A cross-platform-multi-user virtual training environment for waterproofing

Tero Kaarlela[1[0000−0002−6242−3661]], Tomi Pitkäaho[1[0000−0001−7482−8976]], and Sami Salo[1[0009−0009−7040−6632]]

Centria University of Applied Sciences, Vierimaantie 7, 84100 Ylivieska, Finland
tero.kaarlela@centria.fi, tomi.pitkaaho@centria.fi, sami.salo@centria.fi
https://net.centria.fi/en/rdi/

Abstract. Virtual environments enable trainees to develop their skills in diverse tasks, independent of time and location. In the construction sector, virtual environments are primarily utilized for safety training, while there are fewer implemented applications for hands-on construction tasks. This publication presents a platform-independent virtual environment for waterproofing training to address the issue. The presented virtual environment is a cross-platform application enabling multi-user training experience. A pilot was organized to collect feedback on the usability of the implemented virtual waterproofing environment. Results of the user questionnaire are presented and discussed to evaluate the usability and provide insights into the challenges and benefits of virtual training environments for hands-on training in the construction sector. In conclusion, the results highlight the potential of the developed virtual environment for waterproofing training.

Keywords: Cross-Platform · Virtual reality · Hands-on training

1 Introduction

Extended reality (XR) enables the physical world to be extended using virtual elements created by computers [10]. XR is divided into sub-categories of virtual and mixed reality (MR). MR allows the enrichment of the physical world using virtual elements and the enrichment of the virtual world using physical world elements. Unlike MR, virtual reality (VR) provides an entirely artificial virtual environment (VE) generated by computer graphics, enabling location-independent immersive learning and training. Head-mounted displays (HMDs) featuring displays, optics, speakers, a microphone, and, in some cases, a processing unit, immerse the user into an artificial audiovisual environment.

The pioneers who laid the foundations for VR decades ago understood its potential in training, learning, and entertainment [3]. In the Architecture, Engineering, and Construction (AEC), VR has been applied primarily to safety, management, and engineering training; hands-on training in construction tasks represents the minority of the applications. The adaptation of virtual training in AEC is still in its infancy, and to promote the adaptation, applications for training practical construction tasks are required [7].

Li et al. [5] reviewed the XR applications developed for the AEC domain. Construction is one of the most dangerous industries due to the high number of fatal accidents and injuries [1, 9]. Construction sites expose employees to falling, struck-by, electrocution, and caught-between hazards. More than half of the reviewed articles focused on developing applications for safety management on construction sites. Improving safety at construction sites overshadows the importance of training other skills, such as training skills required at construction sites.

VR applications for skill training focus on operating heavy construction equipment such as excavators [6] and cranes [12] at construction sites. In addition to training the equipment operation in a virtual world, some of the presented applications enable the teleoperation of the equipment. The teleoperation of heavy equipment aims to enable safe working in hazardous sites and to address the shortage of skilled equipment operators by enabling remote working. While the existing solutions include the skill training and teleoperation of the construction equipment, virtual training for hands-on skills is mostly unavailable, or the focus is on training safe operation rather than the skill itself [4]. In addition to VR applications for training safety and equipment operation skills, virtual training of practical hands-on skills is essential to addressing the shortage of skilled workers in the AEC.

To complement the virtual training environments for safety and operating equipment, VEs for training hands-on skills such as framing and waterproofing must be developed to increase the utilization of VR and evaluate its usability in hands-on skills training. This publication presents a platform-independent VE for hands-on waterproof training. The presented VE enables an immersive VR experience based on the digital replica of the bathroom the vocational college uses as the physical environment for on-site waterproof training. In addition, the tool selection replicates the tools available in the physical environment. The contributions of this publication are: 1) Present a cross-platform multi-user virtual training environment for waterproofing and 2) Study the usability of the VE for training waterproofing.

The rest of the publication is organized as follows: The next section describes the system specification and architecture, Section 3 presents the VE, Section4 describes the methods and results of piloting the VE, Section 5 discusses the results, and Section 6 concludes the paper.

2 Requirement specification and system architecture

This section presents the requirements specification and the system architecture of the presented VE. The requirement specification was an essential guideline followed during the architecture design and the implementation of the VE.

2.1 Requirement Specifications

The requirement specification was composed to define the functional and non-functional requirements based on the need for training basic skills of waterproofing. The group defining requirements consisted of the authors of this publication and the professionals from the construction department of the local vocational college. The group has in-depth knowledge of virtual training environments, construction, and pedagogy. Requirements were divided into functional and non-functional groups, and the non-functional requirements were further divided into the usability and performance subcategories (Table 1).

Table 1. Functional (F) and non-functional (N) requirements

ID	Description	Category
F1	Waterproofing using the immersive interface is enabled.	Functional
F2	Desktop interface enables one to observe the waterproofing training.	Functional
F3	Applying waterproof liquid using a virtual paint tool.	Functional
F4	Measure, cut, and applying of the waterproofing membranes is enabled.	Functional
F5	The user can hide material layers to expose the structures below.	Functional
N1	Support for twenty simultaneous users.	Performance
N2	Cross-platform support.	Usability
N3	The user can visualize the waterproof layer thickness.	Usability
N4	Updates or upgrades of the VE do not require end-user actions.	Usability
N5	Support for a wireless HMD to enable free movement for the user during training.	Usability

2.2 System architecture

The system architecture is based on the requirements specified for the VE in Section 2.1. Web-based XR applications provide cross-platform support, are accessible, and VE upgrades do not require user actions. Unity and Photon Unity Networking (PUN) were chosen to implement a cross-platform VE and enable multi-user capability. The PUN cloud service allows user clients to communicate with each other and share their status in the VE [2]. Figure 1 presents the solution's architecture.

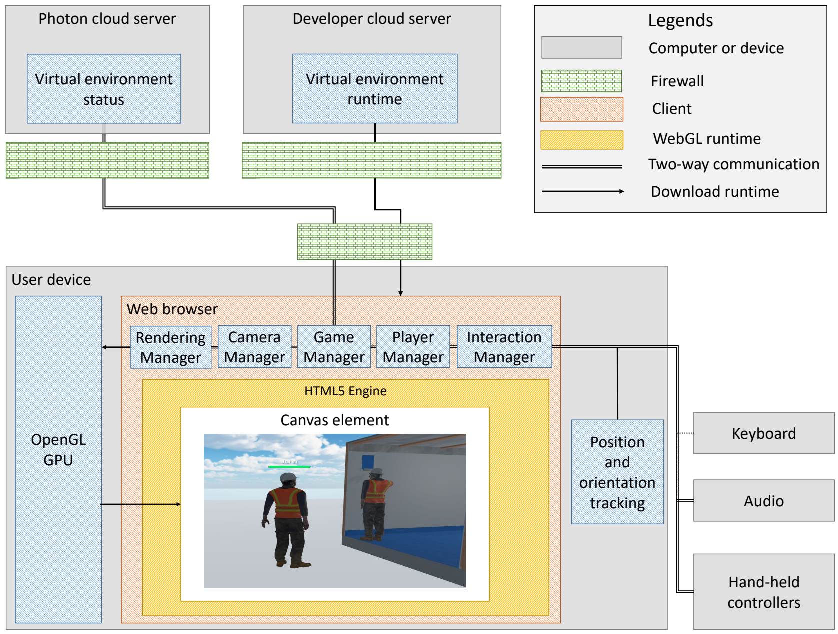

Fig. 1. The architecture of the virtual training environment.

The VE is initialized by accessing an online link to access the binary hosted at the developer server. After accessing the binary, the web browser on the user device executes the binary to render the 3D graphics and connect the input and output devices to enable interaction between the user and the VE. Five software modules enable the immersive or desktop cross-platform VR interfaces.

The GameManager handles the PUN communication, sending the local client's status to the server and receiving the status of the remote clients to update the local VE. The GameManager transfers the user to the training environment from the lobby, updates the position and status of the virtual users and objects, and exits the user from the VE.

The PlayerManager creates the avatar and updates the local user movements and avatar animation based on the VR controller or keyboard inputs. The local user position and rotation are passed to the GameManager to update the local user position on the PUN cloud.

The CameraManager attaches a camera to the user's avatar, enabling a first-person view of the avatar to the user. The camera is linked to the avatar during the initiation of the avatar, enabling each user to view the VE. The RenderingManager utilizes the Web Graphics Library (WebGL) JavaScript API and an OpenGL-compatible graphics processing unit (GPU) to render three-dimensional interactive graphics inside an HTML5 Canvas element.

InteractionManager is based on the WebXR device API standard and enables hardware access to provide an interactive user experience on a desktop PC or a mobile web browser [8, 11]. The interaction module provides the orientation and position of the hand-held controllers and HMD, keyboard input, and bidirectional audio, enabling the rendering of the virtual graphics according to user position and communication between the users.

3 Virtual training environment

The user onboarding into the VE initiates from the lobby. After the client connects to the PUN, the user inputs the desired user name and waits to join the PUN. The logged-in user is transferred from the lobby to the training environment.

GameManager onboards the user to the waterproof training environment. If the user device is identified as an HMD, an avatar for the immersive VE is initialized; if not, an avatar for the desktop user is created. After the player is initialized, the immersive interface users (IISs) can start the training, and the desktop interface users (DISs) can observe.

The IISs are given a task control panel to select the training task. The options are shown in Fig. 2c. Accessory functions include guiding the user by highlighting the surfaces to waterproof or resetting the environment to the initial stage. The VE is a digital replica of the bathroom structure fabricated for wetproof training in the physical environment. The complete VE is illustrated in Fig. 2.

The IIS can select the desired tool from a toolbox activated by clicking the side button of the hand-held controller. The goal for the IIS is to waterproof the virtual bathroom using the tools available. User experience design is important as it will take the user a while to complete the virtual waterproofing training, and some tasks must be repeated multiple times. All the waterproofing tools are easily selected through the toolbox menu with a button press. In some tasks, realistic physical activities are reduced or removed, and attention is instead focused on the user's choices and accuracy of performed actions. The waterproofing procedure is presented in Section 4.

Applying waterproof liquid on the floor and walls with a roller represents a unique approach, which enables a realistic way to waterproof in the VE. Multiple invisible layers are placed on every paintable wall and floor area, showing only the paint applied. The distance between the roller and the surface is calculated when the user brings the roller near the floor or wall surface. After a preset distance threshold is met, color trace is drawn from multiple points along the length of the roller onto the invisible layer. The waterproofing liquid is applied in two phases, and both have separate layers for receiving the paint. The color used for the waterproofing liquid is translucent, so when two overlapping layers of waterproofing liquid are applied, the resulting color has a darker shade, indicating a proper waterproof layer thickness.

Waterproofing tasks in the VE are guided with visual cues and haptic feedback to guide the trainee. During the placement of waterproofing membranes, the user is shown visual guides to highlight the correct inserting position. While

Fig. 2. (a) The lobby for onboarding the users, (b) view of the immersive user, (c) task control panel, (d) view of the desktop user, (e) waterproofing toolbox.

applying waterproof liquid using the roller, the trainee receives haptic vibration feedback on the hand-held controller.

The user can exit the environment by clicking the *Quit* button on the user interface.

4 Piloting

Twelve construction students from a local vocational college piloted the implemented solution. The participants' ages ranged from sixteen to forty years, and the level of experience in construction work was volatile. Feedback was collected after the pilot using a five-question questionnaire on a five-point Likert scale.

A piloting event was organized to validate the functionalities and to study the usability of the presented VE. The participants were physically present in the college classroom, one student at a time, training using an HMD. The piloting was led by an instructor from the vocational college. Before the training, the instructor gave the students an example of a correct waterproof procedure for the bathroom and explained the procedure using a flowchart (Fig. 3).

Fig. 3. Procedure to waterproof the bathroom. Steps 4. and 5. are interchangeable.

After the piloting, comprehensive user feedback was collected to evaluate the usability of the VE. Piloting enabled trainees to evaluate the usability of the training. User feedback was collected after piloting by providing participants an online link to the questionnaire; the online questionnaire was chosen due to easy distribution, automatic summarization of the results, and easy filling out. The questions were defined to evaluate the benefits and challenges of virtual training and to further improve the VE. A comprehensive survey based on the feedback is provided in section4.1.

4.1 Results

The summary of the user feedback is presented in Table 2. Most participants agree that training waterproofing in a VE is easy and that the darkening shade of the wetproofing liquid enables one to visualize the sufficient layer thickness. More than half agreed that the virtual tool selection matches the tool selection in the physical environment.

However, about half of the participants did not feel they had learned anything new about waterproofing during the virtual training, and less than half agreed or strongly agreed that training in the VE prepares them for waterproofing in the physical environment.

Table 2. Results of the feedback questionnaire

The Question	Strongly disagree	Disagree	Do not agree or disagree	Agree	Strongly agree
Training waterproofing in the VE was easy?	0 %	0 %	25 %	58 %	17 %
I did learn something new about waterproofing using the VE?	17 %	25 %	17 %	33 %	8 %
It was easy to visualize the sufficient waterproof layer thickness?	0 %	0%	25 %	67 %	8 %
Training in the VE prepares for work in a physical environment?	0 %	8 %	50 %	25 %	17 %
The virtual toolbox matches the tools in physical environment?	0 %	16 %	17 %	50 %	17 %
Free comment 1: The virtual training environment lacks the functionality to apply primer before waterproofing.					
Free comment 2: Virtual environment is great and prepares for working at the real construction site.					
Free comment 3: Correct the minor bugs, for example the cutting of membrane does not work always.					
Free comment 4: Please modify the application so that the paint tool does not go through the wall.					
Free comment 5: The application does not notify the mistakes such as a thin layer of waterproof liquid.					

5 Discussion

This publication presented a VE for waterproofing training, a hands-on skill required on construction sites. Web-based XR enables cross-platform usage, and PUN enables multi-user interaction for the VE. Users wearing HMDs access the immersive interface, enabling hands-on training to apply waterproofing liquid and membranes. Users not using an HMD access the desktop interface, enabling them to observe the waterproofing process.

A piloting group of twelve participants validated the functionality of the presented VE, and user feedback was collected after the piloting to evaluate the usability and receive feedback for future development.

Based on the feedback, training the waterproofing using the VE is easy. The VE's tools and functionalities match the physical waterproofing environment, and the shades of the waterproofing layer enable easy verification of the correct waterproofing thickness.

Most participants are unsure if the training in a VE prepares them for work in the physical environment. The uncertainty about transferring the skills trained in the VE to the physical environment may relate to the participants' varying backgrounds. Some participants had no prior practical knowledge of waterproofing, and it may be hard for them to define whether they can transfer the skills trained in VE to the physical environment. In addition, the free comments included a remark to add a layer of transparent primer as the first task before using the first layer of waterproof liquid and modifying the behavior of the virtual waterproof tool to collide with the drywall instead of penetrating it. Applying the mentioned changes increases the level of reality for the VE, improving the transfer of virtual to physical waterproofing skills.

6 Conclusions

This publication presented and studied the usability of a VE for wetproof training. The architecture is based on the idea that VE can be utilized independently of the trainee's location and time. Two user interfaces were presented: an immersive interface for the users wearing an HMD and a desktop interface for observing the training. A piloting study was organized to evaluate the usability of utilizing XR in waterproof training.

The presented VE enables training in everyday tasks related to waterproofing a bathroom and applying waterproofing liquid and membranes. In addition, the VE enables multiple users to train and observe the waterproofing using a desktop computer or an HMD. Users can interact with the VE using a keyboard or VR controllers and communicate with other users using a microphone and speakers.

In the future, VE can be extended to enable training in all the skills required for building the bathroom, including framing, drywalling, tiling, and painting. Extending the functionalities to cover all the steps enables comprehensive hands-on training on essential construction skills.

Acknowledgements This research was supported by the European regional development funding (Agreement J10275).

References

1. Brown, S., Harris, W., Brooks, R.D., Dong, X.S.: Fatal Injury Trends in the Construction Industry (2021), https://www.cpwr.com/wp-content/uploads/DataBulletin-February-2021.pdf
2. Chuang, T.J., Smith, S.: A Multi-user Cross-platform hands-on virtual lab within the Metaverse – the case of machining training. Virtual Reality **28**(1), 62 (Mar 2024). https://doi.org/10.1007/s10055-024-00974-5
3. Heilig, M.L.: EL Cine del Futuro: The Cinema of the Future. Presence: Teleoperators and Virtual Environments **1**(3), 279–294 (08 1992). https://doi.org/10.1162/pres.1992.1.3.279
4. Jelonek, M., Fiala, E., Herrmann, T., Teizer, J., Embers, S., König, M., Mathis, A.: Evaluating virtual reality simulations for construction safety training. i-com **21**(2), 269–281 (2022). https://doi.org/doi:10.1515/icom-2022-0006, https://doi.org/10.1515/icom-2022-0006
5. Li, S., Wang, Q.C., Wei, H.H., Chen, J.H.: Extended Reality (XR) Training in the Construction Industry: A Content Review. Buildings **14**(2) (2024). https://doi.org/10.3390/buildings14020414
6. Liu, D., Kim, J., Ham, Y.: Multi-user immersive environment for excavator teleoperation in construction. Automation in Construction **156**, 105143 (2023). https://doi.org/10.1016/j.autcon.2023.105143
7. Lopez, J., Bhandari, S., Hallowell, M.R.: Virtual Reality and Construction Industry: Review of Current State-of-Practice and Future Applications, pp. 174–184. American Society of Civil Engineers (2022). https://doi.org/10.1061/9780784483961.019
8. Maclntyre, B., Smith, T.F.: Thoughts on the future of WebXR and the immersive web. In: 2018 IEEE international symposium on mixed and augmented reality adjunct (ISMAR-Adjunct). pp. 338–342. IEEE (2018)
9. Man, S.S., Chan, A.H.S., Alabdulkarim, S., Zhang, T.: The effect of personal and organizational factors on the risk-taking behavior of hong kong construction workers. Safety Science **136**, 105155 (2021). https://doi.org/https://doi.org/10.1016/j.ssci.2020.105155
10. Milgram, P., Kishino, F.: A taxonomy of mixed reality visual displays. IEICE Trans. Information Systems **vol. E77-D, no. 12**, 1321–1329 (12 1994)
11. Ro'fatulhaq, H., Wicaksono, S.A., Falah, M.F., Sukaridhoto, S., Zainuddin, M.A., Rante, H., Al Rasyid, M.U.H., Wicaksono, H.: Development of virtual engineering platform for online learning system. In: 2020 International Conference on Computer Engineering, Network, and Intelligent Multimedia (CENIM). pp. 185–192. IEEE (2020)
12. Zhang, Z., Wong, M.O., Pan, W.: Virtual reality enhanced multi-role collaboration in crane-lift training for modular construction. Automation in Construction **150**, 104848 (2023). https://doi.org/10.1016/j.autcon.2023.104848