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Virtual Reality Safety Training on Multiple Platforms

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Abstract: A construction site is a highly complex and constantly changing environment, where hazardous areas are difficult to detect if workers lack sufficient knowledge and awareness. Thus, frequent worker safety training is required. Numerous studies on using virtual reality (VR) for safety training were published. While they demonstrate the potential for improving the skills necessary to avoid accidents in the construction industry, they remain difficult to apply at actual construction sites. VR requires specialized hardware and software, limiting workers' access and restricting workers' participation in training sessions. As a result, this paper proposes multiple platforms for immersive virtual reality safety training (VRMP) based on Industry Foundation Classes (IFC) and web technologies such as immersive web (WebXR). The VRMP is compatible with mobile and desktop devices currently by workers and demonstrates scenario models familiar to workers. Also, it reduces development time by utilizing Building Information Models (BIM). Additionally, The VRMP collects data from workers in a virtual environment to assess each worker's safety level, assisting workers in effectively and comfortably gaining a better understanding and raising their awareness. This paper develops a case study based on the VRPM in order to assess its effectiveness.

Key words: multiple platforms, virtual reality, web technology, BIM, safety training

1. INTRODUCTION

A construction site is a dangerous environment with a high rate of accidents. According to the Occupational Safety and Health Administration, 1,061 construction workers died in 2019, with workers aged 25 to 34 being the most vulnerable on a construction site in the United States [1]. In Korea, construction accident rates increased from 0.75 to 0.84 percent. In 2016, fatal accidents decreased across the board but increased in the construction industry by 1.47‰ to 1.76‰ [2]. Up to 80% of fatal accidents occurred due to human error [3]. Workers are critical to the construction and typically perform extremely insufficient safety-related tasks—the fewer workers are capable of describing safe behavior. Workers' lack of safety awareness and knowledge can result in a catastrophic accident [4]. However, safety awareness and skills can be cultivated through education and training.

Numerous studies have established the value of VR in the construction industry, particularly for safety training. VR safety training is more effective than traditional methods such as lectures,

videos, or handouts [5]. However, the effectiveness of safety training systems developed exclusively for a single platform, such as a mobile or desktop[6]–[13], is reduced due to the lack of software and hardware at construction sites that meet the current VR system's requirements. Also, workers who do not have the necessary setup knowledge experience difficulties accessing these training systems. Furthermore, creating a safety training system compatible with mobile and desktop platforms requires a significant investment of time and resources [14]. Moreover, a few studies attempted to use BIM models for VR training but encountered difficulties, necessitating the conversion of IFC files (BIM format) to 3D format [9][11], which takes time. As a result, most construction site training sessions are currently conducted in a traditional manner.

With advances in web-based 3D visualization technology, the integration of virtual models has become possible. Web Graphics Library (WebGL) is a widely used JavaScript library that enables interactive 2D and 3D graphics rendering within any supported web browser without plugins. WebGL is fully compatible with other web standards, enabling the use of GPU-accelerated physics, image processing, and effects within a web page's canvas [15]. By converting IFC files to a different format, some studies attempted to integrate them with web technologies [16] and WebGL [13][17]. The increased use of BIM data occurs due to the 3D visualization of BIM models on the web via WebGL. Furthermore, Web Cross Reality (WebXR), which is based on WebGL, provides the interfaces required for users to develop compelling, comfortable, and secure immersive applications (VR and AR) on the web across a variety of hardware [18].

As a result, this paper proposes a VRMP for safety training to overcome the aforementioned limitations by utilizing workers' devices with IFC files and built on top of a web-based using WebXR, which provides immersive VR that enhances the workers' experience. An application was conducted to validate the VRMP. This application can run on multiple platforms (Android, IOS, Window, Linux, ...). Thus, employees have unlimited access to the training system at any location and are not limited to scheduled training sessions. In addition, the safety training system collects data from the employees in a virtual environment and uses it to evaluate the employee's performance.

2. LITERATURE REVIEW

VR is widely used to educate and train construction workers because VR simulates a dangerous training environment while still capturing the user's attention. The majority of construction sites, on the other hand, lack the resources necessary to conduct VR training, which requires expensive equipment and dedicated space. Additionally, VR frequently necessitates a thorough understanding of calibration, VR setup, and other related tasks [7]. A study used gaming technology to develop a system that circumvented the difficulties associated with risk detection. The system simulated high-risk behaviors and asked complex multiple-choice questions about the activity, requiring the trainee to take time to think before responding [8]. Collecting user data in VR environment was investigated to increase the effectiveness of VR safety training. The study aimed to develop a framework for collecting user data via hazardous scenarios and evaluating users' performance during safety education training [9]. Another study attempted to collect user position data in a mobile VR environment and then analyze the data using BIM software to understand the worker's spatial awareness [6]. Another approach for VR is to create a training scenario by exporting and importing a 4D BIM model and activity data into a game engine [7]. Additionally, one study attempted to enhance the VR environment by including audio and video instructions that described the overall hazardous situations and a module overview [10]. In another study, the users controlled a 3D crane to facilitate their interaction with virtual objects and enhance the VR experience [11]. While another study provides multi-level method training in which users must correctly answer questions before progressing to the next level [12].

The advancement of technology led to the introduction of a new building simulation method via virtual construction technology. BIM technology is primarily used for architecture design, numerical simulation of building performance, construction management, and building maintenance in building design and simulation. Numerous commercial BIM software packages are used. Their form, on the other hand, remains relatively autonomous. Therefore, developing an integrated method that can be applied by various stakeholders involved in the lifecycle of a building is difficult. As a result, IFC is critical in facilitating BIM data exchange. Additionally, numerous BIM solutions and application programming interfaces leverage web technology extensively (API). Previously, most research on this topic has focused on the semantic web and data standards rather than on visualization.

In this field, a study attempted to develop a VR training system by converting the IFC format to the Web Ontology Language (OWL) format using semantic web technologies [13]. The study notes that because 3D BIM models are detailed and complex, geometry optimization is impossible due to the lack of IFC support in modeling and optimization software. Another framework attempted to combine the advantages of IFC and web of data technologies by developing software tools for data conversion, status information exchange, and change management [16]. The aforementioned approaches are still limited to the conversion of IFC models to web-based 3D visualization. A study attempts to accomplish this by developing IFC-driven transformation systems capable of converting IFC to a Geometry Definition File (OBJ) [17]. On the other hand, direct transformation is more efficient for online exchange and sharing of IFC-format BIM models created in a Web browser without the need for client-side plugins.

3. VRMP DEVELOPMENT

This paper utilizes IFC files from the BIM software application and the JavaScript library (Three.js and IFC.js) to develop a VRMP application for displaying IFC elements on the web browser. IFC files generate a logically constructed building model from a pre-defined structure. The contents of an IFC file include geometric and non-geometric. There are three fundamental ways to geometrically represent a 3D IFC object: extrusions, solid body representation via a sweep, or boundary representation. The description of an IFC Element begins with a line categorizing, uniquely identifying, and naming the object. Each definition line for an IFC Element references other lines by the symbol (#). This reference structure is repeated until a logical data model for each object is generated. This method has the advantage of storing specific attributes only once and allowing them to be referenced by other components. Unfortunately, WebGL provides low-level access to hardware that can only draw basic objects such as a point, square, or line. In order to overcome this constraint, this paper uses the Three.js framework—an open-source project utilizing the WebGL API to render 2D and 3D objects on a canvas in the web browser via the GPU. Additionally, utilize IFC.js as a parsing engine and geometry generator; this library was created specifically to read data from IFC files line by line and can load large files in a web browser. The core of IFC.js is written in C++ and combined with WebAssembly (WASM), a language for web-based compilation of other languages, which enables the library to run at near-native speeds and performance.

Operating systems have quite distinct fundamental architectures and support for programming languages. Applications developed for a particular operating system are incompatible with those developed for other operating systems, necessitating the rebuilding of the same applications. As a result, the concept of a multiple platforms system can operate without special preparation across various platforms or operating environments. Web technology is rapidly evolving and is a critical component of the internet. Because web applications are intended to be accessible via any web browser, they are frequently referred to as multiple platforms applications.

They are gaining popularity at the moment, particularly in situations where compatibility and simplicity are valued more than advanced functionality.

Additionally, some studies utilize a database to store material and property data extracted from the BIM model and user data. Structured Query Language (SQL), a programming language designed for managing data and incorporating relationships between entities and variables, was used in previous studies. On the other hand, SQL requires the use of a pre-defined schema, which is incompatible with the VRMP. NoSQL is a good fit for the VRMP because it is intended to be horizontally scalable with a dynamic schema. NoSQL stores data in the JavaScript Object Notation format (JSON), familiar to web technology users. The VRMP is a web application that enables data transfer via the Hypertext Transfer Protocol (HTTP). Each time a user interacts with the virtual environment, a request is sent to the server to save their behavior, such as the user's position and objects with which the user interacts. Likewise, the virtual environment can retrieve the scenario through an HTTP request mechanism. Figure 1 illustrates the structure of the VRMP application.

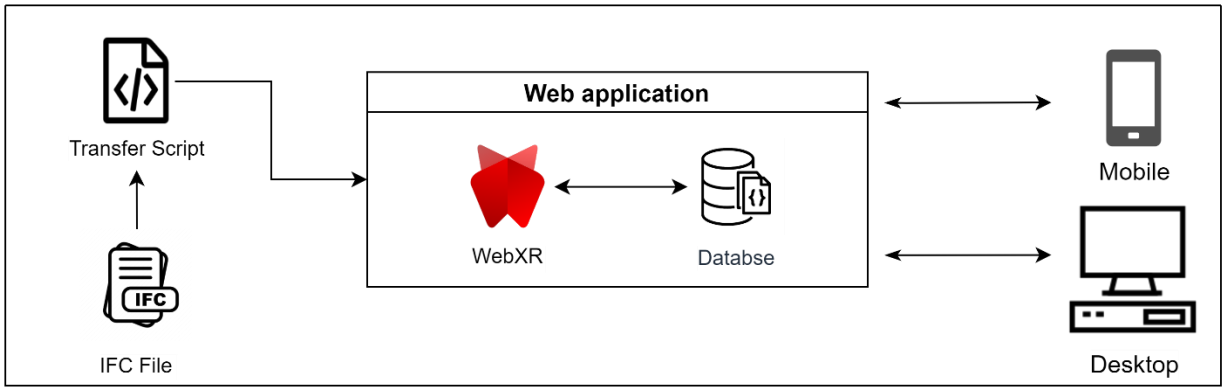

Figure 1. Structure of the VRMP applicaiton

4. SIMULATION AND EVALUATION

In this instance, this paper uses a technical school structural model from Autodesk Revit software and the methodology outlined above. The developed scenario model enables the user to detect and interact with the environment to resolve the hazardous areas (openings and elevator pits) — the scenario's objective. For instance, the user can draw the zoning directly into the virtual environment to highlight the hazardous areas. After that, the trainer can retrieve the data which collecting in the virtual environment to evaluate user performance

BIM software's geometry is extremely complex, making it difficult to visualize. This paper discusses a method for creating custom 3D geometry. WebGL geometry comprises multiple triangles meshes, each with three vertexes. Three.js provides the class to create custom geometry; the class contains positions, face indices, normals, colors, and UVs. Additionally, transferring an IFC file to WebGL is fraught with difficulties, where IFC.js comes in. As mentioned previously, we must define the vertex of each triangle in order to create custom geometry. Regrettably, the IFC file is a plain text file in which each line defines information and is identified by a unique number. Therefore, it does not contain vertex positions but instead expresses them using extrusions, solids, or boundary information. The script was created to read data from the IFC file and combine it with three.js to generate geometry in the web browser before using WebXR to provide immersive VR.

The VRMP is based on a web application compatible with a wide variety of different platforms. Web applications leverage a variety of specialized technologies and industry-standard

patterns to combine web and native app functionality. Installability is critical because it enables users to have application icons on their home screen and launch applications in their native container. It works with the vast majority of modern smartphone browsers. Additionally, Web applications can function independently of the internet by utilizing a service-worker feature to manage page requests and offline data storage. The VRMP will run on both desktop and mobile devices, and it will require the development of a mechanism for the user to navigate within the VR environment and the support of a variety of input devices. Furthermore, the VRMP stores user data, scenario details, and user behavior data gathered from the virtual environment in a NoSQL database, enhancing the application's effectiveness. The VRMP application is depicted in Figure 2.

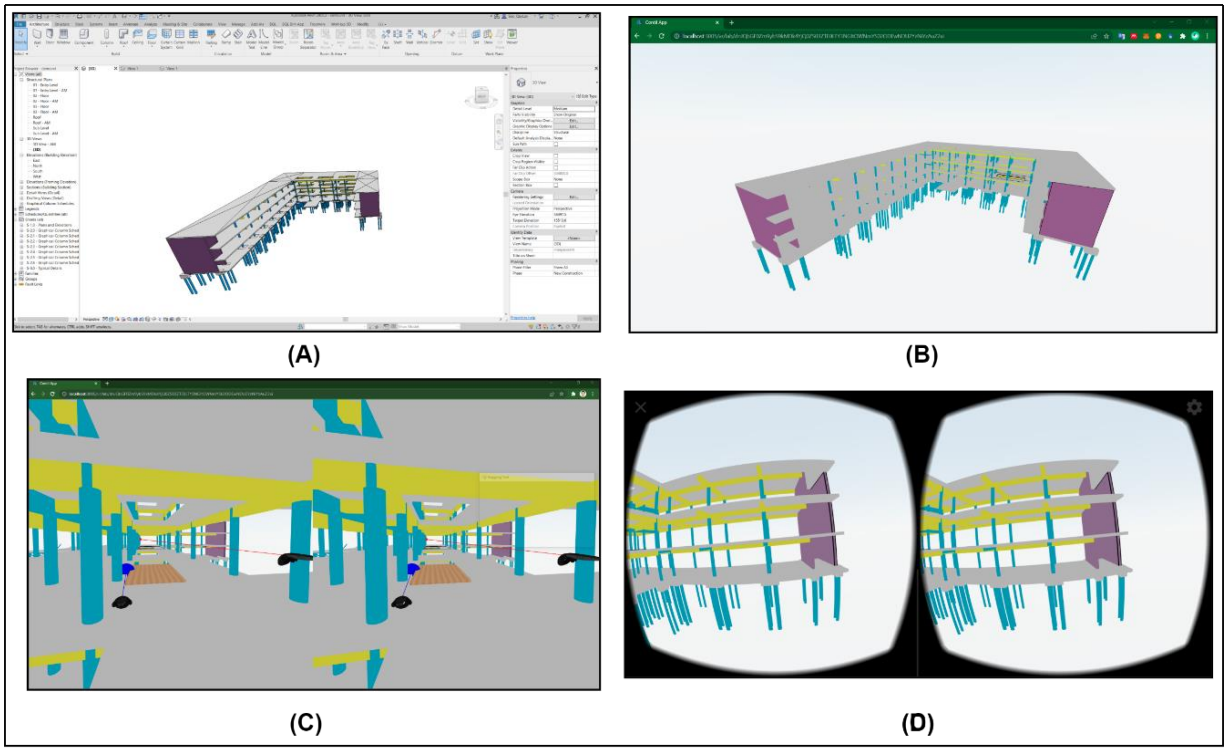

Figure 2. **(A)** BIM model in the Revit software; **(B)** IFC model in the web browser. **(C)** Immersive VR on desktop; **(D)** Immersive VR on mobile.

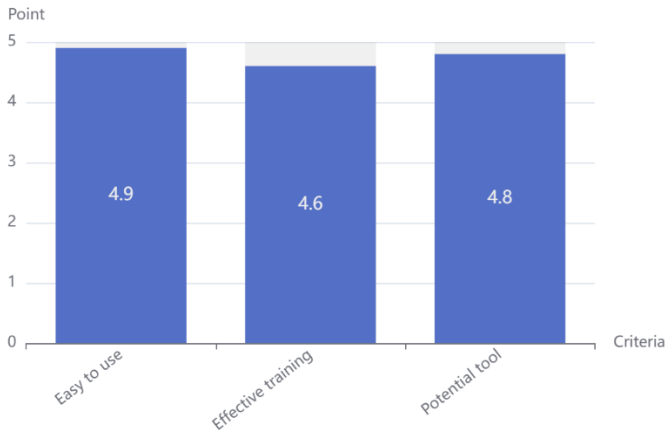

Figure 3. The evaluation result (Likert scale from 1 to 5)

Ten users, including professors and experts, have accessed the proposed application. It runs on various platforms, including desktop (Windows OS, Mac OS) and mobile devices (IOS, Android). After completing the scenario, users are prompted to participate in a survey to determine the feasibility of the VRMP. According to the survey results (Fig. 3), VRMP demonstrates the application's ease of use, accessibility, and compatibility with various platforms with a score of 4.9. Additionally, by utilizing the BIM model, the application provides a familiar experience for users by indicating their workplace and reducing the time required to develop scenarios, thereby increasing training effectiveness and highlighting at 4.6. Although the survey was conducted in a small sample size; however, the result of 4.8 demonstrates the VRMP potential to significantly improve VR safety training on construction sites by being simple to use, compatible with a wide variety of platforms and appealing to users.

5. CONCLUSION

Safety training is critical and must be conducted regularly during construction projects. A comprehensive platform for safety training is required to improve understanding and awareness of all roles involved in projects. By utilizing VR as a valuable tool, users can be immersed in a virtual environment similar to the real one, enhancing their experience and awareness of potential risks associated with the actual project. The main contribution of this paper presented an approach to developing a VRMP for safety training with advanced features and benefits that enables employees to easily access and use a safety training system via a web application, which can run on multiple platforms; therefore, employees easily receive regular safety training. In addition, VRMP can replace traditional safety tools at a low cost with minimal time investment.

With the rapid growth of technology, more features are required to increase the effectiveness of the VRMP. The VRMP is a single-player environment, which requires the user to train individually. However, experts suggest that team training should be used, as users can connect with one another and thus increase the effectiveness of the training. Multiple users and communication features should be supported in future work. Besides that, the virtual environment is less detailed due to device configuration considerations. Therefore, the VRMP needs a mechanism to improve the quality of virtual environments in the future. These features have the potential to improve the user experience and engagement significantly, thereby retaining users to receive safety training regularly. Finally, the VRMP should increase the number of validators, including construction site employees, to conduct evaluations.

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REFERENCES

[1] "Commonly Used Statistics | Occupational Safety and Health Administration." https://www.osha.gov/data/commonstats (accessed Nov. 29, 2021).

[2] "Ministry of employment and Labor." http://www.moel.go.kr/english/mobile/view.jsp?idx=1355 (accessed Dec. 09, 2021).

[3] T. Vondráčková, V. Voštová, and V. Nývlt, "The human factor as a cause of failures in

building structures," *MATEC Web Conf.*, vol. 93, p. 03005, 2017, doi: 10.1051/MATECCONF/20179303005.

[4] R. A. Haslam *et al.*, "Contributing factors in construction accidents," *Appl. Ergon.*, vol. 36, no. 4, pp. 401–415, Jul. 2005, doi: 10.1016/J.APERGO.2004.12.002.

[5] Y. Gao, V. A. Gonzalez, and T. W. Yiu, "The effectiveness of traditional tools and computer-aided technologies for health and safety training in the construction sector: A systematic review," *Comput. Educ.*, vol. 138, pp. 101–115, Sep. 2019, doi: 10.1016/J.COMPEDU.2019.05.003.

[6] V. Getuli, P. Capone, A. Bruttini, and S. Isaac, "BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach," *Autom. Constr.*, vol. 114, p. 103160, Jun. 2020, doi: 10.1016/J.AUTCON.2020.103160.

[7] V. Getuli, P. Capone, and A. Bruttini, "Planning, management and administration of HS contents with BIM and VR in construction: an implementation protocol," *Eng. Constr. Archit. Manag.*, vol. 28, no. 2, pp. 603–623, Feb. 2021, doi: 10.1108/ECAM-11-2019-0647/FULL/PDF.

[8] H. Li, G. Chan, and M. Skitmore, "Visualizing safety assessment by integrating the use of game technology," *Autom. Constr.*, vol. 22, pp. 498–505, Mar. 2012, doi: 10.1016/J.AUTCON.2011.11.009.

[9] E. L. Jacobsen, A. Solberg, O. Golovina, and J. Teizer, "Active personalized construction safety training using run-time data collection in physical and virtual reality work environments," doi: 10.1108/CI-06-2021-0113.

[10] S. Joshi *et al.*, "Implementing Virtual Reality technology for safety training in the precast/ prestressed concrete industry," *Appl. Ergon.*, vol. 90, p. 103286, Jan. 2021, doi: 10.1016/J.APERGO.2020.103286.

[11] S. Pooladvand, H. Taghaddos, A. Eslami, A. N. Tak, and U. (Rick) Hermann, "Evaluating Mobile Crane Lift Operations Using an Interactive Virtual Reality System," *J. Constr. Eng. Manag.*, vol. 147, no. 11, p. 04021154, Sep. 2021, doi: 10.1061/(ASCE)CO.1943-7862.0002177.

[12] Z. Xu and N. Zheng, "Incorporating Virtual Reality Technology in Safety Training Solution for Construction Site of Urban Cities," *Sustain. 2021, Vol. 13, Page 243*, vol. 13, no. 1, p. 243, Dec. 2020, doi: 10.3390/SU13010243.

[13] B. Schiavi, V. Havard, K. Beddiar, and D. Baudry, "VR Simulation of Operating Procedure in Construction Based on BIM and Safety Ontology: A Proof of Concept," pp. 126–141, Nov. 2021, doi: 10.1007/978-3-030-90739-6_8.

[14] M. Palmieri, I. Singh, and A. Cicchetti, "Comparison of cross-platform mobile development tools," *2012 16th Int. Conf. Intell. Next Gener. Networks, ICIN 2012*, pp. 179–186, 2012, doi: 10.1109/ICIN.2012.6376023.

[15] "WebGL: 2D and 3D graphics for the web - Web APIs | MDN." https://developer.mozilla.org/en-US/docs/Web/API/WebGL_API (accessed Dec. 27, 2021).

[16] S. Törmä, "Web of Building Data-Integrating IFC with the web of data," 2014, doi: 10.1201/b17396-27.

[17] Z. Xu, Y. Zhang, and X. Xu, "3D visualization for building information models based upon IFC and WebGL integration," *Multimed. Tools Appl.*, vol. 75, no. 24, pp. 17421–17441, Dec. 2016, doi: 10.1007/S11042-016-4104-9/FIGURES/13.

[18] "WebXR Device API." https://www.w3.org/TR/webxr/ (accessed Dec. 27, 2021).