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COLLABORATIVE VIRTUAL REALITY IN CONSTRUCTION COMPARATIVE STUDY OF TWO REMOTE MULTI-USER SYSTEMS

Skandar Gueddiche[1], Conrad Boton[1]
1 *École de Technologie Supérieure, 1100, rue Notre-Dame Ouest, Montréal, Canada*

Abstract
Ineffective collaboration and communication between the stakeholders of a construction project are one of the most difficult problems to solve in the AEC industry. The rapid development of new technologies has reformed the construction industry in recent years. Indeed, adopting BIM technology and its dimensions improves the collaboration process. The integration of emerging technologies such as virtual reality (VR) based on a BIM model is a potential solution to optimize communication. However, most of the studies on virtual reality and its applications in the construction industry have so far focused on the single-user experience which does not support collaboration and interaction between construction project teams. Multi-user remote virtual reality can offer a solution to the problems mentioned above. Several tools have been developed in other fields such as the video game industry, but their applicability in the construction industry has not been evaluated in the literature. Our research aims to compare two remote multi-user virtual reality support systems to characterize their potential use in the construction industry with BIM models. We then performed a demonstration in the form of two fictitious scenarios to evaluate the proposed tools. This allowed us to identify the potential benefits of the two remote multi-user VR systems to support collaboration and to identify limitations and future improvements. While both systems offer interesting remote multi-user functionality, the Vizard multi-user application can only work over a local area network, which is a major limitation to remote user collaboration. In addition to the features common to both systems, Photon Unity Networking (PUN) offers the ability to communicate with voice in real time.

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Keywords: Remote multi-user virtual reality, BIM, remote collaboration, Unity game engine, Vizard, Photon Unity Networking

1. Introduction

The construction industry is one of the pillars of the Canadian economy. However, it has been lagging for years in terms of productivity and performance compared to other industrial sectors because of the great technological, technological, and organizational fragmentation among the team members of a construction project [1,2].

Many people in the sector admit that this gap can be bridged through the adoption of new information technologies such as building information modeling (BIM) Building Information Modelling (BIM) and virtual reality (VR) [2]. Building information modeling (BIM) is the keystone of the fourth industrial revolution in construction, also called construction 4.0. This technology allows the digitization and virtualization of the built environment. In addition, it is a tool that facilitates decision-making during the entire life cycle of a construction project [2]. However, there are some relevant avenues such as the use of the principle of virtual reality. Indeed, several researchers have studied the use of this technology in the construction industry, but it is rare to see solutions based on multi-user virtual reality at a distance multi-user virtual reality-based solutions to support collaboration, communication, and communication and support for constructability analysis meetings. Typically, VR applications are limited to a single user. The diversified geolocation of a construction project's stakeholders is common in the construction industry. Bringing together people who are in an immersive environment will be a potential solution to facilitate communication and collaboration.

Thus, this study proposes a comparison between two remote multi-user virtual reality support systems, to characterize their potential use in construction with BIM models. This paper is composed of four sections. The first section is the literature review. It presents a review of previous scientific studies related to our topic. The second section presents the methodology of the research. The third section presents a comparative study of the two remote multi-user virtual reality tools. The report ends with a section that presents a demonstration of two hypothetical scenarios to evaluate the usefulness of the two proposed tools in the construction industry.

2. Literature review

In recent years, the construction industry has undergone a radical digital transition. Many companies have adopted several technological tools to improve collaboration and productivity. Our literature review will focus on virtual reality, remote multi-user virtual reality, its characteristics, and its applications in the construction industry. Then, we will focus on the scientific studies concerning multi-user virtual reality in construction.

2.1. Multi-user virtual reality

Collaborative virtual reality is a shared virtual environment designed to support collaborative activities. It is an extension of single-user virtual reality. This technology allows participants to share the same virtual environment to achieve a common goal. Indeed, collaborative virtual reality offers an infinite graphical digital landscape allowing multiple users to interact with each other. The representations of individuals or data can be in the form of an advanced 3D graphical representation, 2D representations, or simply text pasted on a plane [3]. The video game industry and the training of military and industrial teams are the main application areas of collaborative virtual reality [4]. Collaborative VR systems proposed in the AEC industry are usually CAVE-based applications where users must be physically present in the same location hence the need for the development of a multi-user remote virtual environment [5, 12]

The development of remote multi-user virtual reality was started in the late 1970s by Richard Bartle and Roy Trubshaw. They created a remote multi-user VR system that allowed users to collaborate via a computer network. Interaction in the VR environment and visual cues were very limited given the network limitation and hardware at that time [6]. Du et al. [5] define remote multi-user virtual reality as a system to bring participants with different geolocations into the same virtual environment via a cloud-based network. This technology has several advantages. According to Octania [7], it allows the entire team to meet at any time without being physically present, which limits long-distance travel and subsequently optimizes the carbon and time footprint. On the other hand, it allows improved productivity and understanding of the project thanks to real-time visualization. Moreover, it allows for the improved efficiency of training. Indeed, Dede et al. [8] proposed to integrate this function into their virtual reality system to facilitate learning. They found that a remote multi-user virtual reality tool improved the method of collaboration and learning through virtual interaction. In the medical sector, the multi-user feature was integrated into VR technology by Schäfer et al. [9] to overcome people's phobia of the real world. Tests have shown that this virtual collaboration improves the treatment of several phobias.

2.2. Multi-user virtual reality in construction

BIM-based virtual reality technology is showing every day the potential of its application in the construction industry. However, there is not much research in the literature review dedicated to the application of remote multi-user virtual multi-user virtual reality experience in the construction industry. Among the studies we found, we can cite a study on remote multi-user virtual reality for communication [5], and remote multi-user virtual reality for safety [10].

Du et al. [5] proposed a cloud-based multi-user virtual reality system that uses the metadata of a BIM model to improve communication among project stakeholders in a virtual reality environment. The CoVR system allows for improving communication between stakeholders in construction projects. Indeed, the participants of a project are usually located at a distance. CoVR allows them to connect to a cloud server in the same immersive environment to discuss and solve design problems in real-time. It thus optimizes interaction in a multi-user interactive virtual environment [5].

The construction industry experiences many fatal and non-fatal workplace accidents each year. Proper safety training for workers is therefore mandatory. The use of new technologies such as virtual reality has proven to be more effective and motivating than traditional methods. Furthermore, its experiences are limited by a single user [10]. Thus, Moelmen et al. [10] developed an asymmetric multiplayer prototype based on virtual reality. This concept allows for representing a more realistic work environment. Indeed, it allows presenting a scenario with several hazards with unpredictable human interactions when using crane lifting operations or heavy machinery. This multiplayer VR system allows trainees to test their role on a dense and dynamic construction site and anticipate hazards thanks to the warning signals implemented in the prototype [10].

Luo et al. [11] proposed a prototype virtual reality-based multiplayer platform that supports safety knowledge. This system enables the interaction of multiple trainees in an immersive environment for simulating worker-equipment interactions. User performance can be monitored in real-time and stored in a database to analyze training effectiveness.

3. Research Methodology

To carry out our research project that targets the use of remote multi-user virtual reality in the construction industry to bring together construction project team members in an immersive virtual environment to support collaboration, we followed 4 main steps: Identification of the problem and motivation, the definition of the objective, design, and development and finally demonstration and evaluation.

3.1. Identification of the problem and motivation

First, we identify the problem based on our literature review completed in the first section. Indeed, virtual reality in construction as well as multi-user virtual reality at a distance are the main themes covered in connection with our research. This first section allows us to better understand the problem and identify the motivation of this research.

In the literature, we found that the use of multi-user remote virtual reality based on a BIM model is very limited in the construction industry. Typically, users must be present in the same location to immerse themselves in the virtual environment. Most virtual reality tools are limited to a single user, which does not enhance collaboration and communication. The development of a multi-user remote virtual reality platform based on BIM models can be a solution to bring together the stakeholders of a remote construction project in the same virtual environment to support collaboration.

3.2. Design and development of two prototypes

This step consists in designing and developing a prototype that answers the problems listed in the previous step. We will design two prototypes based on two different tools. (Photon Unity Networking " PUN2 " from Unity3D and Vizard). The development process of each prototype is divided into 3 stages: The pre-VR stage, the basic VR configuration stage, and the VR multi-user remote configuration stage. To develop the two prototypes, we used several tools that are available in the LaRTIC lab.

For prototype 1, we used the video game engine Unity3D and Photon Unity Networking (PUN2) since free versions are available. For prototype 2, we used Autodesk Revit. It is available for free to students and allows us to export the BIM model to an FBX file. We also used 3DsMAX to import the FBX file and export the BIM model to an OSGB file for transfer to Vizard Inspector. To create the virtual reality application, we used the Vizard application. To configure the remote multi-user feature in Vizard, we used two enterprise licenses of Vizard available at the research lab. The configuration is based on the integrated clustering-based collaboration module of vizard.

Finally, to live the multi-user remote virtual reality experience, we used the Oculus Quest headset, the 3D glasses, and the PPT wand of the multi-projection system (CAVE) installed at the lab.

3.3. Demonstration and evaluation

In this step, we presented a use case for each proposed tool. We then defined a hypothetical test scenario for each tool to perform our demonstration. The purpose of a test scenario will allow us to evaluate the usefulness and ease of use of the two applications in the construction industry. The two remote multi-user virtual reality support systems will be evaluated according to the following criteria:

- The maximum number of users in the same multi-user VR environment remote VR environment

- Voice communication between users in the VR environment.

- The type of network required (local/cloud) for the user to connect in the multi-user VR environment the remote multi-user VR environment.

4. Main results

In this section, we present the results of the comparative study of the two remote multi-user virtual reality systems. We will start with a detailed presentation of the use of the Unity3D and Photon PUN2-based system. We will then detail the use of the Vizard-based system. We will focus on the main process steps, including the PRE-VR step (integration of the BIM model into the VR system), the VR-Basic configuration step, and the VR-Remote multi-user configuration step. We will then define several criteria to characterize the potential of the two systems studied.

4.1. Remote multi-user VR environnent based on Unity3D + Photon PUN2

In this section, we will present the first process steps regarding the development of a remote multi-user VR environment based on the Unity3D + PUN2 game engine. Our method consists of integrating a cloud-based network into the Unity game engine to facilitate multi-user interaction in the virtual environment. It is composed of 3 main steps which we detailed in Figure 1.

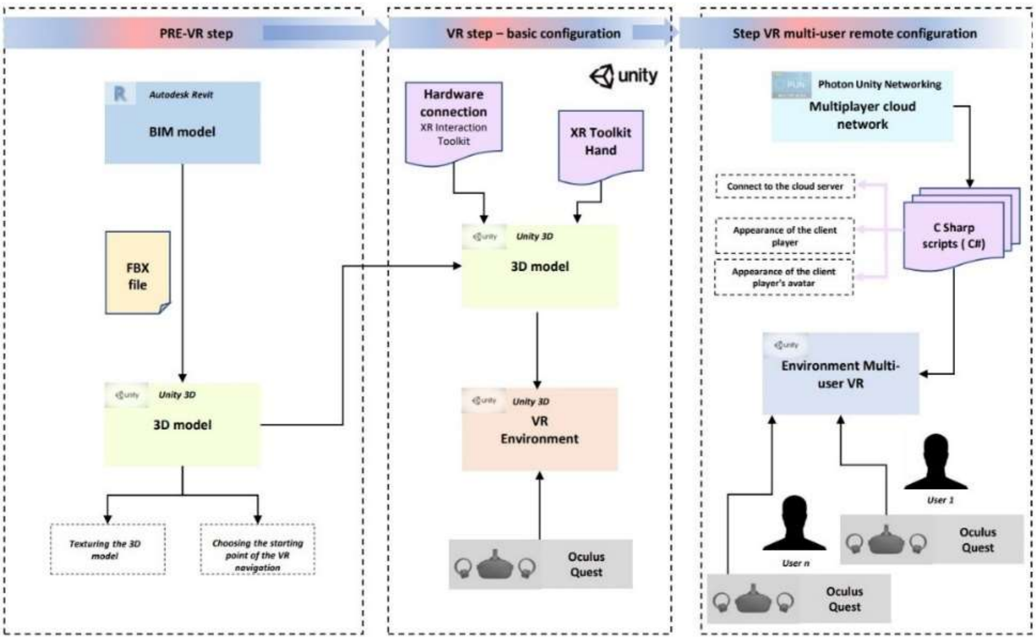

Figure 1: General development process of a multi-user VR environment based on Unity 3D + PUN2

We started to configure the VR environment in the Unity 3D game engine. Then, we implemented the Photon Unity Networking (PUN) library as a multi-user platform in Unity. To do this, we need to create a new Photon cloud account (free) on the official website. After that, we created the Photon cloud application The next step would be to connect to the PUN cloud server. For this, we created a code (script) with Microsoft Visual Studio that uses the C# programming language (C-Sharp).

Text-based communication is very limited in virtual environments due to the slow nature of VR keyboards. Voice communication can be a very interesting and more efficient collaborative solution. PUN 2 has simplified the process of implementing this functionality. Indeed, it has Voice over IP (VOIP) technology that allows the integration of a voice interactive system in the cloud server. Users who are present in the same VR environment can talk to each other with voices and make conversations. The virtual VOIP conversation is only possible if the two avatars are in proximity.

4.2. Remote multi-user VR environment based on vizard

In this section, we will present the process steps concerning the development of a multi-user VR environment based on vizard. The diagram below (Figure 2) summarizes the process of the proposed method concerning the development of a multi-user virtual reality environment based on Vizard.

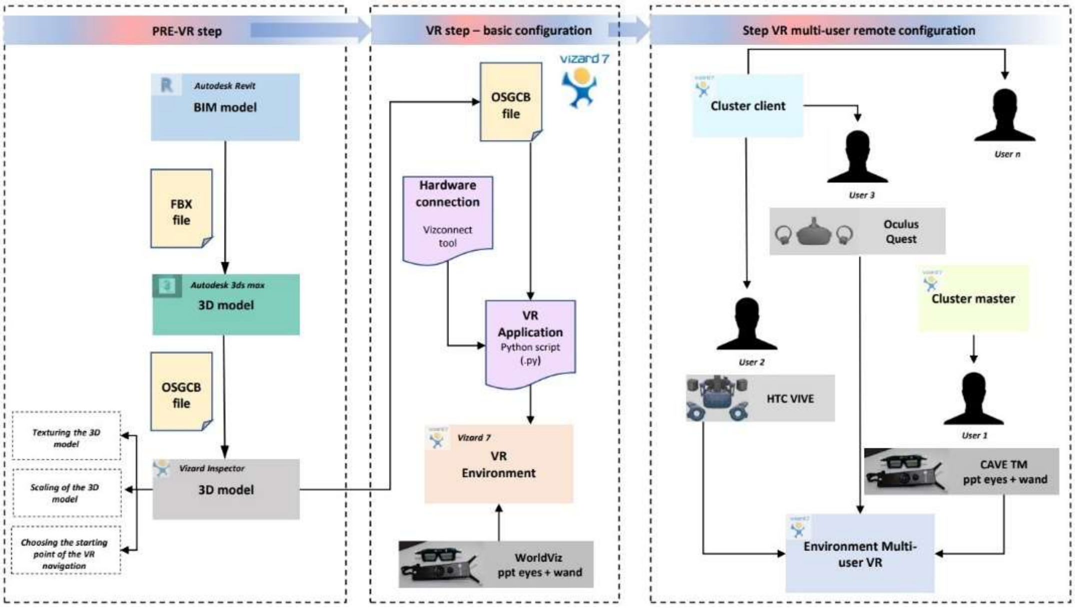

Figure 2: General process of developing a multi-user VR environment based on Vizard

The BIM model in Revit is first exported to an FBX file. The FBX file is then imported into 3DsMAX. At this stage, we noticed that the FBX file is very heavy to import into 3DsMax. To solve this problem, we had to clean up the model on Revit to make it light (remove parts, lights, etc.). Then, the 3D model in 3DsMAX is exported to an OSGB file using the "OSG Exporter" plugin. To have the 3D model at scale in the VR environment, it is necessary to adjust it in the export settings. The OSGB file is then introduced into the Vizard inspector. At this stage, it is possible to modify the scene by adding shadow and light and to modify the textures of the model's sub-parts if necessary. In addition, we can choose the starting point of the virtual visualization in vizard. To know the point of origin, we must add an avatar in the scene and then move the 3D model so that the avatar is in the desired initial position. In the second step, another script has been developed with Vizard allowing to execution of the virtual reality application.

To interact and collaborate in the VR environment, we tried to add 2 interesting tools to our VR application:

- The Pencil Tool: This tool allows you to make annotations in the VR environment or on the surfaces of objects. To add this function to our VR application, we improved our first script based on the documentation of vizard.

- The tape measure tool: This tool allows to measurement of the distance between two points in the VR environment. Indeed, when the user places the first point, the second point will automatically be placed orthogonally in front of the first point. The Vizard tape measure works with any geometry that exists in the VR environment.

This step involves configuring multiple users to be able to view the same virtual environment remotely with Vizard. This can be configured with several VR headsets (Oculus Quest, HTC VIVE Pro ...) and with the CAVE (Cave Automatic Virtual Environment) system. So, we used the cluster tool (cluster client/cluster master) of vizard. The implementation of the remote collaborative VR environment with the cluster tool requires that all users are connected to the same local network and that all machines have an enterprise license of Vizard. With the demo version, the cluster is limited to 5 minutes of execution.

a

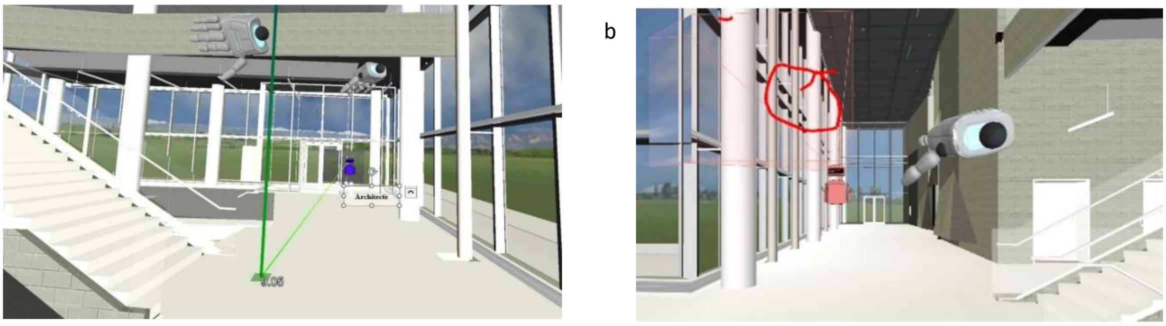

Figure 3: (a) The measuring tool in the multi-user VR environment; (b) the annotation tool in the multi-user VR environment

4.3. Comparison of two systems studied.

In this section, we will compare the two remote multi-user virtual reality support systems Unity3D + Photon Unity networking (PUN2) and Vizard. The results of the comparison can be seen collectively in Table 1 and are described in detail in the following paragraph.

Table 1. Comparison of the two tools proposed to support a remote multi-user VR environment based on a BIM model

Criteria	Sub-criteria	Remote multi-user VR based on Unity3D+PhotonPUN2	Remote multi-user VR based on Vizard
General	Price of a license	Free	Business license 2000$
	Number of users	20	No limits
	Open source	No	No
	Limitation (free version)	No limits	5min of execution
Type of network	Local Area Network (LAN)	Yes	Yes
	Cloud-based network	Yes	No
Tools for collaboration	Voice communication	Yes	No
	Annotation tool	Yes	Yes
	Measuring tool	Yes	Yes
Friendliness and Programmability	Visual inspection	Yes	Yes
	Programming language	C-Sharp (C#)	Python (Py.)
	Conviviality	Complicated	Simple
Supported hardware	Oculus Quest Compatibility	Yes	Yes

	VR CAVE compatibility	No	Yes
	Oculus Rift S Compatibility	Yes	Yes
	HTC Headset Compatibility	Yes	Yes
Interconnectivity	File type of the 3D model	FBX file	OSGB file
	Preservation of the texture	No	Yes
	Retention of model information	No	No
Realism graphic	Realism	Very good	Depends on the 3D model
	Light	Good	Complex
	Shadow	Automatic	Manual

General criteria:

The number of users in the remote multi-user environment is a potential sub-criterion for our comparison. The maximum number of users for the multi-user VR application based on Unity3D and Photon PUN2 (free version) is limited to 20 people while the number of participants is unlimited if we use the Vizard application. On the other hand, Unity3D and Photon (PUN2) are free, but they are not open-source. However, Vizard is available in several versions, and it is not open source. The multi-user version costs 2000$. The free version limits the execution time to five minutes.

Network type:

The type of network is another criterion for comparing the two proposed tools. To run the vizard application in multi-user mode and share the same virtual environment with team members, all users must be connected to the same local network. The geographical distance between users will be very limited because of this requirement. For example, it will not be possible to collaborate in the VR environment with team members who are located in another city using the Vizard application. However, the Unity and Photon (PUN2) based multi-user remote VR application uses a cloud network thus allowing users, with different geolocations, to connect and collaborate in the same virtual environment.

Collaboration Tools:

Collaboration tools are the second criterion for comparison. The multi-user Vizard application based on cluster nodes (master + clients) does not support voice communication between users. However, talking to each other with voices and making conversations between users in the virtual environment is possible with the VR application based on Unity and Photon (PUN2). Regarding the tools for interaction with the VR environment, Vizard has built-in tools such as the pencil for making annotations and the tape measure tool for taking measurements. Its tools are also available on the Unity game engine, but we did not integrate them into our application.

Supported hardware:

We used several other criteria to make our comparison such as compatibility with different VR hardware. Indeed, the Vizard application works with most virtual reality hardware through the "disconnect" display and tracking configuration tool.

For example, one user can use the CAVE system, the second user wears the Oculus Quest (HMD) video headset, and the third user uses the HTC VIVE headset and can meet in real-time in the same virtual environment. Moreover, the Unity3D-based application is compatible only with VR headsets (HMD, HTC VIVE). During our research, we explored a solution to integrate the Unity3D game engine into a CAVE system: MiddleVR. We did not test this solution because of costs and the unavailability of an educational license.

Usability and programmability:

The Vizard tool works with the Python programming language (Py.). To create a VR application with vizard, it is necessary to develop a script, many of the basic features of which are already provided in the application's documentation. However, Unity3D and photon (PUN2) use the C-Sharp (C#) programming language which is more difficult to understand.

Interconnectivity:

Interconnectivity with BIM software is another criterion that should not be overlooked. During the Pre-VR stage, the BIM model must be converted to an FBX file to integrate it into the Unity +Photon PUN2-based remote multi-user VR application, whereas the BIM model must be converted to an OSGB file to integrate it into the Vizard-based remote multi-user VR application.

5. Demonstration and evaluation

5.1. Demonstration of the Test Scenario

5.1.1. Scenario 1 based on remote multi-user VR using Unity3D + PUN2

In our hypothetical scenario, three users A, B, and C were using this application. Each participant was wearing the Oculus Quest video headset. The connection of each VR headset to the application is via Oculus Link, which connects the headset to the computer. User A played the role of the project owner who was not satisfied with the design of the coffee shop. User B played the role of an architect who is trying to redesign the design of the café according to the client's requirements. User C played the role of an interior Designer who was helping the architect redesign the coffee shop. As shown in Figure 56, the three participants are conducting the meeting in the same virtual environment.

Although the three users are not in the same location, the architect, interior designer, and owner, were able to meet in the same VR environment where they could discuss possible solutions to the problem during the meeting using the real-time voice tool (VOIP) integrated into our application. This voice system allows to stimulation of natural conversations. the voice is distributed according to the distance between the avatars of each user in the VR environment. This application allows a better communication approach between the project stakeholders compared to a traditional design review using 2D drawings or 3D models. This could minimize communication costs in the construction process.

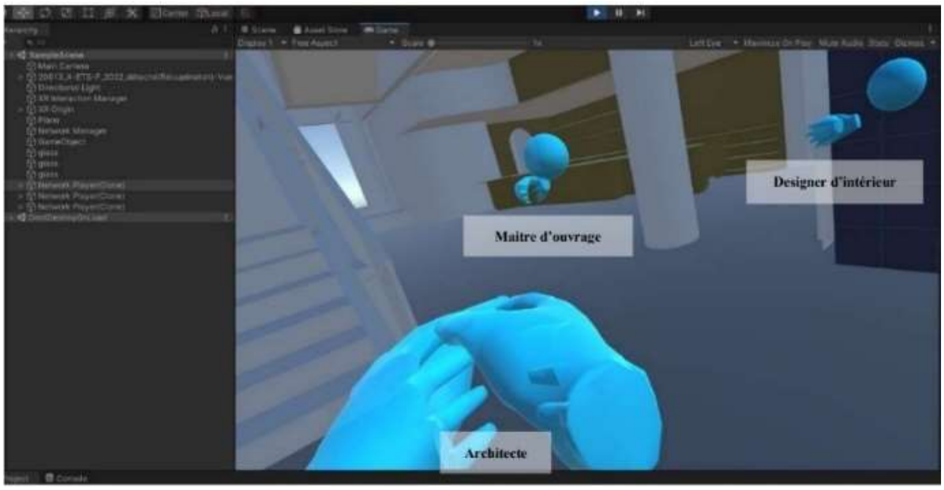

Figure 4: Meeting of 3 users in the multi-user VR environment based on Unity3D and Photon (PUN2)

5.1.2. Scenario 2 based on remote multi-user VR using Vizard

We have imagined a hypothetical scenario to demonstrate the usefulness of Vizard's remote multi-user VR environment. It is a design coordination meeting between two members C and D of the Pavilion D construction project team. We used 2 machines for our demonstration. The first machine is a Lenovo workstation (ThinkStation). It is linked to the 3-wall multi-projection virtual reality system (VR-CAVE) installed in our LaRTIC lab. It is equipped with a Quadro RTX 6000 graphics card. The second machine is an Alienware laptop. It is equipped with an RTX 3080 graphics card and linked to the Oculus Quest headset via Oculus Link. User C, who played the engineer, was using the Oculus Quest VR headset. User D, playing the role of the architect, used the 3D stereoscopic glasses and PPT wand of the CAVE-VR system.

The architect and engineer were able to meet in the same virtual environment from their respective remote locations. Both meeting participants can see each other, move around, and explore the 3D model to review the design from different angles without being limited to a single viewpoint as in 2D drawings. Each user can use his laser pointer as a measuring tool to verify that spaces meet construction standards.

Figure 5: Meeting between architect and engineer in remote multi-user VR environment based on vizard

5.2. Evaluation and discussion

In this section, we discuss the potential benefits that the two systems Vizard and Unity3D based on Photon PUN2 can bring to the construction industry as well as their limitations in supporting a remote multi-user virtual reality environment dedicated to the construction sector.

The two proposed systems Vizard and Unity3D+Photon PUN2 have the potential to play an important role in the construction industry. They enable the creation of a multi-user remote virtual reality environment that can bring many benefits to the industry, such as

Increased efficiency: Remote multi-user VR environments can be used for remote collaboration, project management, and virtual meeting allowing for more efficient teamwork while reducing the need for travel.

Improve design quality: Remote multi-user VR environments can be used for design review, allowing stakeholders to navigate and coordinate together in real time in the virtual environment to identify potential problems before construction begins.

Improve communication: Remote multi-user VR environments also improve communication between construction project teams, making it easier to understand the project and identify potential problems early on.

While Vizard and the Photon PUN2-based Unity3D game engine can be useful tools for VR collaboration in construction, they have limitations that must be considered:

Integration with BIM models: both proposed tools have limitations in integrating BIM models. The models must be converted into a format readable by each software. This conversion does not allow the transfer of model data into the VR environment. This makes the use of VR collaboration tools difficult and inefficient for reviewing and analyzing BIM models in real-time.

Technical Knowledge: Both Vizard and Photon PUN2 require a certain level of technical knowledge in programming languages (Python / C-Sharp) to use them effectively. This can make it difficult for some users such as non-technical members to participate in the collaboration session in the remote multi-user VR environment. In addition, Vizard and Photon PUN2 are not widely used in the construction industry, making it more difficult to find experienced consultants.

Cost: The cost of the enterprise license for the vizard tool is relatively high, which may limit the accessibility of this application, especially for small and medium-sized construction companies. In addition, both proposed systems require powerful computers and dedicated VR hardware to function properly, which may be beyond the budget of some companies.

6. Conclusion and future work

We can confirm that the two remote multi-user virtual reality support systems Vizard and Unity3D based on Photon PUN2 have the potential for use in construction with BIM models. However, both of its solutions have allowed us to identify some areas for improvement. Future work could include:

- Improving integration with BIM models: ways need to be developed to be able to transfer BIM models without losing model data into the Photon PUN2-based VR environment of Vizard and Unity3D so that remote VR collaboration can be better explored for real-time review and analysis of BIM models.

- Develop new functionalities: identify new use cases and develop new collaboration tools in the VR environment (screen capture, VR annotation export).

- Compatibility improvement: Develop a tool for the Unity3D game engine to be used with the CAVE multi-projection VR system.

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