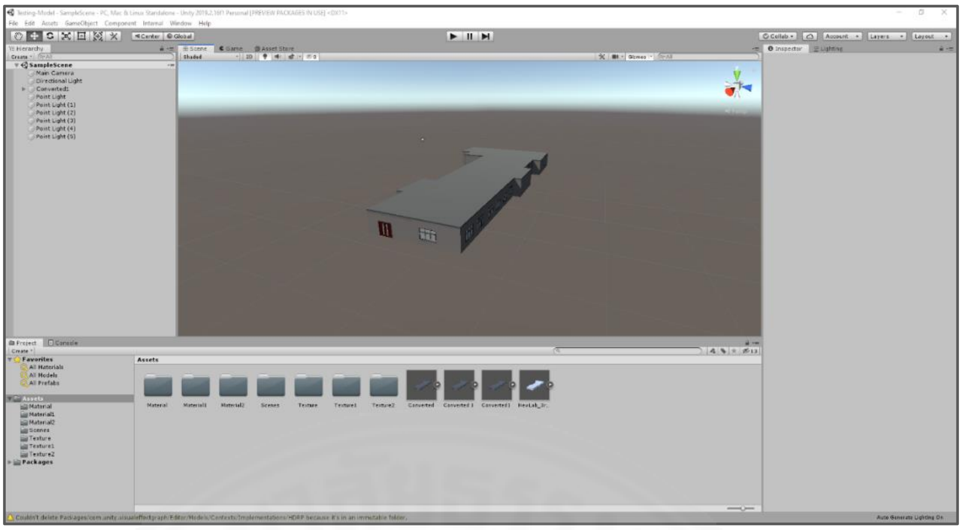


Figure 3.13 Unity software version 2019.2.16f1.

3.4.1.2 Microsoft Visual Studio

Microsoft Visual Studio is an Integrated Development Environment (IDE) from Microsoft. It is generally used to develop console and Graphical User Interface (GUI) applications along with Windows Forms applications, web sites, web applications, and web services. In this study, it was used to write C Sharp (C#) scripts to generate the functionalities and interface of the developed application (as shown in Figure 3.14).

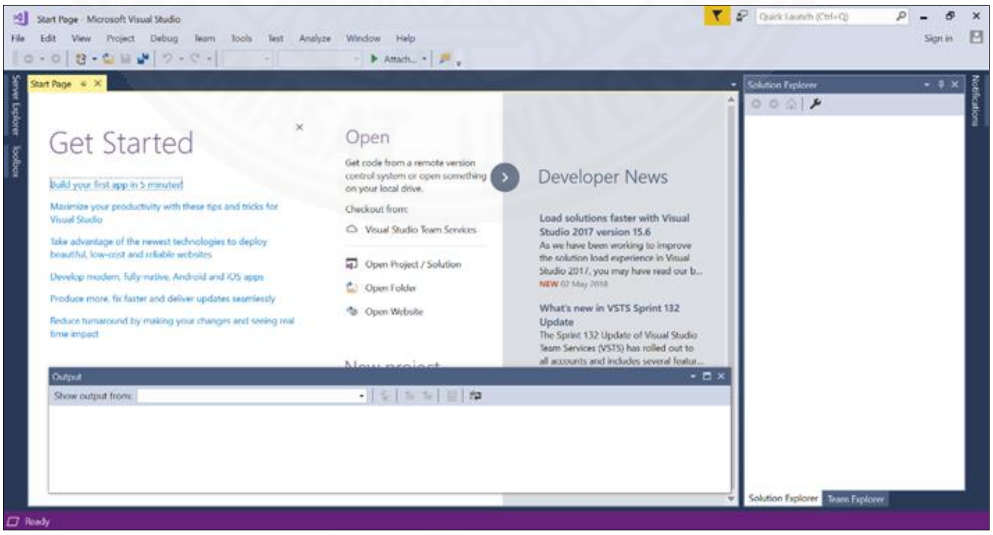


Figure 3.14 Microsoft visual studio Enterprise 2017.

3.4.1.3 Autodesk AutoCAD

A student version of Autodesk AutoCAD (as shown in Figure 3.15) was used in this research study to view the 2D drawings of the Laboratory and modify for the discrepancies. The final 2D or technical drawings were imported to 3D modeling software (Autodesk Revit) to produce a complete 3D model for conducting the research experiment.

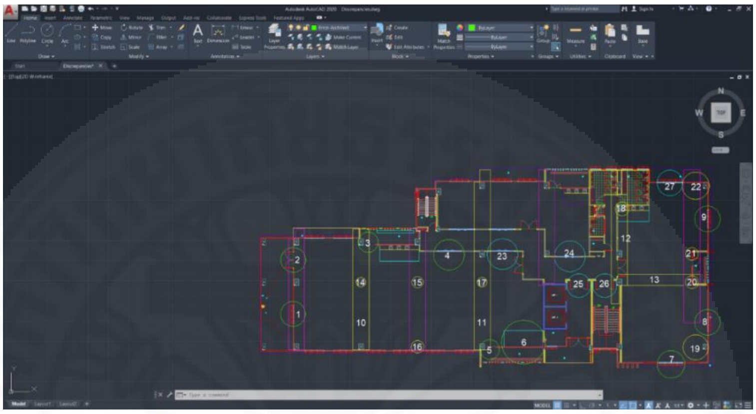


Figure 3.15 Autodesk AutoCAD 2020— Education license.

3.4.1.4 Autodesk Revit

A student version of Autodesk Revit was used in this research to create a 3D model for the third floor of the SIIT Advanced Laboratory building (as shown in Figure 3.16). The model needed to be modified to be different from the real site for the review session in order to let the users of the developed application review the model and identify the discrepancies in the building inspection session.

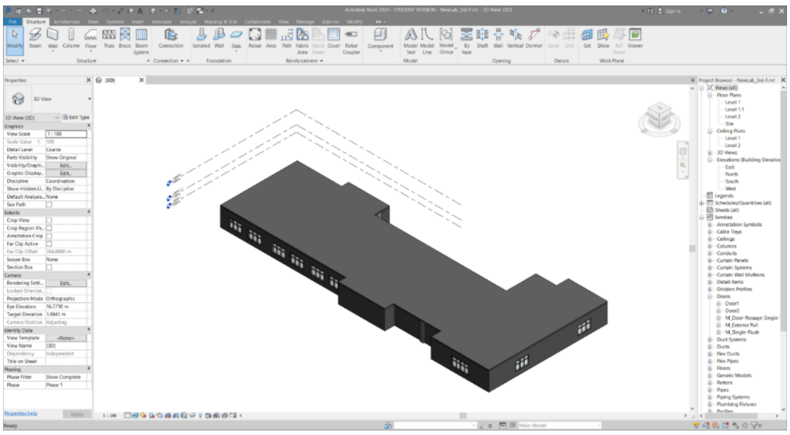


Figure 3.16 Autodesk Revit 2020—Education license.

3.4.1.5 Autodesk 3ds Max

The student version of Autodesk 3ds Max was used in this research to facilitate material translation for better utilizing in the game engine. Currently, most game engines can interpret geometric data compressed by the BIM modeling software, yet few can reproduce BIM authoring materials. Therefore, direct import of FBX file from Revit to Unity induces the loss of original materials and textures that were already generated in the Revit, and all elements totally turn to grey color. As a result, 3ds Max is a good solution to deal with the technical problem by converting Autodesk materials to the standard materials (as shown in Figure 3.17) that the game engine can capture. Furthermore, the standard materials are more user friendly for editing material and lighting in the Unity engine.

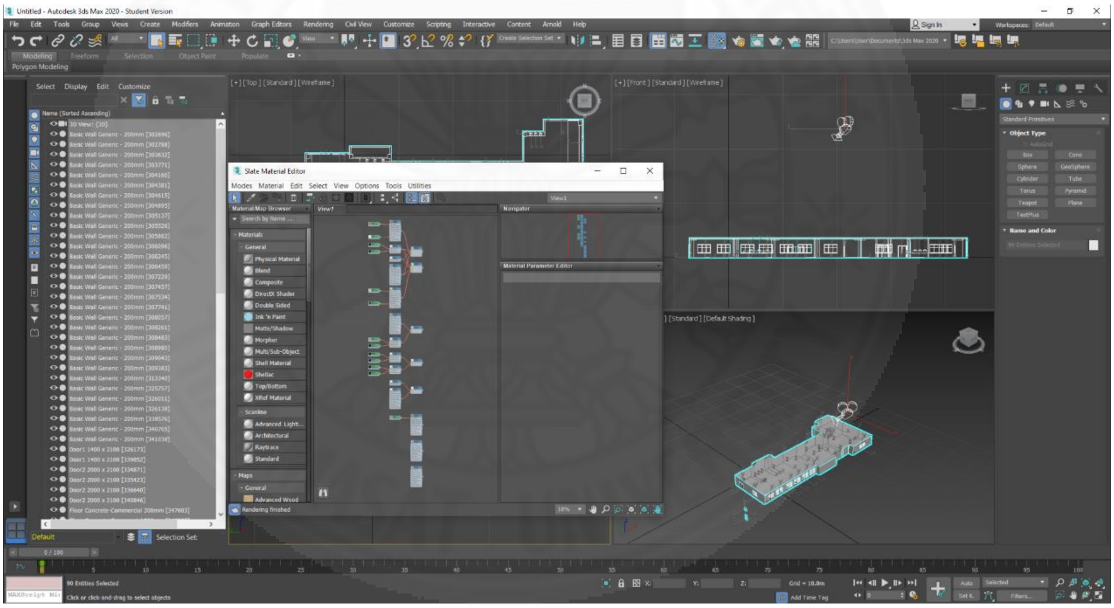


Figure 3.17 Autodesk 3ds Max 2020—Education license.

3.4.2 Hardware

In this study, certain hardware used in the design and development of VR prototypes and applications are a wearable headset called “HTC Vive” (the first generation shown in **Error! Reference source not found.**) which was utilized to deploy the fully-developed multiuser VR applications and simultaneously to create a collaborative working environment for the users, and a gaming laptop running

Windows 10 Education which was also used to develop the VR prototypes and applications.

3.4.3 Programming language

To enable all functionalities and interactions, the programming language used in all VR prototypes and all versions of the developed applications is "C#" developed by Microsoft.

3.4.4 Photon cloud computing service

Photon was used to host a server for the developed application in terms of the multiuser feature and verbal communication. The service that was used in this research was Photon Unity Networking (PUN). PUN is a Unity package for multiplayer games provided by Photon Company. It is one of the most famous networking libraries in the game industry since it is open-source and easy to implement. The company provides not only the real time multiplayer plugin, but also voice communication plugin (as shown in Figure 3.18) which are very necessary for the developed application. The company provided a free usage for all users under a condition of 20 concurrent users meaning 20 connections at the same time. Therefore, this free trial was sufficient for conducting this study.

Figure 3.18 REALTIME multiplayer plugin and VOICE communication plugin of PUN.

CHAPTER 4
MULTIUSER VR APPLICATION DEVELOPMENT

This chapter presents how the multiuser VR application was successfully developed in terms of 3D asset creation, the setup of networking protocol and the multiuser functions. The extensive and critical review of previous studies and literatures pertinent to VR technology could provide the research gap as well as a practical solution to the current traditional approach after the pilot test (as shown in Figure 4.1).

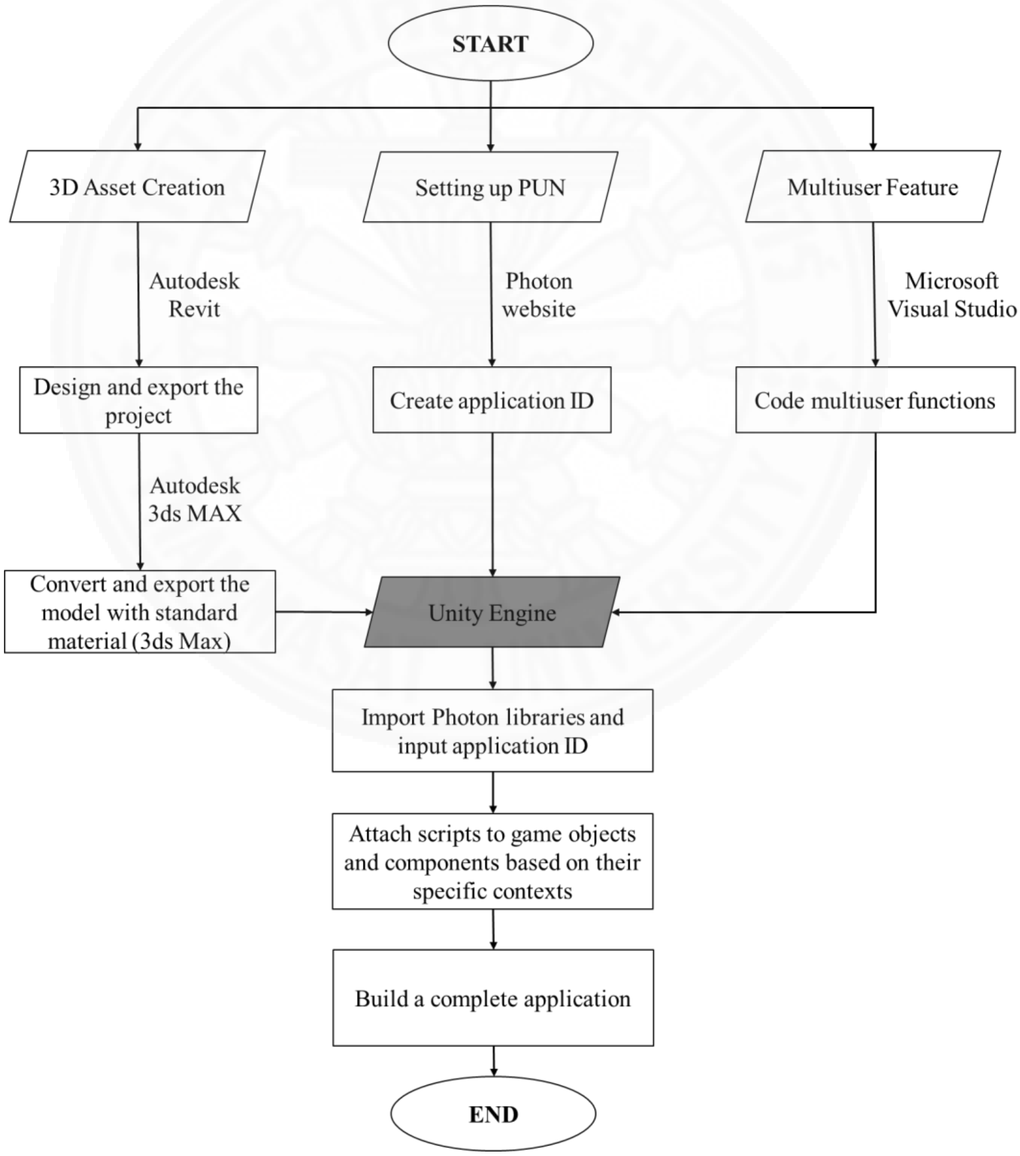


Figure 4.1 Development flowchart of the proposed application.

4.1 3D asset creation

3D asset creation is one phase starting from modeling the virtual project to the complete virtual project in the Unity engine for setting up the concurrent scene, so the project participants, particularly owners could feel and sense their real projects before construction. Furthermore, the designers have a chance to effectively review and discuss about the project in the VR environment by using VR headset. In this research, the Civil Engineering Laboratory was used as a 3D model to simulate the whole process of the design review as well as to know the performance of the review process by inspecting the real site in order to look for the discrepancies that were intentionally placed in the virtual model. The 2D drawings were provided by the facility manager of SIIT, and it would be easy to generate the 3D model from those drawings. The whole process of this phase is elaborated as follows:

- The 2D drawing of the Civil Engineering Laboratory was modified in AutoCAD software to generate the discrepancies for the experiment.
- The modified drawing was imported to Revit software to model the complete 3D drawing including the real materials and textures to match with the real site. After finishing the model, the project was exported as Filmbox extension (.fbx) with the default setting of Autodesk material.
- The exported file was then imported to 3ds Max software to convert all Autodesk materials to the standard materials by using standard material preset which are user-friendly and supported in the Unity (as shown in Figure 4.2). After finishing the converting process, the project was exported as .fbx with the setting of standard material. Although Unity game engine supports .fbx file, this step is necessary because directly importing .fbx file to Unity will induce the loss of material and texture information, resulting in the model turning into grey color (as shown in Figure 4.3).
- The converted file was finally imported to the Unity as an asset that can be used for the construction of the virtual environment and other features.

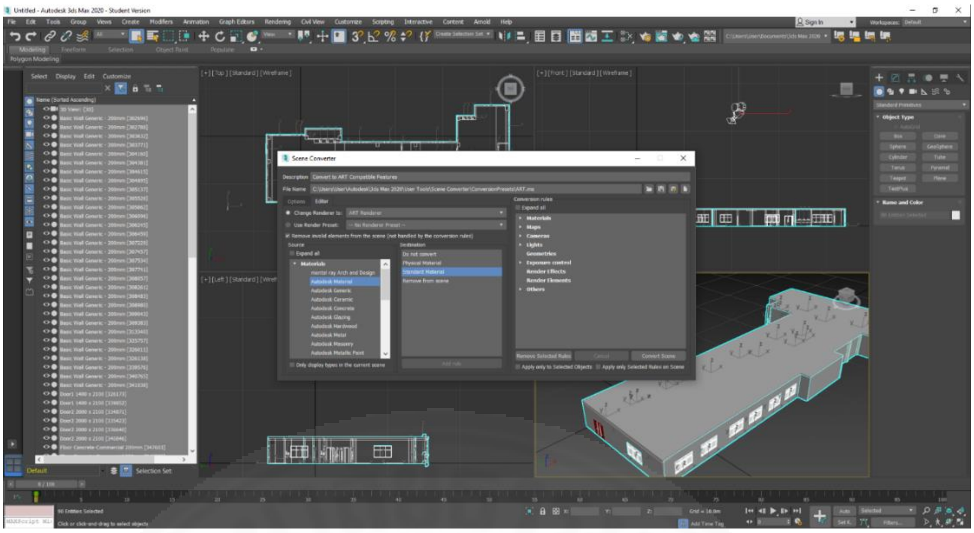


Figure 4.2 The process of converting Autodesk materials to the standard materials.

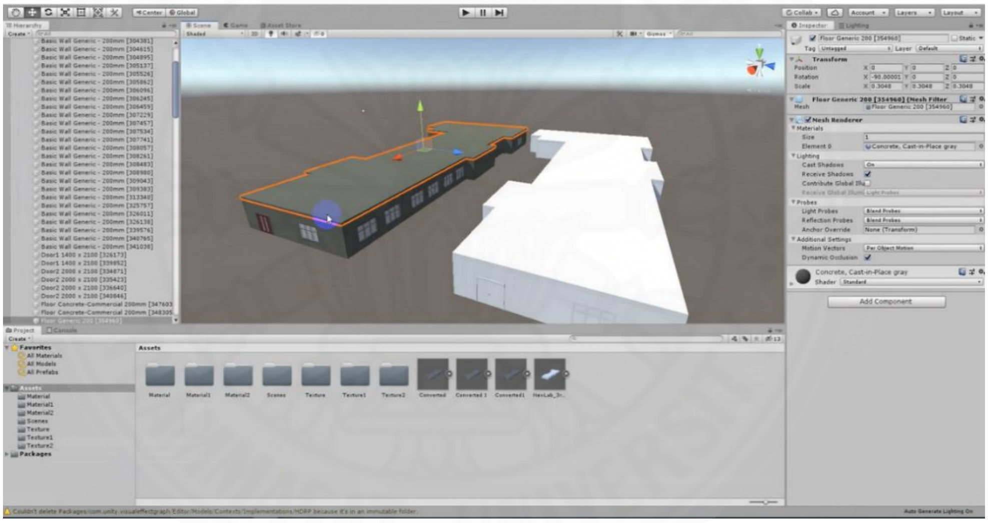


Figure 4.3 Importing the model with standard materials (left) and with default Autodesk materials (right).

4.2 Setting up the networking protocol

The most important construct in the application development is the networking protocol because it enables the multiuser feature for the application. In this research, PUN was chosen for the development of the application since it provides fast synchronization with enough concurrent users for conducting the experiment. In addition, there is no risk of cyber-attack because Photon does not require users to host their own server, and the master server is provided to every user. In order to connect to the master server of Photon and enable multiuser functions, there are steps for setting up the PUN:

1. Create application ID on the Photon website. The developed application needs both realtime multiuser and voice communication libraries; thus creating 2 application IDs (as shown in Figure 4.4).
2. After getting the application ID for the required libraries, launch the Unity software and go to the Unity Asset Store in order to download both PUN and voice libraries (as shown in Figure 4.5).
3. After importing both libraries into the Unity project, go to "Photon Unity Networking" folder inside the "Assets" folder of the "Project" panel and click on the Resources "folder"; as a result, the "Inspector" panel shows the input field for adding both application IDs in order to activate connection to the master server and all multiuser functions inside the libraries (as shown in Figure 4.6).

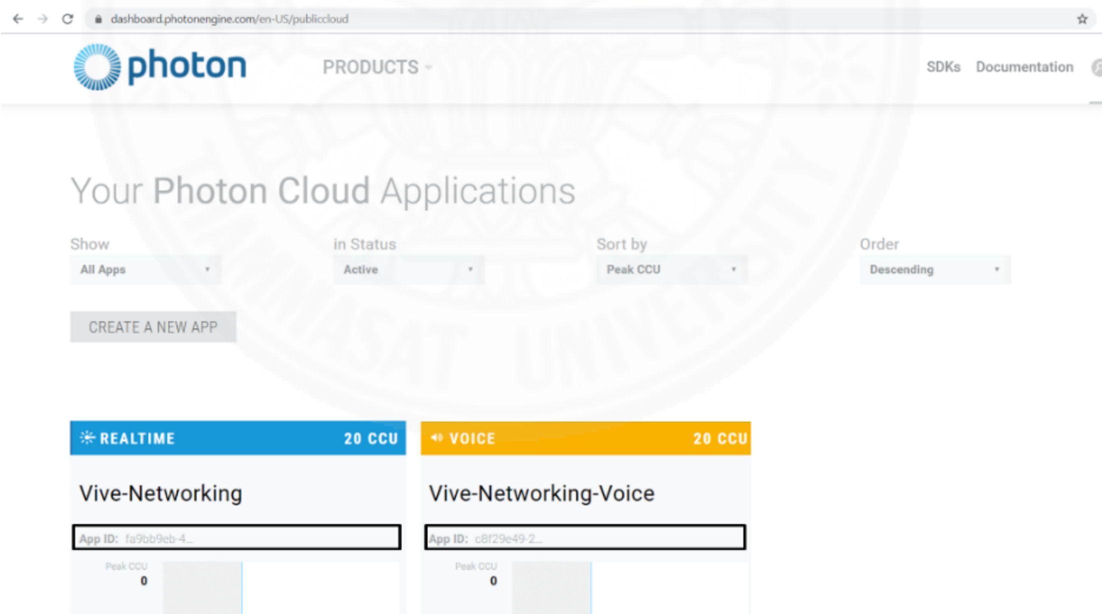


Figure 4.4 Step 1: Creating application ID on the Photon website.

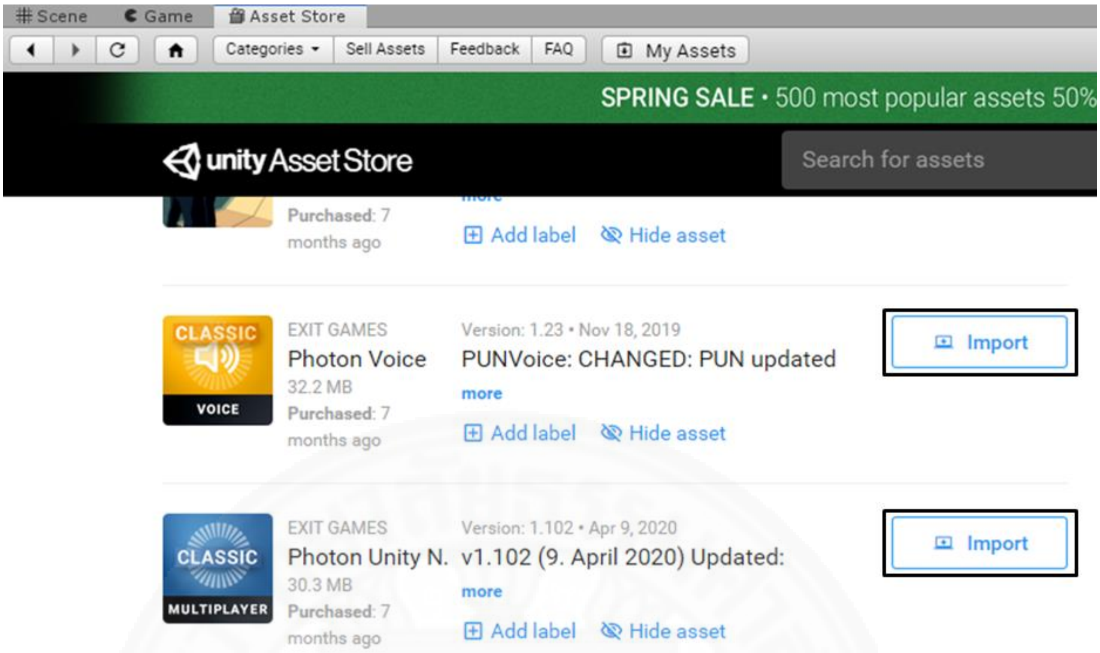


Figure 4.5 Step 2: Downloading the libraries and importing into the Unity project.

Figure 4.6 Step 3: Adding the application IDs for activation.

4.3 Multiuser functions

The multiuser functions were developed in the Unity. After importing the virtual model, the Unity can generate game objects and game components such as Physical avatar, collision, rigid bodies, and lighting environment that look similar to the real environment. The most important thing is the networking protocol that needs to be implemented into the developed application in order to allow remote connection and generate synchronizations such as view, transform, interactions and voice communication. Most of the activities in this task depend on the scripts that were attached with the game objects in order to activate the multiuser feature for all networking objects and components. The majority of the scripts were developed by the author, and the rest was modified from PUN libraries. The scripts and their functionality were used in the developed application:

- Network Manager script was used to connect to the Photon master server and create a space for all remote users to join. Besides, it handles all connections from remote users and instantiations of them.
- Photon View script was used to identify an object across the network (viewID) and configures how the controlling client updates remote instances.
- Photon Transform View script was used to help synchronize position, rotation, and scale of a “GameObject”. It also gives users many different options to make the synchronized values appear smooth, even when the data is only sending a couple of times per second. Simply add the component to “GameObject” and make sure that the Photon Transform View is added to the list of observed components.
- Photon Voice Recorder script was used to transmit audio stream. Using this component, the developer chooses what to stream (Input Audio Source), how to stream it (Audio Quality), when to start and stop transmission (Transmission Toggles) and to whom it was transmitted (Receiver Target). Also the Recorder requires initialization.
- Voice script was used to activate the Photon Voice Recorder script after instantiating a new user in order to assign recording component to that user.
- Vive Manager script was used to get access to both Vive controllers and Vive headset.
- Copy script was used to duplicate the translation and rotation of the instantiated controllers and headset as an avatar and synchronize across the networking scene.
- Vive Controller script was used to provide a navigation feature to every user

and synchronize across the network. The users can use the touch pad of the controllers for moving and headset for changing direction.

- Player Name script was used to provide a name tag to every user by showing it on the head of the avatar in the scene to allow the visual identification of users joining the same scene.
- Pointer script was used to provide a laser gun tool to every user, so the user can point to anywhere and discuss on that matter.

Figure 4.7 illustrates the development workflow of multiuser functions inside the Unity game engine for the developed application.

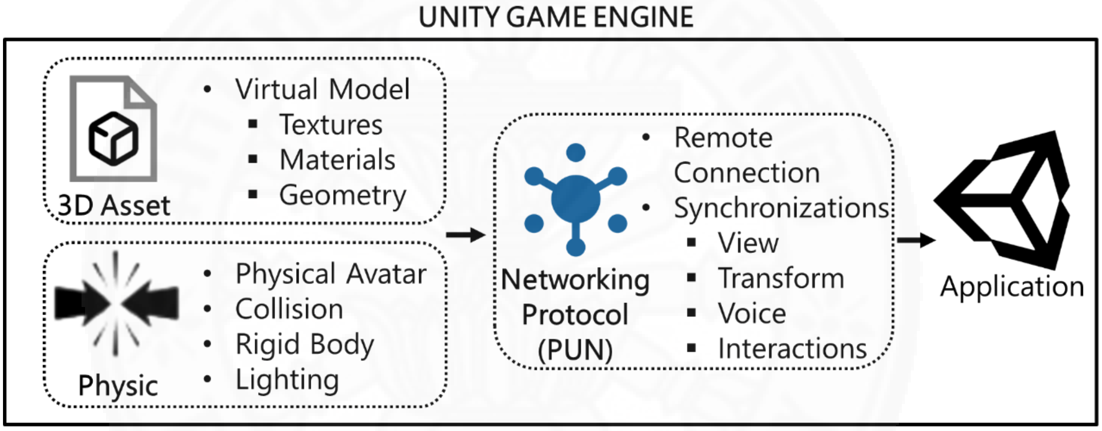


Figure 4.7 Development workflow of multiuser functions inside the Unity engine for the developed application.

4.4 Application workflow

The complete application is compatible with the immersive VR platform running on Window 10 operating system with graphic card at least GeForce GTX 1060 (MSI and ASUS in this research). In terms of the frontend, before launching the application, the user have to set up the VR devices, make sure both base stations are properly set and configure the height to be the same as the real height of the user. After that process, the user can launch the application. Then, the white canvas is shown with the input field (for username and position) and a connect button for clicking after inputting the name (as shown in Figure 4.8). When the button is clicked, the avatar of the user is instantiated into the network scene (as shown in Figure 4.9).

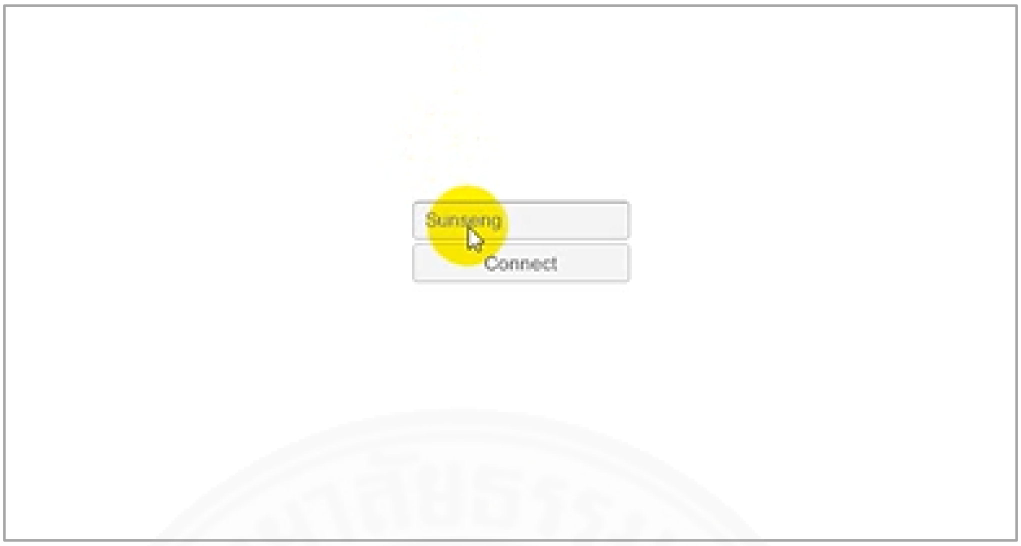


Figure 4.8 Canvas asking for username.

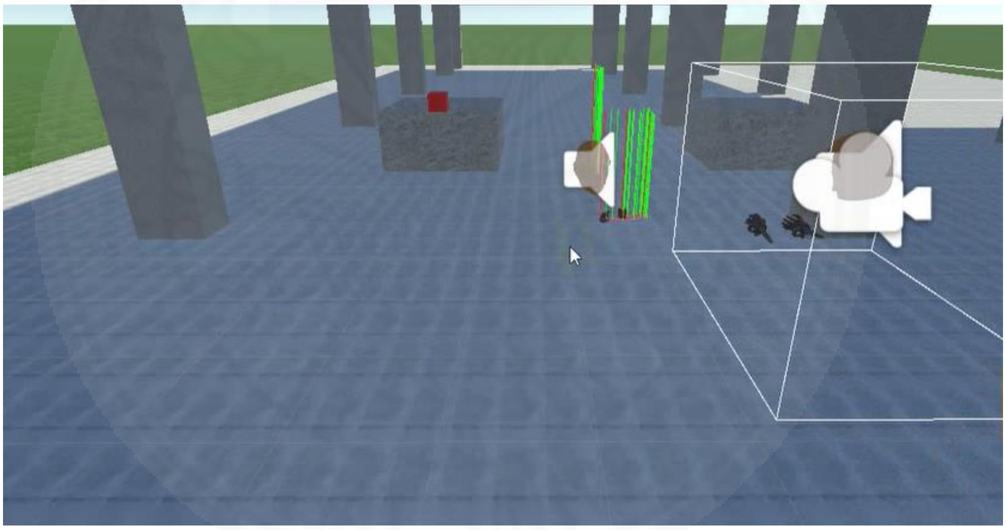


Figure 4.9 Instantiation of two users into the same network scene.

Meanwhile, in terms of the backend, the first user who launches the application will be automatically connected to the Photon master server and create the room. By using the previously mentioned Application IDs as a map to find the host in the Photon master server, every remote user can connect to the host user. After finding the room, the host user and remote user can communicate directly resulting in fast synchronization. The application transmits every executing message to all remote users in every update of the user in the network scene including movement and voice through Remote Procedure Call (RPC) and Voice Over IP (VOIP) (as shown in **Error! Reference source not found.**).

Figure 4.10 describes how current design review process is performed. First, the owners put their expectations and requirements of the project, so design professionals could produce their design by using BIM authoring tools or conventional 3D modeling software. The design in every discipline needs to be combined to reach the owners' satisfaction. Therefore, a collaborative design review process is performed, and this process would take a considerable time and many meetings if collaborative review approaches are not effective.

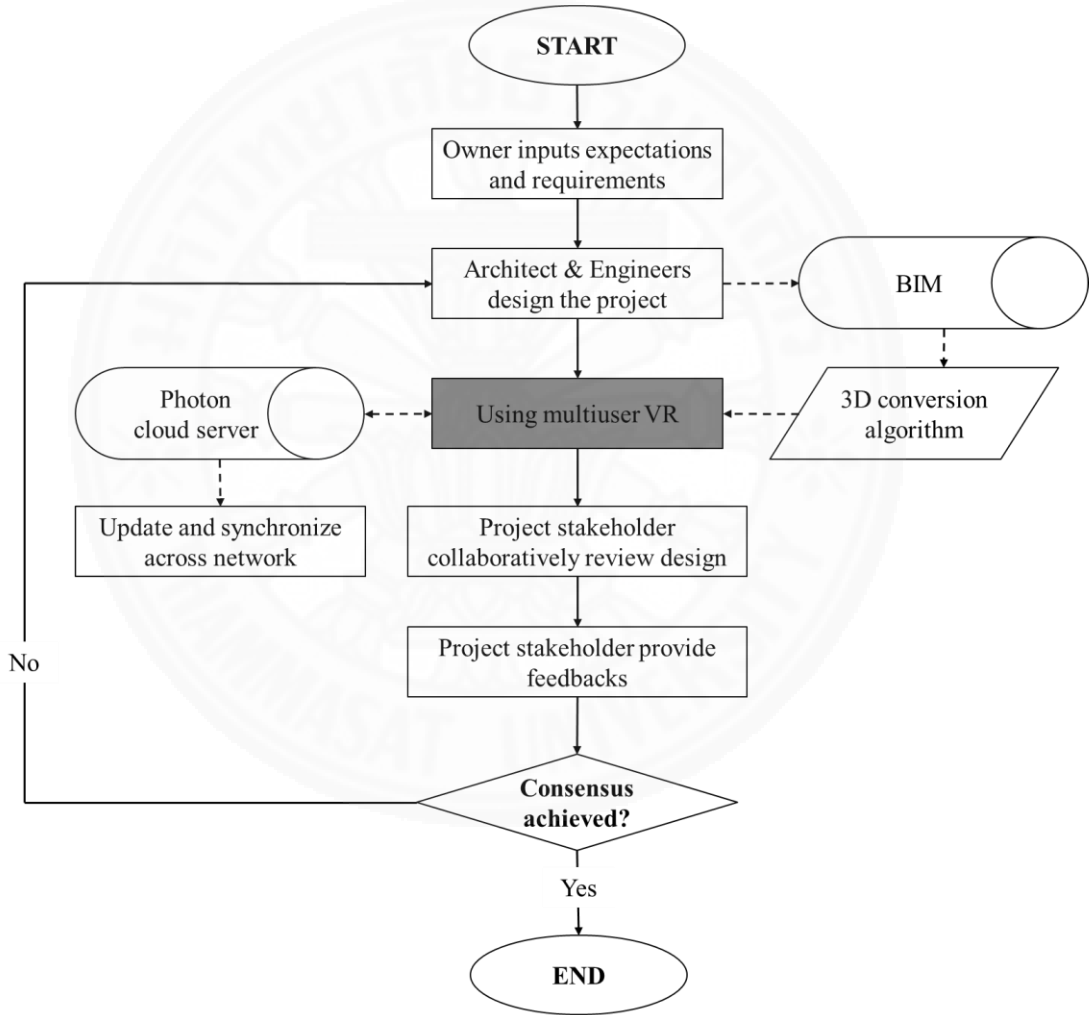


Figure 4.10 Execution flowchart of the developed application in practice.

4.5 Issues and considerations on networking protocol for application development

This section elaborately presents some issues pertinent to choosing the networking protocol that the author confronted throughout the application development phase. The developed application was first implemented with Unity networking protocol (UNet). UNet is built-in networking protocol of the Unity which also provides the developers with the same multiuser feature as PUN. As a result, a small prototype was successfully built, and it allowed remote connections and synchronization of 2D movements from players in different locations. In terms of the development workflow of UNet, two applications were built. One was the client which handled user interface and every functionality such as player view, player movement and interactions, and another one was the server which handled the networking protocol to allow communication among all connected players. In addition to this, the server application had to be hosted on Amazon Web Service (AWS) to allow remote connection from any locations. Figure 4.11 illustrates the development workflow of UNet.

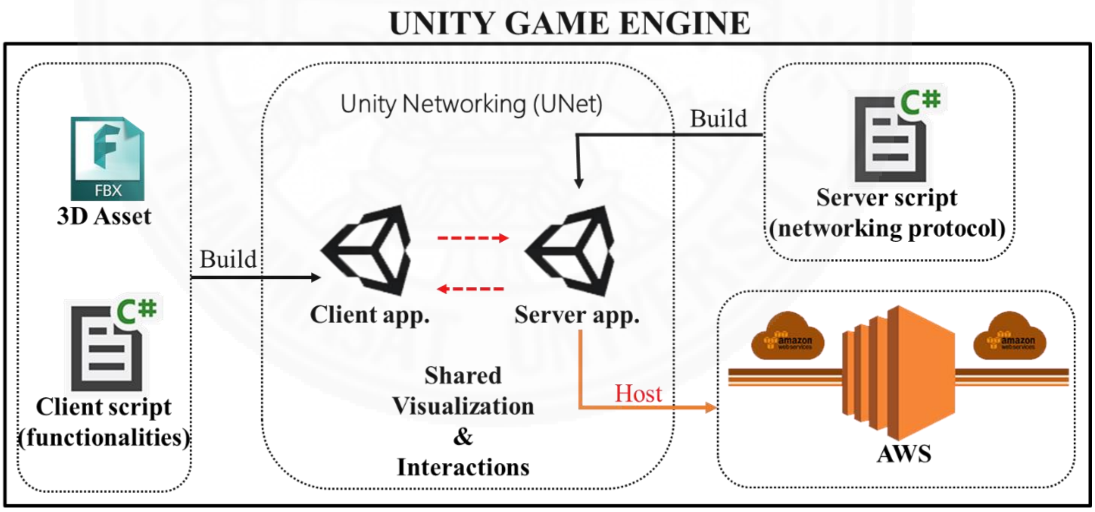


Figure 4.11 Development workflow of UNet.

During the development, there were difficulties of using UNet that took a considerable time for the implementation. For instance, server scripts had to be built to be compatible with the client application. Moreover, hosting the server on AWS required more technical skills. Although the author faced some difficulties, a small prototype was still built by following the above-mentioned procedures. However, the author found 3 problems pertinent to the workflow of the application after the implementation as described below:

4.5.1 The workflow of UNet protocol

The workflow of UNet induces the delay of the movement update or lag to every user due to its system architecture. Figure 4.12 depicts how messages are transferred between nodes in a network for Unity and for PUN.

- Unity Networking supports a server/client architecture. All messages have to go through the Host and cannot be sent directly between nodes. For example, messages transmit from client B to client C using the following path: Client B to Server to Host A to Server to Client C. As a result, the message takes a total 4 hops from source to destination.
- Whereas PUN has a similar server/client architecture, but also supports peer-to-peer sending of messages. For example, messages transmit from Client B to Client C using the following path: Client B to Server to Client C. That is a total of 2 hops compared to the 4 in Unity for the same message transferred between two nodes. In addition to this, PUN could potentially bypass the Server entirely and Client B can communicate directly with Client C, thus reducing the hops to 1. Because of this, PUN is faster than Unity.

In terms of difficulty, the server application has to be built and hosted for UNet which requires more technical skills and implementation, whereas Photon provides its own master server with the advance security and automatic configuration for every user. Furthermore, there is no technical leverage on using UNet, since every script needs to be developed for specific purposes. PUN is a library containing many build-in scripts such as Photon view and Photon transform which handle shared view and movement tracking of the connected users. Lastly, Photon provides additional features compared to Unity especially Photon Voice plugin which allows all connected users to make verbal communication.

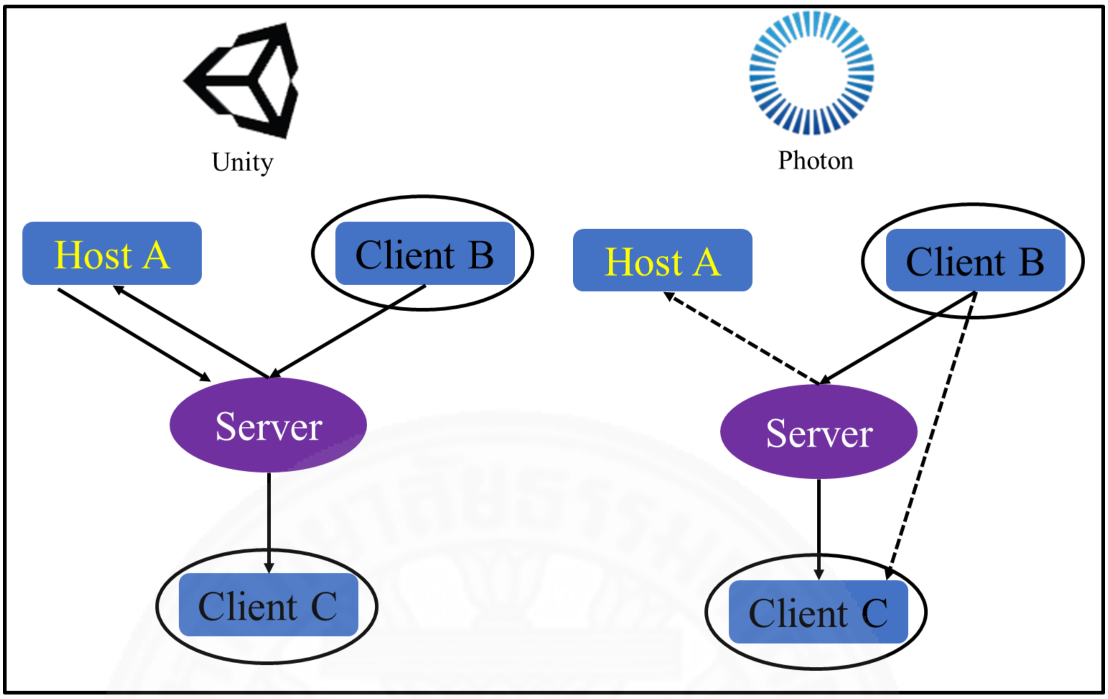


Figure 4.12 The system architecture regarding the networking protocol between Unity and Photon.

4.5.2 The workflow of AWS

The second problem is pertinent to the workflow of AWS. Every update from AWS server affects the running server which requires to rehost the server again and again because there is no automatic configuration in the developed server application (as shown in Figure 4.13). This process takes considerable time due to a frequent update of AWS server. Configuration highly demands many technical skills in coding or specialists in ICT field which goes beyond the author's ability. Additionally, this kind of work mostly is done by a group of specialists who are responsible for maintaining the server. With no assistance and limited time period of the study, it was a big obstacle for the author to conduct the study. As a result, the author made a small change by changing networking protocol from UNet to PUN since Photon does not require users to host their own server. The users only need to follow Photon's guide, and Photon will handle the server update.

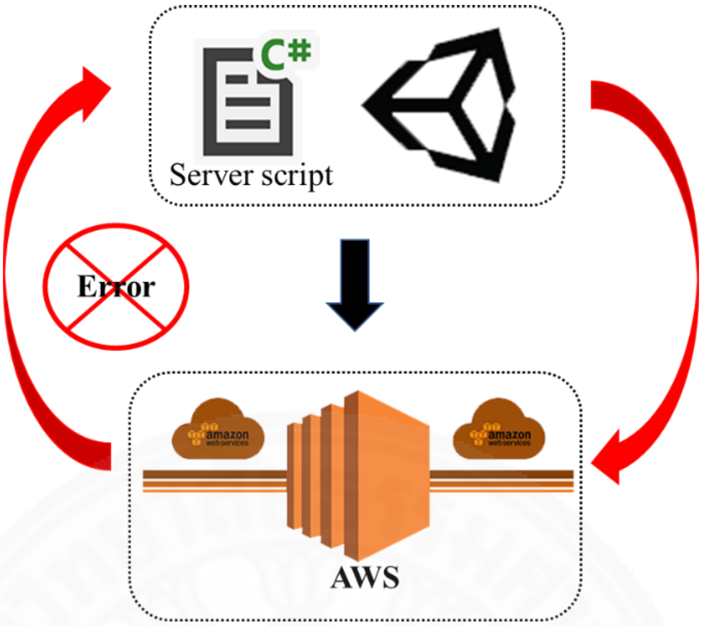


Figure 4.13 The workflow of hosting the server without automatic configuration.

4.5.3 Cyber-attack on the server

Cyber-attack is another problem since there are limited resources for conducting the study, and this kind of problem goes beyond the technical skill of the author. During the development, there were anonymous connecting to the server to host their application. As result, data transfer went beyond the allowance of the free account result in monetary charge up to 28$ (as shown in Figure 4.14).

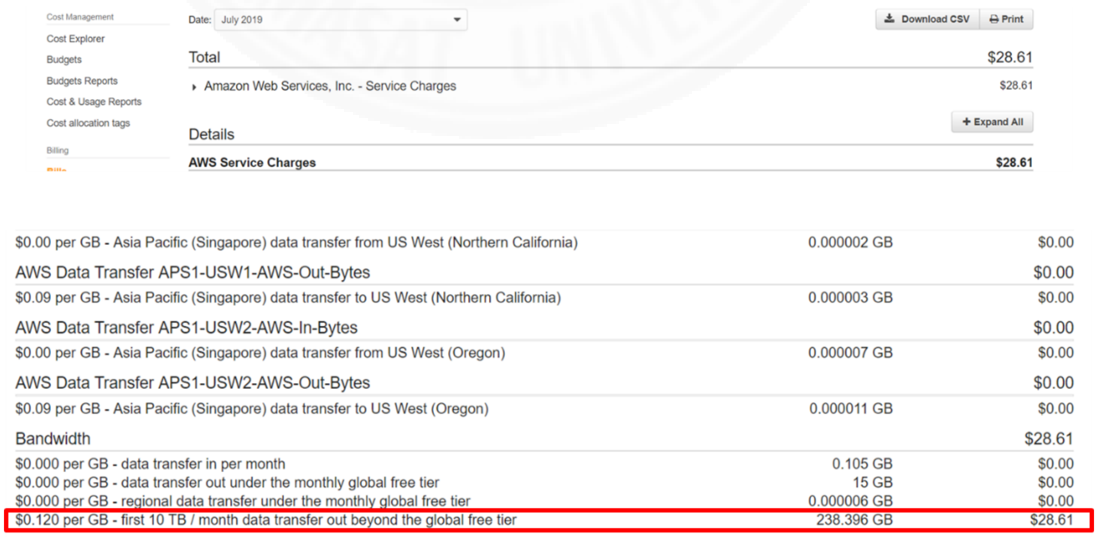


Figure 4.14 The report of monthly expense on AWS regarding the hosting server.

4.6 Application prototypes

This section presents application prototypes, mostly focusing on the experimentation of the multiuser feature and the final product of the develop application.

4.6.1 Unity and its procedures for building a VR application

Unity is a feature rich, cross-platform game development engine that is used to build 2D and 3D video games, simulations, VR and AR in any devices or even in a web browser with the different operating system. Furthermore, it provides many functionalities that support inputs, control, interactions, networking protocol, etc. Technically, there are 3 main features that are needed to build an application such as "Asset", "Scene" and "Build Settings". The "Asset" allows to store any development tools such as 3D models, plugins, scripts, etc. importing from any supported files in the machine; and the development tools can be used to build the scene by attaching the scripts into game objects for interactions, inserting the plugin to support the functionality of the buttons or controllers, etc. Besides, the "Build Settings" allows the developers to configure any target device's support, design screen size, application name, an icon as well as to choose any platforms for the target deployment.

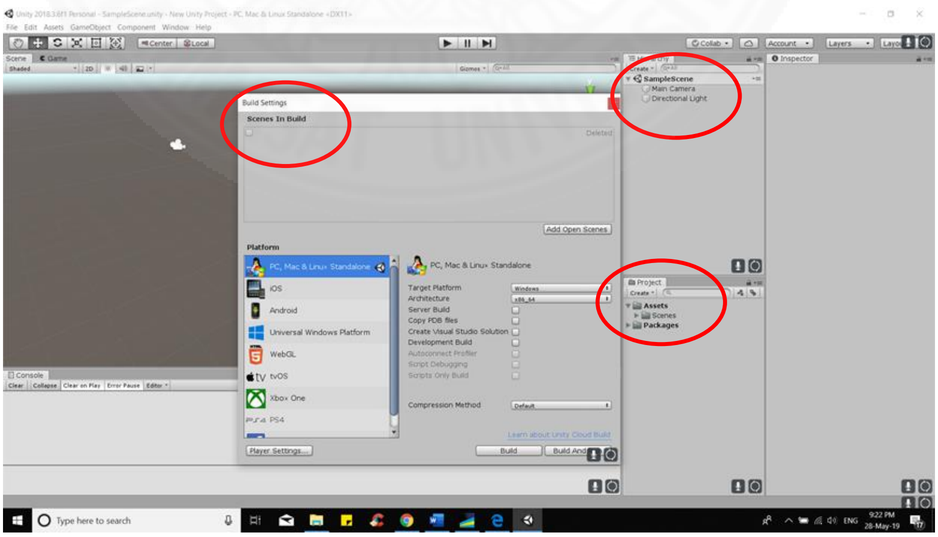


Figure 4.15 The main features and UI of Unity software.

4.6.2 Multiplayer chat application on a stand-alone server

In this application, the main purpose is to understand the networking protocol in Unity through shared messages. This application was built for allowing multiplayer chat through the inbuilt standalone server on the laptop. By running the server on the standalone machine, the users are able to connect to the server, join the assigned ID room, and chat with each other. Technically, coding networking scripts in terms of server and client via Microsoft Visual Studio is one of the most essential components in this application, and the scripts are assigned to empty game objects in the scene to process. In the scripts, server IP address (127.0.0.1—default IP in every local machine) and channel information for sending and receiving the data are important elements that were used as a map for connection between clients-server and all connected users. Apart from that, the UI of this application was simply designed by using the inbuilt tools in Unity such as panel as backgrounds and chat tables, input field as input space for inserting parameters, and button for clicking to connect. Finally, the client side was built in the Windows platform, and the server was running on the Unity Editor. By using this application, users can communicate any non-verbal information with each other via the chat table.

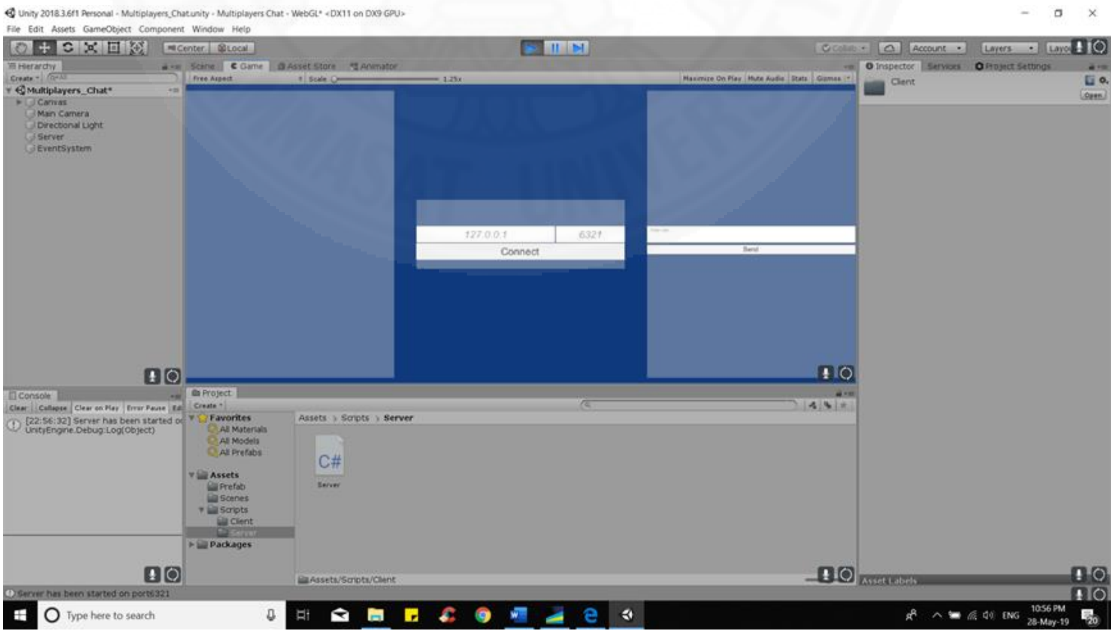


Figure 4.16 The first client side with the running server on the Unity Editor.

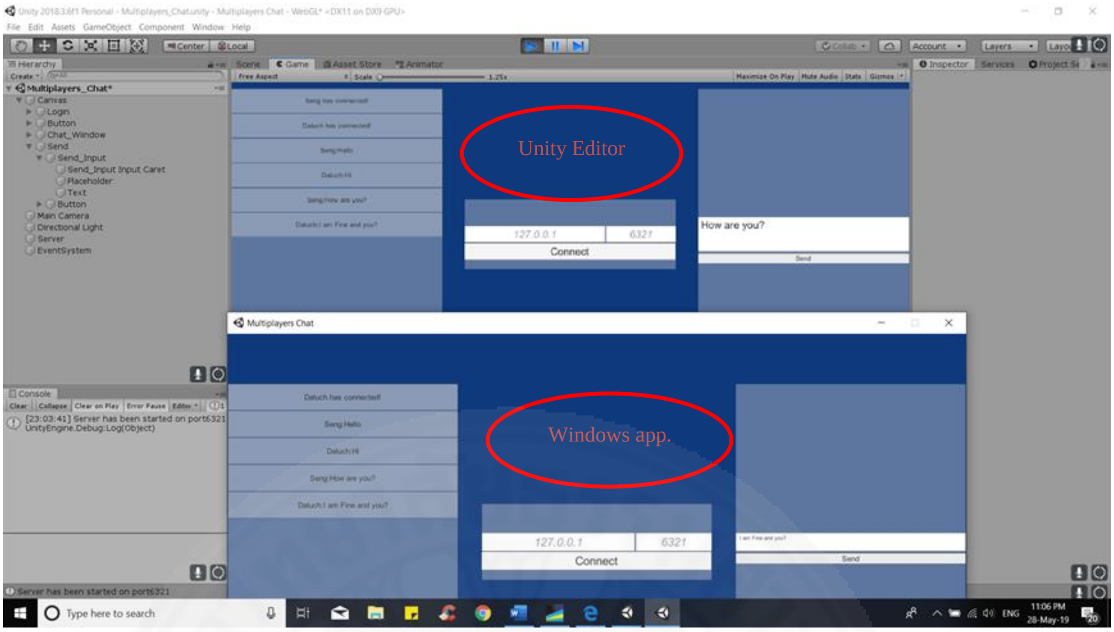


Figure 4.17 Both views of the first client (Unity Editor) and the second client (Windows application) chatting with each other.

4.6.3 User authentication with Mongo database

This application is more complicated since it is connected to a database called “MongoDB.Atlas”. It is an opensource database that allows users to store any data for the clients and use that data whenever the clients need. The purpose of this application is to connect to the database, store users’ authentication and communicate with that data. The system workflow of this application consists of three main components, namely the server, the clients and the database, and the workflow between the server and clients. It is similar to the previous application except between the server and the database because the server needs some functions for storing data and requesting data. Therefore, the providers already built some plugins such as MongoDB drivers (libraries) for configurations of their users’ connection. Moreover, the server could be linked to the database and conduct any transferring activities by adding those plugins into the Asset. In this application, the server was simultaneously running and connecting to the database. When it was done with the connection between the server and the database, the clients could connect to the server and create their authentication, and this data was sent to the database when the clients were done creating their authentication and were called back when the clients logged in with their data. After finishing these procedures, the application changed into another defined scene with another UI.

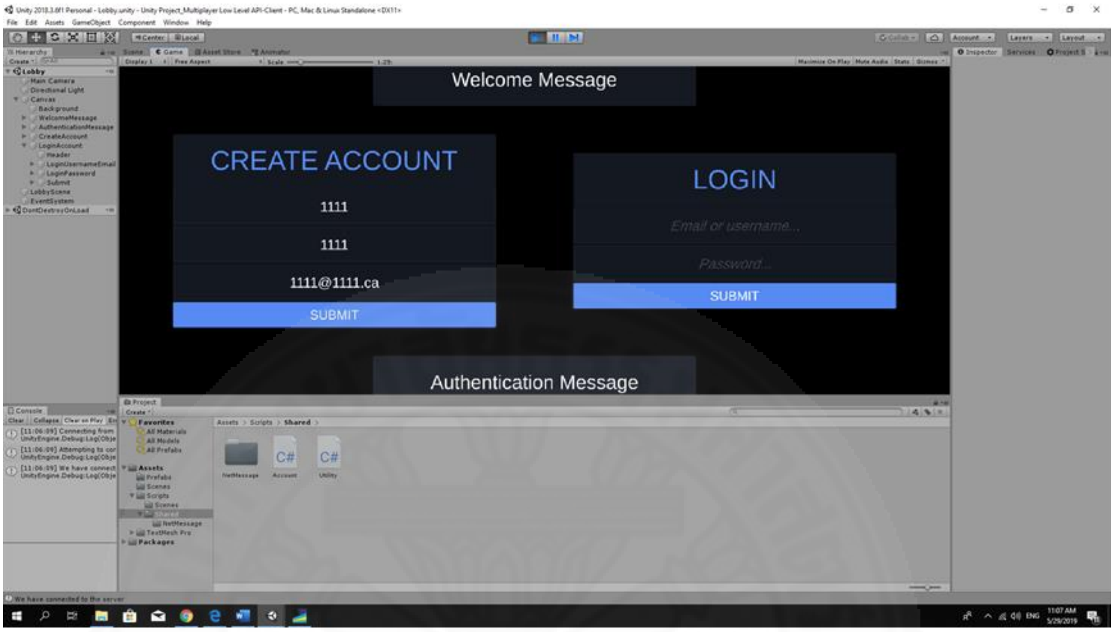


Figure 4.18 UI of the application with the authentication data of the user.

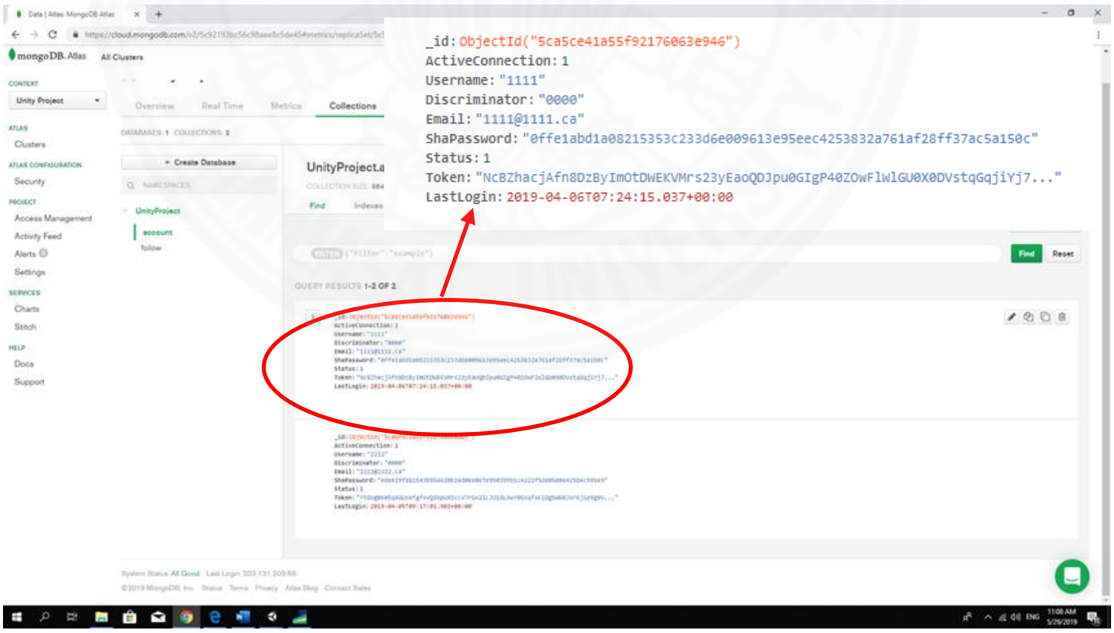


Figure 4.19 The authentication data storing in MongoDB Atlas database.

4.6.4 Hosting a server on Amazon Web Service

A server application is hosted on AWS to allow remote connection from the clients since the previous server applications were built and run on the standalone server of the local machine. Hosting an AWS service provide remote connections to the clients, they can collaborate inside the application anytime by just having an internet connection through the public IP address provided by AWS. AWS is the world largest commercial cloud computing company that provides varieties of service depending on consumers' demand. AWS EC2 service was chosen on which the server application was hosted because it provided many operating systems to run the server application. In order to host a server on AWS, the server application was built without UI but only the script attached to the empty game object in the scene for processing the code. Regarding the server's script, sending function and receiving function had to be defined clearly to cover all the functionalities of the client application. For example, the server and the client both need to know the messages sent and received in order to execute the defined functionalities and update the scene of other clients to be in the same situation and environment.

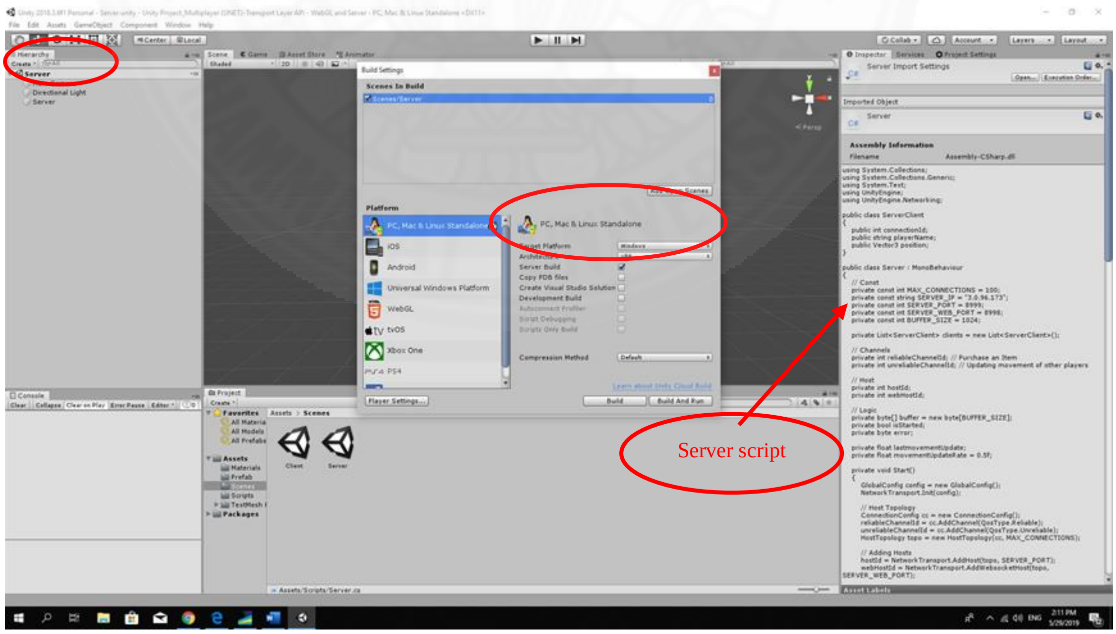


Figure 4.20 Building a server application.

After having already built the server application, an instance of an operating system was launched on AWS. Besides, connection to the operating system and any controls include launching the application were done through the command prompt. Furthermore, the server application was transferred to the operating system by using WinSCP.

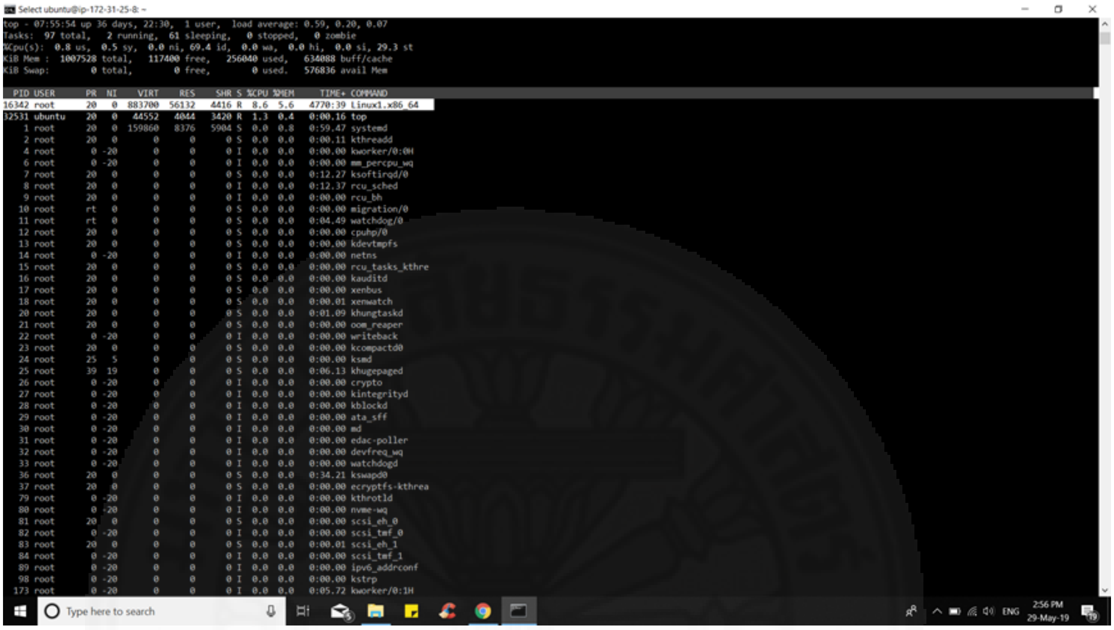


Figure 4.21 The establishment of the server application on the command prompt.

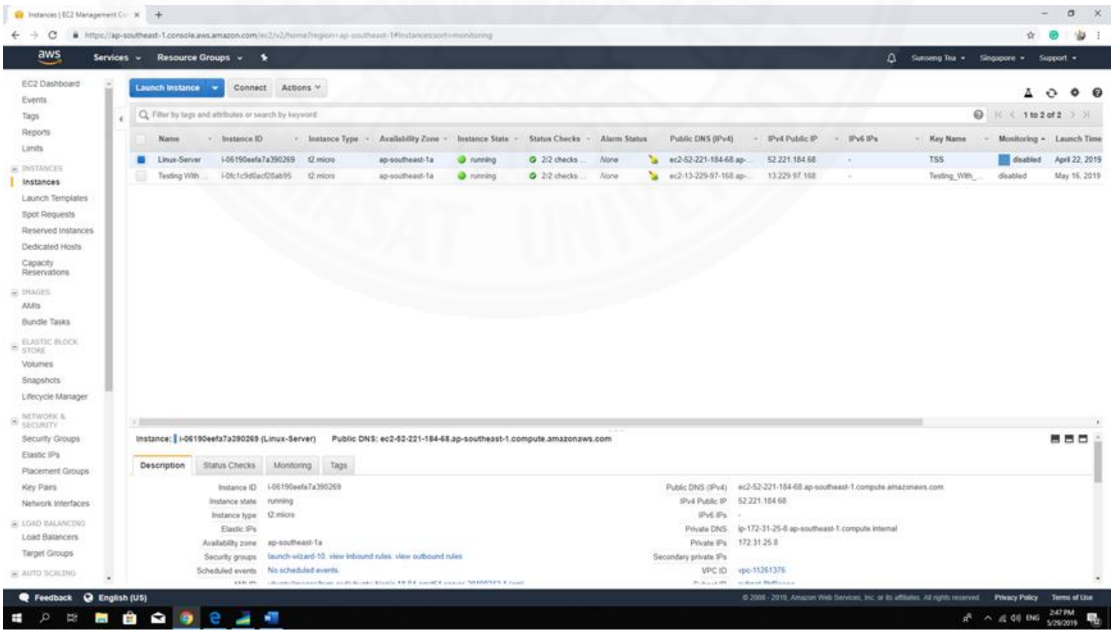


Figure 4.22 The established operating system and running server on AWS dashboard.

4.6.5 Building a shared visualization application on a simple cube with the existing AWS server

This application is more advanced than the previous application because it allows users to join the scene with each other and share visualization and movement of the objects (cubes). The application was built depending on the previous protocol of networking but added some improvement on execution messages from clients' request and send them from the server to other clients for updating their scenes to be the same (shared visualization). In this application, users need to input their name on the input field before connecting to the server. After connecting to the server, the application changes into another scene and spawns the cube (players) with users' name on the top; so, they can see their own player and other players (if there are connections from others) with the name input on the input field and perform their movement by using the computer keyboard. On the connection situation, the visualization and the movement of any players are being shared on every clients' application. Moreover, one of the most important capabilities of the application is the connection to the server from anywhere and at any time since the application was built to connect to the previously established server on the AWS. However, it should be noted that this application was just a proof of concept, and the final developed application was implemented with PUN instead of AWS due to a number of factors discussed in Section 4.5.

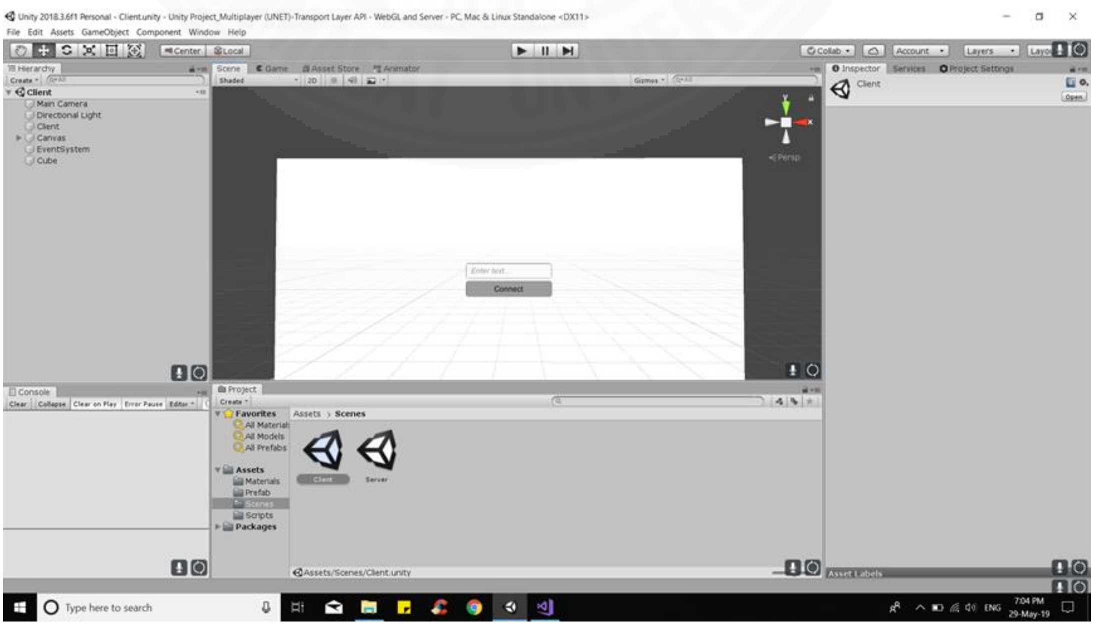


Figure 4.23 The UI of the client application on the Unity Editor.

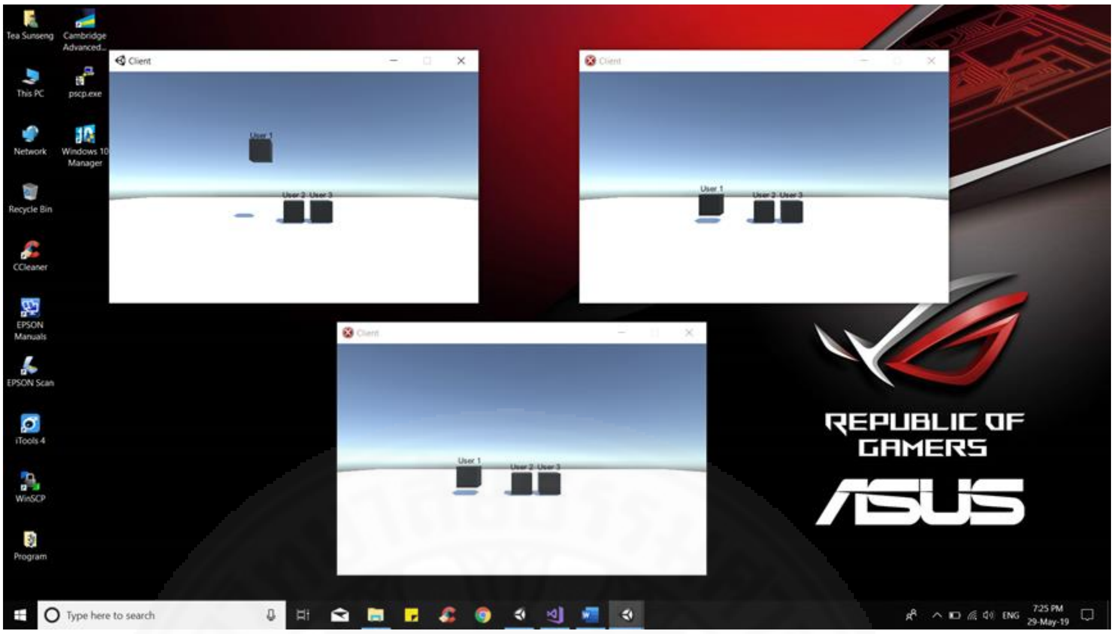


Figure 4.24 Shared visualization and movement of three clients (cubes).

4.6.6 Building a desktop VR application for testing with immersive VR application

The desktop VR application was built to only allow the user to connect and join the networking scene the other users in immersive platform, and it was equipped with only just a movement functionality; so the user can use the keyboard (W, S, A, D) to move and the mouse to change the direction. Unlike the previous mentioned application, this application was a multiuser 3D scene with the avatar of human head, and PUN was used instead of UNet. Furthermore, when the application is launched, it automatically instantiates the user with an avatar head in the networking scene, and the users could totally see what is happening in the networking scene. Moreover, the users can make a verbal communication while they are in the networking scene. The main reason that the application was built is that it was used for the aid of the study since the author had only one HTC Vive during the initial period of development. Developing such a multiuser immersive VR application is a challenging task, and even more so when there are not enough devices to test along the development period. First, VR device has to be connected in order to run the application in the Unity Editor mode. Therefore, it is difficult to know whether there is error or not with the scripts or the scene setup. Another thing is that it is hard to know what is happening in the networking scene if there are no other users joining the scene since the multiuser feature need to be developed. Successfully running on the Unity Editor with the multiuser feature does not mean that it works or updates on the other side of the user; so it is really important to have another user to join the networking scene together in order to see whether the movement is being updated or synchronized across the network or whether other functionalities are working or not. As a result, the desktop VR application could help deal with the above-mentioned problem by joining the same networking scene to see whether the immersive platform works well with all the functionalities that have already developed. Additionally, the most important thing is the realtime talking system that could allow both users to communicate with each other in the networking scene. The study effectively took the advantage of this kind of solution; thus, the developed multiuser immersive VR application could work well when another VR device became available. Figure 4.25 illustrates the view from the desktop VR application while the immersive platform was grabbing the cube. Figure 4.26 illustrates the view from the immersive VR application (only the avatar head was visible in the networking as previously described).

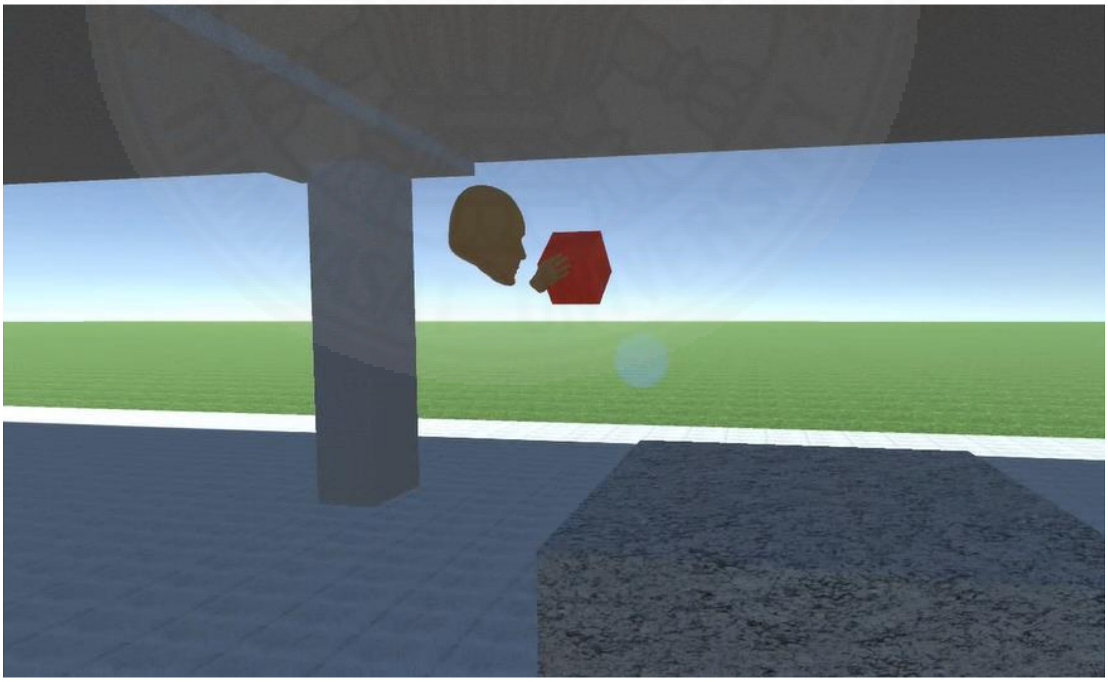


Figure 4.25 Immersive VR's avatar head grabbing an object as viewed from the desktop VR application.

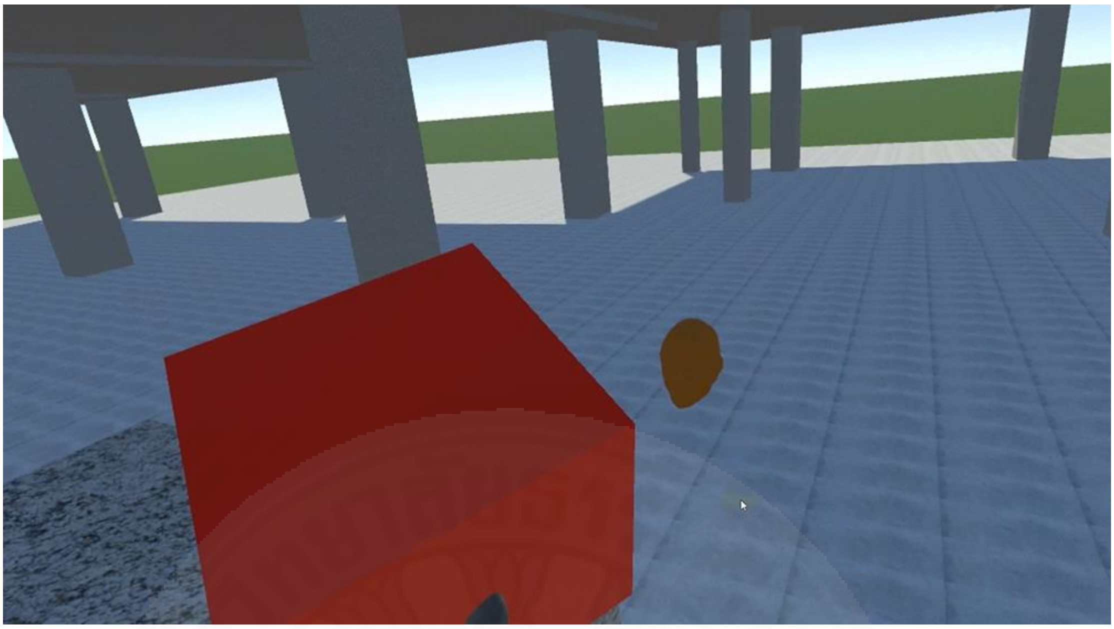


Figure 4.26 Desktop's avatar head as viewed from the immersive VR application.

4.6.7 Building a multiuser immersive VR application

To produce well-design and well-developed multiuser immersive VR applications for VR devices, it technically requires a proof of concept in order to determine the feasibility, applicability, and practicality of VR technology in the context of design review conducted by professionals. Therefore, certain functionalities were designed, developed, built, and discussed as follows:

1. Shared immersive virtual environment: in Unity, the networking protocol is used to allow all remote connections and multiuser feature activation. In order to enable the networking protocol, the process of setting up PUN was taken in the application as previously described. Then, the empty "GameObject" was created into the scene in order to attach the "Network Manager" script to it, and this "GameObject" handled all connection into the networking scene including user instantiation. In terms of PUN workflow, every avatar and both hands need to be attached with "Photon View" script and "Photon Transform View" script and stored in the "Resources" folder in the asset for the instantiations; otherwise, it will induce an error. The shared immersive virtual environment is an important task throughout the development phase because it could bring all the remote user into the same

networking scene; thus, to see the same environment. It is also the main purpose of the study to provide a realtime collaborative environment for conducting the design review process. Figure 4.27 illustrates development workflow of a shared immersive environment function.

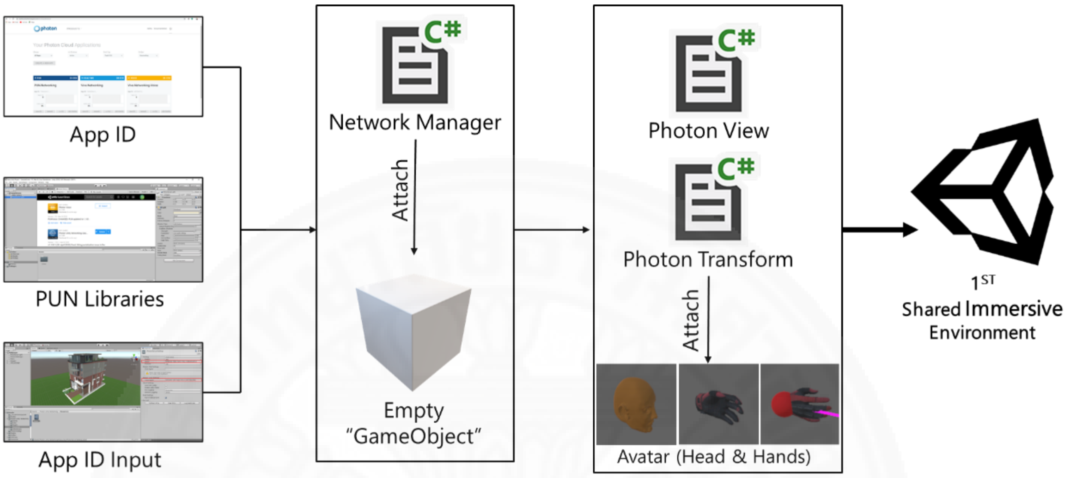


Figure 4.27 Development workflow of a shared immersive environment function.

2. Realtime talking system: in this application, the realtime talking system was implemented in order to allow the users or project participants to make a verbal communication in the networking scene, so they are able to discuss about their design. It is an important task to allow the capability of not only seeing each other, but also talking in realtime. To make this functionality works, every avatar head needs to be attached with "Photon Voice Recorder" script and the was first deactivated before the instantiation of the user into the networking scene. The reason it was done this way is because the avatar needs to be properly assigned the recording component when it is instantiated into the networking scene. Furthermore, the avatar needs one more script which is "Voice" script in order to activate the recording component for the avatar after it is instantiated. Figure 4.28 illustrates development workflow of a realtime talking system function.

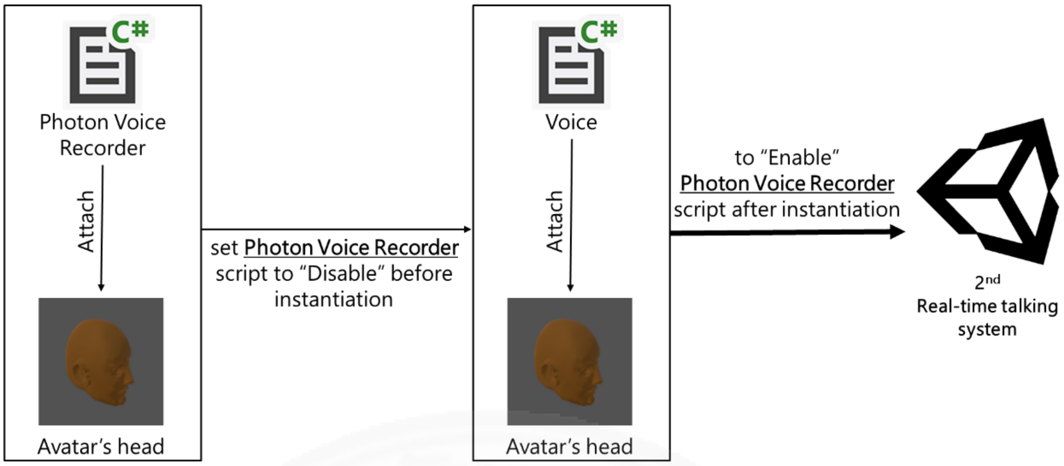


Figure 4.28 Development workflow of a realtime talking system function.

3. Navigation feature: in this phase, the avatar was first set to be a child of VR controller game object. Then, the character control and controller scripts were developed according to the SteamVR plugin and attached to VR controller game object in order to provide first person controller in VR mode to remote users. As a result, they can move and turn to any direction in the concurrent scene by using HTC Vive headset and both controllers. Figure 4.29 illustrates development workflow of a navigation feature function.

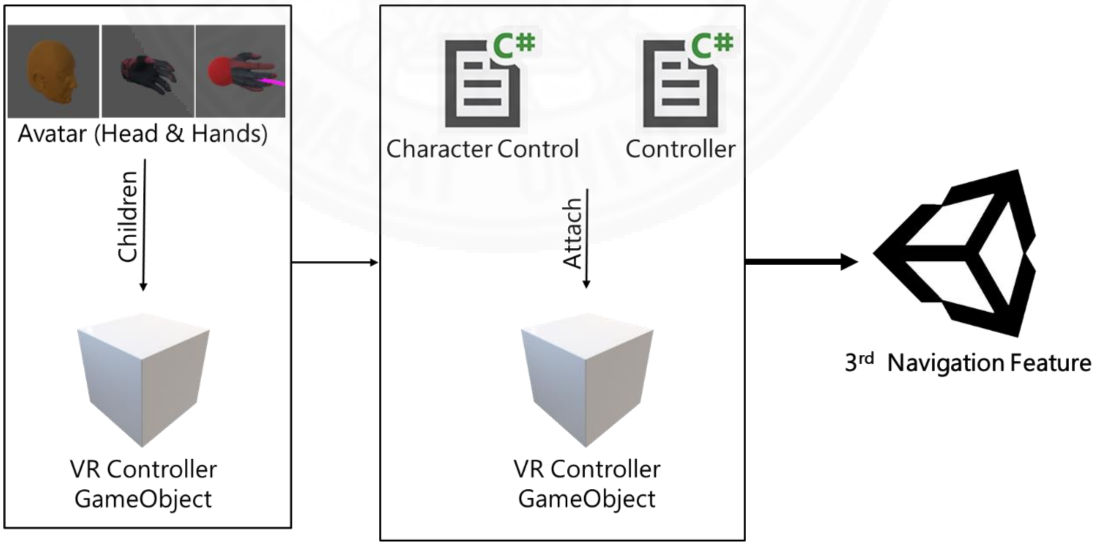


Figure 4.29 Development workflow of a navigation feature function.

4. Name tag of connected users: in this application, the name tag of connected users (as shown in Figure 4.32) was added on the top of the avatar head in order to allow all the connected users to know who is in the scene with them. Therefore, the project participants can collaborate and discuss on the design review effectively and easily with any other participant whom they intend to do. To make this functionality work, an empty "GameObject" was created and arranged to the top and as a child of the avatar head in the scene. "Text" component was added to the "GameObject" for receiving the text from the user input of their name. Additionally, "Player Name" script was added to the avatar head in order to synchronize the player's name across the network, so the remote user could see the name on the head of the avatar. Figure 4.30 illustrates the development workflow of the name tag function.

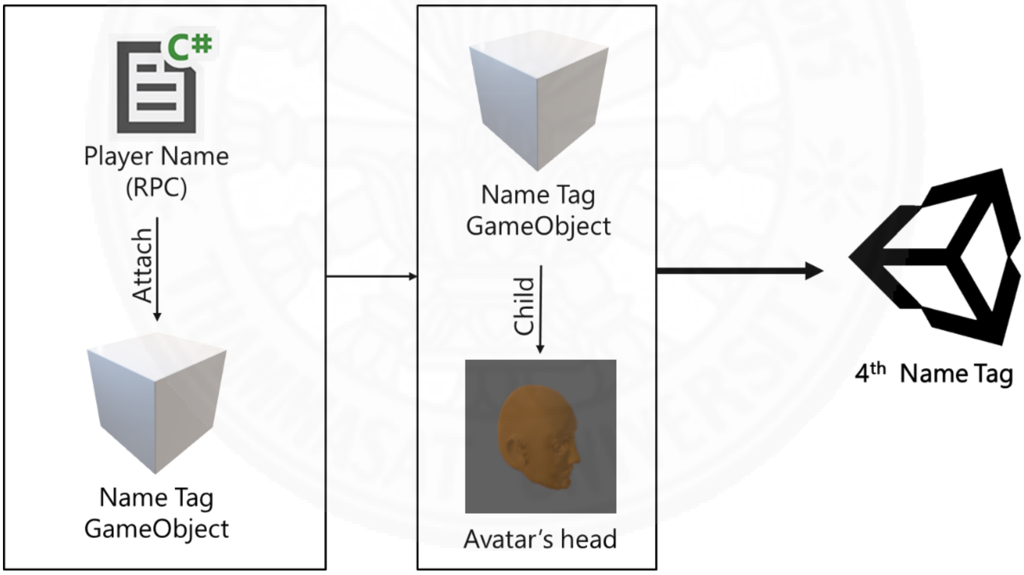


Figure 4.30 Development workflow of the name tag function.

5. Laser gun tool from users' right hand: in this application, the laser gun tool was added to the users' right hand in the scene in order to allow the users to point at the design in the virtual environment because it is essential to know which part that the project participants see as the problem and want to discuss. Thus, this functionality could draw an attention of all the project participants to focus on the edge of the laser beam (as shown in Figure 4.32). To make this functionality work, an empty "GameObject" was created and

arranged as a child of the right-hand prefab, and light beam component was added to the “GameObject”. The component was set to generate a red square ball when the beam collides with another “GameOject”. Moreover, “Pointer” script was added in order to synchronize the laser beam across the network, so the remote users could see the laser from the right-hand of another user. Figure 4.31 illustrates the development workflow of the laser gun tool function.

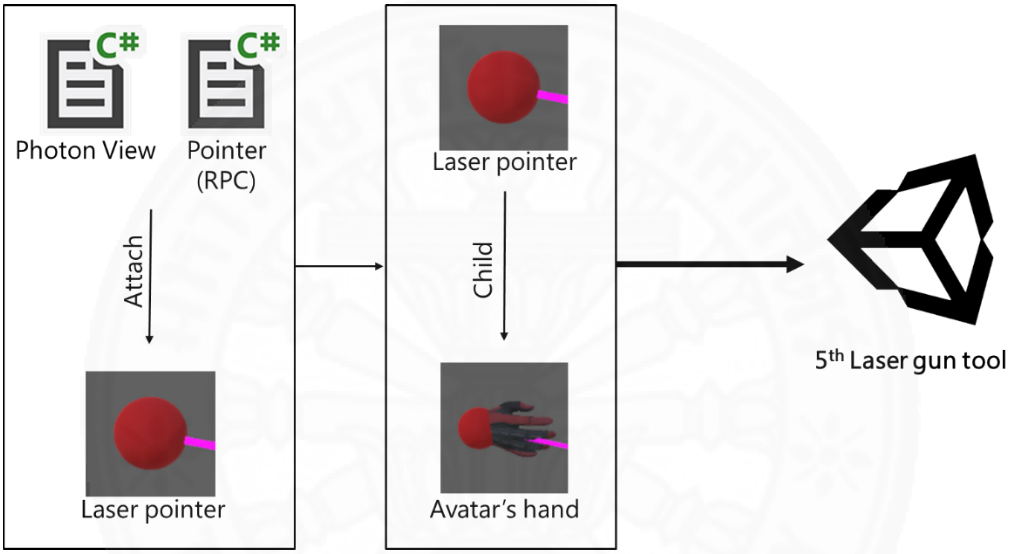


Figure 4.31 Development workflow of the laser gun tool function.

Figure 4.32 The name tag and the laser gun tool of the remote user.

6. 3D model for building inspection experiment: in order to provide an evidence for the applicability of the developed application, the comparative advantage was tested through realtime collaboration on a building inspection experiment between the developed application and the non-immersive VR application. To conduct this experiment, the 3D model of SIIT Advanced Laboratory was imported to be the networking scene to allow the realtime collaborative review before the inspection task. The main reason that the building was chosen because there are 2D drawings provided by the facility manager of SIIT, so it is easy for the author to model the 3D drawing. 3D model was generated in Autodesk Revit software and configured to be supported by the Unity in Autodesk 3ds Max software. After the configuration, the final product was imported to the Unity to set up the networking scene. Figure 4.33 illustrates the workflow of 3D asset creation for building inspection experiment. Figure 4.34 illustrates the user joining the networking scene of the SIIT Advanced Laboratory building.

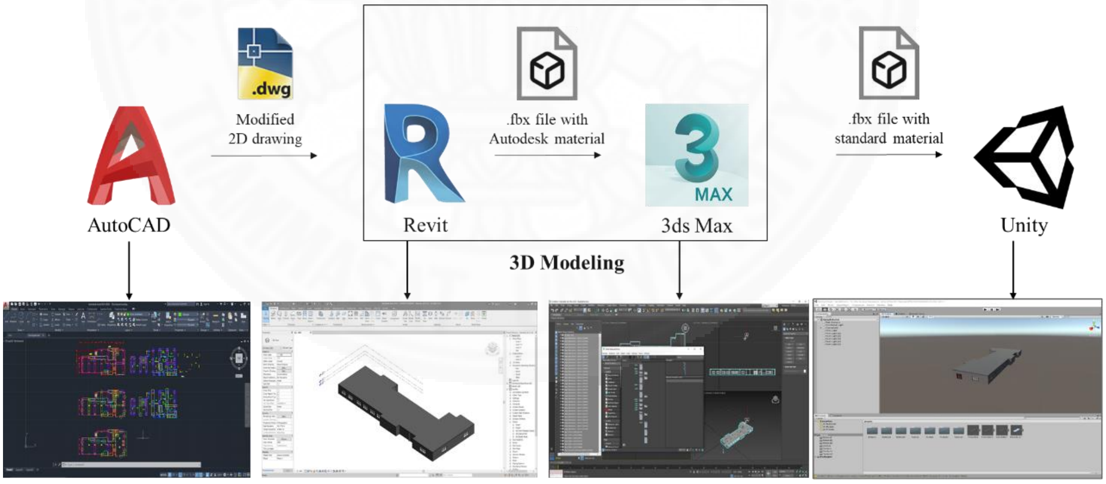


Figure 4.33 Workflow of 3D asset creation for building inspection experiment.

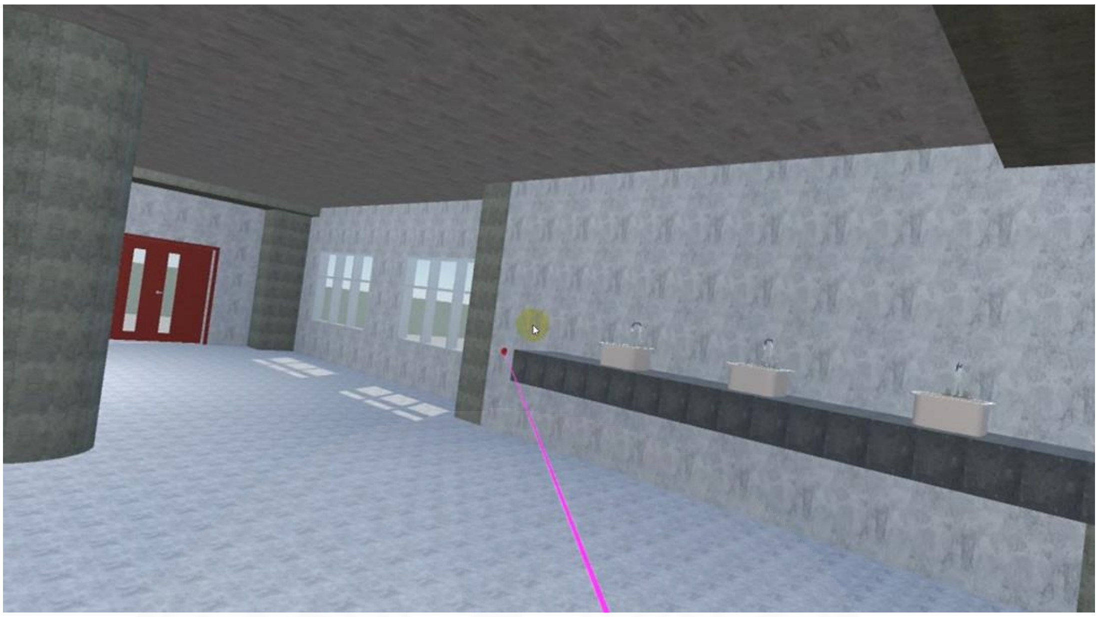


Figure 4.34 The user joining the networking scene of the Civil Engineering Laboratory.

CHAPTER 5
RESEARCH RESULTS AND DISCUSSION

5.1 Results and data analysis

In this study, the performance difference was observed between two groups in the building inspection experiment. Outperformance percentage (OP) was defined as the measurement value in percentage of the two groups performance. OP is determined as follows:

$$OP = \frac{I_i - I_n}{I_n}$$

Where I_i is the average number of net identifications for the immersive group computed as the difference between the average number of correct identifications and the average number of incorrect identifications, and I_n is the average number of net identifications for the non-immersive group computed as the difference between the average number of correct identifications and the average number of incorrect identifications. In the experiment, the average number of net identification in the building inspection task was separated into 2 zones—zone A and B (as shown in Figure 3.8) for data analysis and results because the author wanted to examine whether there is any difference between the results from the separated and combined zones.

5.1.1 Participants

There were totally 44 students volunteering to take part in the experiment. This group of participants consisted of 8 females and 36 males; 16 were graduate students and 28 were undergraduate students. The age of the participants varied from 19 to 28 years old, and the median age was 23. They were asked whether they have any experiences of playing video games or using VR by rating on a 6-point Likert scale (where 0 = no experience and 5 = a lot of experience) because it could be factors influencing their performance task. The report of students in average with gaming experience was 2.82/5 and with VR experience was 0.3/5, meaning that most participants had little experience with VR. Importantly, all participants recruited to be the research samples had never been to the specific floor of the Civil Engineering

Laboratory used in the experiment.

Table 5.1 Student demographics.

Demographic Factors	Response Range	Mean or Percentage	Median
Gender	Male/Female	81.82% male	-
Age	19-28	22.89	23
Degree level	Undergraduate /Graduate	63.64% undergraduate student	-
Game experience	0-5	2.82	3
VR experience	0-5	0.3	0

5.1.2 Results of building inspection experiment—zone A

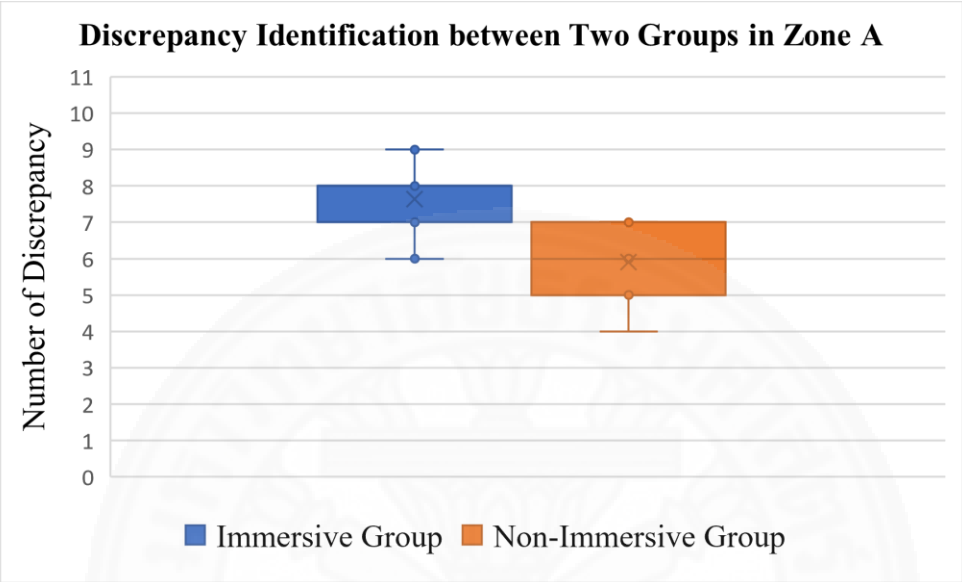
According to the results of zone A (with an area of 465 square meters and more difficult to identify the discrepancies than zone B) (as shown in Figure 3.8), both the immersive group and the non-immersive group received the same average of 0.55-point penalty since the author presented a point penalty of an incorrect identification from any participants. The immersive group achieved I_i = 7.64 with SD = 1.03, whereas the non-immersive group achieved I_n = 5.91 with SD = 0.94. According to one-way ANOVA analysis, the author found a significant difference in mean of identification number between these two groups ($p<0.001$) (as shown in Table 5.2). As a result, the immersive group significantly performed 29.3% better (OP = 29.3%) than the non-immersive group.

5.1.3 Results of building inspection experiment—zone B

According to the results of zone B (with an area of 220 square meters and less difficult to identify the discrepancies than zone A) (as shown in Figure 3.8), the immersive group received an average of 0.27-point penalty, whereas the non-immersive group received an average of 0.36-penalty point. The immersive group achieved I_i = 7.27 with SD = 1.01, whereas the non-immersive group achieved I_n = 6.36 with SD = 0.92. According to one-way ANOVA analysis, the author found a significant difference in mean of identification number between these two groups ($p<0.05$) (as shown in

Table 5.3). As a result, the immersive group significantly performed 14.3% better (OP = 14.3%) than the non-immersive group.

Table 5.2 The performance comparison of building inspection experiment in zone A.



ANOVA: SINGLE FACTOR (ZONE A)

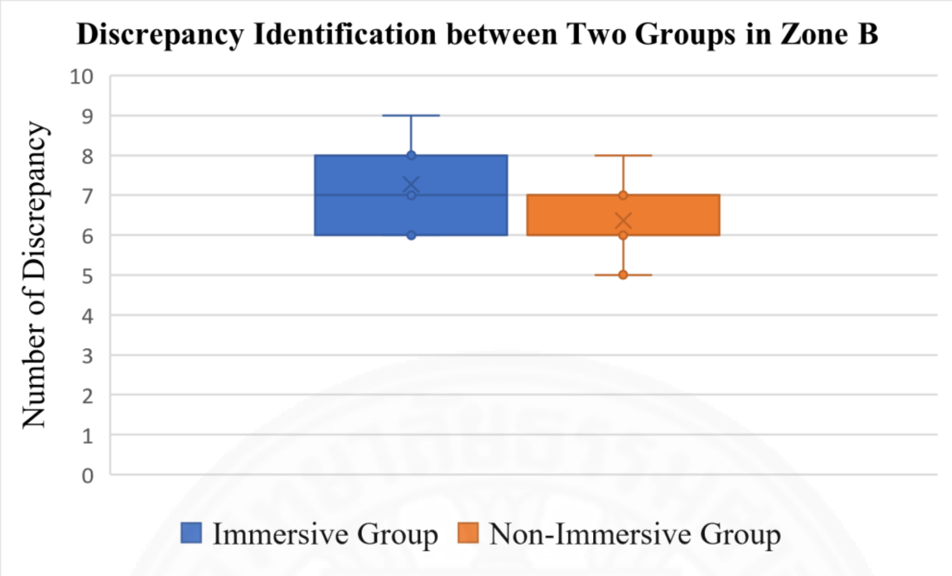
SUMMARY

Groups	Count	Sum	I (net)	SD
Immersive Group	11	84	7.6364	1.0269
Non-Immersive Group	11	65	5.9091	0.9439

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	16.4091	1	16.4091	16.8692	**< 0.001**	14.8188
Within Groups	19.4545	20	0.9727			
Total	35.8636	21				

Table 5.3 The performance comparison of building inspection experiment in zone B.



ANOVA: SINGLE FACTOR (ZONE B)

SUMMARY

Groups	Count	Sum	I (net)	SD
Immersive Group	11	80	7.2727	1.0090
Non-Immersive Group	11	70	6.3636	0.9244

ANOVA

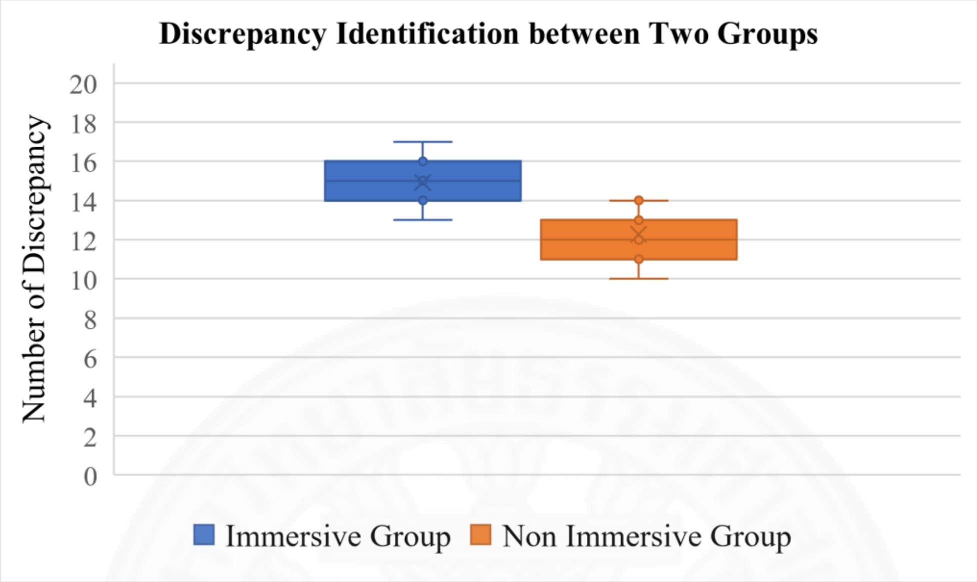
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.5455	1	4.5455	4.8544	**< 0.05**	4.3512
Within Groups	18.7273	20	0.9364			
Total	23.2727	21				

5.1.4 Combined results of both zones

Regardless of zone division, the immersive group received an average of 0.82-point penalty, whereas the non-immersive group received an average of 0.91-penalty point. The immersive group achieved I_i = 14.91 with SD = 1.07, whereas the non-immersive group achieved I_n = 12.27 with SD = 1.27. According to one-way ANOVA analysis, the author found a significant difference in mean of identification number between these two groups ($p<0.0001$) (as shown in Table 5.4). As a result, the immersive group significantly performed 21.5% better (OP = 21.5%) than the non-immersive group. In terms of results for zone A and zone B, the immersive group tended to perform better than the non-immersive group in both zones. Specifically, OP equals to 29.3% in zone A (as shown in Table 5.2), whereas OP in zone B equals to 14.3% (as shown in **Table 5.3**). In zone B, performance of both groups is almost the same (with a slight OP difference) because area is small and has few components for co-reviewing and co-inspecting. Therefore, OP increase based on level of spatial complexity of the zones since zone A is bigger and more complex than zone B. This research experiment was just a small simulation with simple problems, and the collaborative tasks were eased by the developed application according to the results, so the virtual models would be more complicated and the design problems could be more serious in reality. As a result, co-review by using collaborative VR approach (the developed application) could be more effective than the conventional approach due to the current complex projects in the construction industry because immersive environment enriches the collaborative conceptual design review through sharing mutual understanding for remote project stakeholders and reducing spatial complexity of the virtual model.

Building inspection performance is improved because the developed application provides the capability to immerse remote inspectors into the same virtually designed project. This experiment was carried out to determine whether the developed application could enable the realtime collaboration in the virtual environment of the project during the design review session, particularly when most project participants are remotely located. Since the AEC industry is fragmented and highly requires concerted actions, it must find a medium to bring remote stakeholders virtually together in collaborative tasks. Therefore, the feasibility to provide the real presence inside the same virtual project is through the application of multiuser immersive VR since it creates a shared immersive environment contributing to less complexity and effective discussions of the project design; as a result, it improves the performance of the building inspection task. The research finding suggests that the co-review of the immersive experience created by the multiuser VR application is important in building inspection as well as effective for the implementation of consensus decision in the preliminary design. As a result, the multiuser VR application could share common understandings through its collaborative VR environment among the project stakeholders during the review session.

Table 5.4 The performance comparison of the building inspection experiment.



ANOVA: SINGLE FACTOR

SUMMARY

Groups	Count	Sum	I (net)	SD
Immersive Group	11	164	14.9091	1.0659
Non Immersive Group	11	135	12.2727	1.2721

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	38.2273	1	38.2273	26.2813	**< 0.0001**	23.3995
Within Groups	29.0909	20	1.4545			
Total	67.3182	21				

5.2 Discussion

This thesis introduced main components and development workflow of the multiuser immersive VR application. The applicability of the developed application was ensured by two main features:

1. The developed application can provide remote connections for all project stakeholders who are located at difference geographical locations, via a cloud master server of Photon. Remote project participants are able to log into the same immersive environment as well as to have a realtime communication in order to discuss issues relate to the project. At current state, the developed application can connect up to 20 users at the same time.
2. The developed application provides a shared immersive environment of the virtual project based on the design. The designers and the owners can feel and sense their real project before the construction to gain better understanding and reach consensus of the design through the navigation feature provided by the application. The project participants can use the avatar to see each other and discuss in order to make the concurrent scene more realistic. This feature draws attention of the owners and designers who wish to effectively reach consensus on their preliminary design in a timely manner. Besides, the laser gun tool can enhance the effectiveness of discussion in the immersive environment. In addition, name tag provides identification of every remote project participant, especially the name and position of each participant in the current project. The developed application is expected to provide an effective collaboration resulting in reducing the number of requests for information (RFIs) and change orders. Apart from the above-mentioned benefits, the developed application can simulate realistic environment of emergency or training situations that are too costly to execute in practice.

In terms of the research experiment, there are relationships in both conditions of education level and professional experience with spatial perception according to Paes, Arantes and Irizarry (2017) and Stanney, Mourant and Kennedy (1998), meaning that they found out undergraduate or graduate students had both better spatial perceptions than high school students, suggesting that educational level may be an influent factor in spatial cognition in the building inspection experiment. Additionally, design professionals (architects and engineers) understood the 3D model better than architecture, engineering students and other professionals, suggesting that professional experience could be another influent factor of the experiment. However, the proposed experiment was conducted by a group of undergraduate and graduate students with no professional experience, but the research results might somehow be influenced by the above-mentioned factors. Therefore, this is the limitation of this research that needs further investigation.

On the other hand, there is a case study conducted by Zaker and Coloma (2018) about the application of a multiuser VR-based workflow in a real project. They used a commercial software called Fuzor for evaluating multiuser VR feature in project collaboration and design review. Their research experiment was conducted by a group of real AEC professionals that were involved in the project. The participants were allowed to test the VR software feature and give feedback. According to the feedback from the professionals, the multiuser VR feature could benefit project collaboration the same way as that was found in this thesis. Furthermore, they also claimed clash detection, that was conducted in the experimental method could be practical. However, they stated that the adoption of this new technology has been impeded by 2 main factors in terms of the investment in required hardware and new software as well as the ease of use. The developed application in this thesis could be built by the author—non-professional developers without any investment on software, and it is user-friendly since it is operated by just one click to join and both VR controllers. Therefore, by removing these two main obstacles, the developed application might promote its employment in AEC practices. Moreover, Du, Shi, Zou and Zhao (2018) compared multiuser VR with single user VR, and the result showed that users of multiuser VR performed better than those who were using single user VR. As a result, they interpreted that two minds are better than one mind showing that the importance of interpersonal communication in collaborative AEC's activities.

The developed application was also compared with other commercial applications such as WebVR, IrisVR and Fuzor. The author found that there is a lack of flexibility regarding commercial packages because they are not open source application meaning that their functionality cannot be tailored to different AEC activities. For example, neither IrisVR nor WebVR enables users to customize their built-in functions into users' demand. Moreover, Fuzor does not provide any in-built realtime talking system, so users need to subscribe to another third-party application such as Skype, etc. for communication. Besides, the author also monitored whether the commercial packages comply with original texture and material of Revit models, and results indicate that those commercial applications (IrisVR, InsiteVR and Enscape) utilize their own material library and fail to preserve the original one of Revit in order to increase conversion and rendering speed in VR. Consequently, it could induce deviations from the original design. In contrast, the developed application in this thesis strictly follow the original texture and material because these two components partially define the beauty of the design; thus, affect the owner's decision regarding conceptual design. However, the commercial application provides additional design functionality, whereas the developed application provides only the capability to review the virtual model. To sum up, the developed application provides a sufficient functionality for the collaborative design review in the conceptual design phase as other advanced functionalities are not commonly required in this phase.

CHAPTER 6
CONCLUSION, LIMITATIONS AND FUTURE RESEARCH

6.1 Conclusion

The natural characteristics of the AEC industry are geographically dispersed and multidisciplinary contributing to growing demand for realtime collaboration and digital technology. With the advent of VR system and cloud computing technology, the AEC industry has drawn its attention to invest in virtual environment studies for project collaboration due to better spatial understanding and utilization from visualization and remote access. Therefore, AEC activities can be leveraged with the integration of these technologies. However, the advancements to provide remote connection and allow project stakeholders to join the same immersive environment of the project is still highly required for this fragmented industry. This thesis proposes a realtime collaboration approach by using a multiuser immersive VR application that provides a shared immersive environment of the project design as well as realtime interactions. The developed application enhances effectiveness of the project discussion by providing strong feeling of presence, navigation feature, laser gun tool and identification of all connected project participants. To successfully conduct the study, a research design and framework containing 5 main research tasks was followed to answer all research objectives and elaborated as below:

1. Literature review was critically conducted to draw an insight and identify the gap of the current states and approaches in the design review process. This task was mainly conducted to achieve the first research objective (to examine the current states and approaches in the design review process).
2. The proof of concept was conducted to examine whether there is feasibility for development of multiuser VR application and how it can be employed in geographically distributed and multidisciplinary working environment during the design review process. This task included certain application prototypes to achieve the second research objective (to introduce a digital or VR approach for realtime collaboration in the design review process).

3. A multiuser immersive VR application was specifically built with 5 multiuser functions for realtime design review approach. This task was conducted to achieve the second research objective.
4. A pilot test was conducted with a construction management professional who was experiencing communication problems during the conceptual design review phase in the real project. This task established a baseline understanding and fundamental concept guiding author to an appropriate start and effective development steps of the study. It was also conducted to achieve the first and second research objective.
5. A comparison was made between immersive VR and non-immersive VR experience by 44 students in terms of realtime collaboration in a building inspection task in order to assess the applicability and performance of the developed application. This task was conducted to achieve the last research objective (To investigate the applicability and performance of the developed approach whether it can be adopted and incorporated into the design review process through enhanced collaboration).

The study resulted in applicable approach that could enhance performance of design review. To sum up, the results indicated that the group that went through the design review using the multiuser immersive VR application perform better compared to the group that use traditional desktop, so this alternative approach has potential to be used to improve the design review. The contribution of this study exists in its introduction of an additional approach and the integration of VR with cloud computing technology to increase understandings of project participants and effectiveness of project collaboration. This alternative approach is expected to provide an enhanced digital approach for design review for the AEC industry.

6.2 Limitations

The research should be interpreted in light of certain limitations. In terms of technical implementation, functionalities of the application are also considered as the limitation. For example, the author used most of the commercial development tools from different companies, so they surely limit the technical support from the outsources or need advanced configurations from their experts; this limits the design capability of the application's functionalities. Additionally, the geometry of the 3D models in the scene somehow has a different scale from the reality that might affect the spatial perception of the users due to improper height calibration, and the developed application could not show the BIM metadata got from Revit in the VR scene. Besides, there are few factors in terms of experiment design influencing data analysis and research findings. Firstly, a small sample size was taken to conduct a statistical analysis, so it could affect precision of analytical results. Secondly, the experiment was conducted with a student population, and the application was developed to be a practical solution for construction industry problems. Consequently, the output from the analysis could not effectively deduce and assume an overall of the real situations. Moreover, the experiment was conducted only in two merely different sites. To get an effective interpretation of results, the experiment should be conducted in the sites with different areas and environments (level of difficulty) because these factors might affect the interpretation. The participants taking part in the experiment should also include design professionals who have experience in the design review process. The immersive and non-immersive groups should include different disciplines (the owner, architectural designers, engineers, etc) in order to match with the real environment of the design review process.

6.3 Future research

Many directions could be taken into consideration for future work. Even though the results obtained from this research have illustrated positive and good results in general, the research experiment should be conducted widely in many different types of real sites and with AEC professionals to achieve practical results. For example, the research experiment should be conducted in the sites with different size of areas and in quantity of building components (different levels of difficulty). Furthermore, the research samples should be classified in different categories in terms of age and experiment. Every compared group should have the same disciplines with similar age and professional experience, particularly a group including the owner, architect, and engineers.

In terms of application development, the next version of the developed application for realtime collaboration in the design review process should be developed and equipped with a complete functionality and user interface, and these below activities and functionalities should be included:

- Notation (post-it): design professionals can leave a note in the concurrent scene in case others who miss the realtime review could see it when they log into the concurrent scene. Technically, since the developed application has the server to handle all connections, this functionality could be possibly developed by creating another cloud database in order to store the notes in the concurrent scene. Another networking script needs to be developed and attached with the “Network Manager” game object for information transfer (storing and calling) between all connected users and their database. All transfer operation will be handled by the server. In terms of the frontend, a canvas that has a text input field inside and a virtual keyboard need to be created in the concurrent scene, so the users can add the text or sign during the review.
- Direct import and synchronization (both data and geometric update) between the application and BIM authoring tools: design professionals can immediately import and link their virtual project, so every change in the application or BIM authoring tools can be automatically and immediately updated and saved in both sides.
- Metadata import: design professionals can use the laser to point at the building component in order to show properties panel (metadata) in the scene. There is additional technical work for importing BIM metadata to the Unity scene. First, Revit Dynamo tool needs to be used for automatically registering all building components in the Revit model with their IDs, so those components with their properties (metadata) has their own name (IDs). Secondly, the properties of the building components can be imported as text file (.txt) including their IDs. Finally, the Unity can create an array of input fields for receiving the metadata in order to show on a canvas. With the aid of the C# script, the Unity can read that text file and duplicate all properties including IDs into the created array. By using SteamVR action of the pointer, all building components’ properties will be shown while the laser hits the

body of the components. Beside Revit, there is software such as ArchiCAD, SketchUp, etc. that could be used to create the 3D model and export as .fbx file. However, SketchUp is not a BIM authoring tool, and its texture and material of the model are not as real as Revit. Furthermore, ArchiCAD could not provide the above-mentioned process for importing metadata into Unity.

- Users' height configuration: the imported 3D model was already in the real scale (1:1), so what the users looks in VR is the same in the real environment in the case of a proper height calibration. However, there is a problem regarding the users' height in the VR that affects spatial perception (height of the 3D model) due to a conflict regarding users' height configuration in VR. SteamVR provides a "Room Setup" setting to the users in order to customize their height based on the level of the headset, and the developed application used the first person controller that allows the users to calibrate their height again depending on the headset and their eyes. To solve this problem, the VR device should be properly set up by putting on the floor (as a zero level), and the first person controller should be set to 0.9 of the real height of the users because the headset was worn at the eye level where the height should be reduced by 10% of the real height.
- Preferable interface by project stakeholders (user-friendly): Interview and survey should be conducted with the professionals regarding useful functionalities and interface. For example: user login and authentication.
- Avatar's body and animations: these components could increase level of realism during the design review process.
- Motion sickness reduction: movement and turning speed (sensitivity) should be calibrated to avoid nausea and dizzy due to long period of design review process.

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