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Developing a Hybrid Learning Environment for Architectural Robotics

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The physical infrastructures needed for hands-on learning can be enhanced for efficiency and flexibility, meeting the rising student interest and adapting to the evolving educational landscapes. This article presents the ongoing development of a Hybrid Learning Environment (HLE) that adopts a blended approach to teaching robotics in design disciplines like architecture, building technology, and industrial design. Common platforms cannot replicate the experience of a physical learning space with tangible tools and materials, which are essential for hands-on learning in design education. This project tackles these concerns through an HLE that integrates VR and Robotics. The HLE includes a digital twin of the physical workspace created using a game engine. Different methods were explored to establish communication between physical and virtual environments. The empirical analysis of a preliminary version of the HLE demonstrates that it can enhance learning by making it more intuitive and engaging, making it easier to understand the complex operations of the robotic arm. The study also highlights further research directions, including addressing network security and latency issues, integrating multisensory approaches, and tackling the challenges in collaborative learning activities.

Keywords: *Architectural Robotics, Human-Robot Interaction, Virtual Reality, Hybrid Learning Environments, Architecture Education*

INTRODUCTION

This paper presents the ongoing development of a Hybrid Learning Environment (HLE) towards a blended approach to teaching robotics in architecture. The demand for robotics education has been growing and it requires specific physical equipment and skilled instructors, making it time and resource-intensive. To address this, new teaching methods and technologies are needed to make it more accessible using scarce resources. This paper introduces an ongoing project that responds to this need by integrating Virtual Reality (VR), Extended Reality (XR), and Human-Robot Interaction (HRI) in an educational context.

Problem Statement

Garrison and Kanuka (2004) define blended learning (BL) as the thoughtful integration of classroom face-to-face learning experiences with online learning experiences. According to Norberg et al. (2011), online and blended learning is the new normal, and they increase access for students to education, responding to their lifestyles through flexible learning opportunities. BL requires combining different learning modes such as synchronous and asynchronous, guided and self-paced, distance and on-campus, or individual and collaborative. Current multimedia-based materials and online platforms are fairly efficient and widely used for audio-visual and verbal communication in education. However, they cannot replace a classroom with physical materials and tangible tools such as a model-making workshop or a laboratory. So, the courses that require such facilities are not easily operable in all blended forms.

This project addresses this concern within a course that introduces robot programming and operation through training, experimentation, and production with a robotic arm. Adapting this course to blended learning presents challenges, including (i) the available infrastructure and allocated staff hours being inadequate in meeting the needs of large student groups, (ii) each student having a different learning curve and, therefore, (iii) the course is being inoperable when the laboratory is not accessible.

Objectives

The project aims to enhance the utilization of existing infrastructure and staff hours, enabling students to personalize their learning experiences based on their skills and expectations and ensuring continual access to the laboratory. To do so, the new learning environment and related pedagogical approach should align well with educational objectives.

One of the key objectives is to allow and encourage the students to construct new knowledge through experience, as addressed by constructivist learning theories. Marougkas et al. (2023) state that among the most frequently addressed learning theories within using VR in education is the constructivist learning approach, which emphasizes the active participation of learners in understanding a subject matter through hands-on experiences and interactions with their environment. This argument justifies the potential of VR to enhance constructivist learning when appropriately formulated. Similarly, Bashabsheh et al. (2019) argue that VR can be an essential tool to transform from teacher-centered to student-centered learning, which relates to the same key objective.

Specific to the type of education addressed in this research, embodiment is a crucial feature of learning activities, especially in design disciplines. Macedonia (2019) proposes embodied learning as an alternative to mentalistic education and points out the idea of creating learning contexts that allow brain-based instruction and embodied learning. de Klerk et al. (2019) emphasize VR's capacity to fill a gap by creating spaces in direct relation to the body, making it possible to assess the design of spaces at full scale as they are created. Thus, VR can be utilized to enable embodied learning with the right pedagogical approach.

Accordingly, this project develops and integrates a digital twin of the laboratory into the physical workspace, and a specific pedagogical approach and corresponding learning materials and activities are crafted within a blended learning format.

Method

The project produces an HLE by combining the physical laboratory with its digital twin. It is accessible through standard computers and ideally through VR headsets for a more immersive experience. Following the provided learning materials, students can engage with it using a game-like setup for self-paced learning. It supports both individual and collaborative tasks through single and multi-user access.

Additionally, the system allows controlled remote connection to the physical robot. This feature lets users operate it remotely and experience real-time tactile feedback via an integrated tele-manipulator. Eventually, specific learning activities and materials seamlessly integrate this HLE into the course. Herewith, it is aimed to; (i) enhance the infrastructure use by practicing some learning activities with the digital twin; (ii) optimize the staff hours by self-paced training; (iii) make the learning experience more adaptable to the skills and expectations of students; (iv) make education more inclusive for students and educators with special needs; (v) make education more resilient and sustainable in times of crises like pandemics.

RELATED WORK

The research in industrial applications that aim to integrate VR, XR, Augmented Reality (AR), Mixed Reality (MR), and Robotics is expanding. Coronado et al. (2023) present a review that explores the integration between physical robots and virtual environments through game engines, highlighting applications in social robotics, teleoperation, end-user programming, and Human-Robot Collaboration (HRC). Dianatfar et al. (2021) discuss the potential of AR, VR, and XR to increase the communication between the human and the machine. Cimino et al. (2019) present a review of digital twin applications in manufacturing, which provides insights into their use in educational contexts.

The research into the applications of VR in education is also broadening. Rojas-Sánchez et al. (2023) present an analysis highlighting the increasing interest in VR in education. Marougkas et al. (2023) point out a need for greater consideration of theoretical frameworks to optimize the alignment and effectiveness of VR in education.

Various reviews explore the benefits and challenges of VR, XR, AR, and MR in STEAM education (Science, Technology, Engineering, Arts, and Mathematics). There exist reviews on their use in AEC-related (Architecture, Engineering, Construction) education. Wang et al. (2018) provide a review of VR in construction engineering training and education, highlighting the potential of immersive VR, 3D game-based VR, and AR to enhance students' participation and motivation. Kamińska et al. (2019) point out the inclusiveness that VR can provide in education and emphasize the need for human interaction in learning activities. Kharvari and Kaiser (2022) present a review of XR in architectural education, showing their positive impact on learning outcomes and the design process, highlighting their benefits in design education, and addressing shortcomings in architectural education. (Tan et al. (2022) review the application of AR/VR in education and training in the AEC industry, and predict future trends.

More closely related to this research, there exist projects that address education where tangible interactions or spatial explorations are needed. Vergara et al. (2017) explore how virtual laboratories can enhance technical students' understanding of concrete compression tests through self-learning, improving their performance and providing a cooperative learning experience. Román-Ibáñez et al. (2018) explore the positive impact of VR on teaching robotics courses, presenting a custom simulation software that enables immersive experiences, enhances learning quality, reduces costs, and improves safety in education. Soliman et al. (2019) indicate the benefits of cost reductions by replacing existing expensive laboratories with VR, reduced infrastructure requirement for lab spaces, safer lab working environment for the students, and inclusivity for students with special needs. de Klerk et al. (2019) explore VR for architectural design review, highlighting its potential as an alternative and valuable complement to existing Computer Aided Design (CAD) applications, providing architects with direct spatial ideation and expeditious interaction for conceptual architectural models. Özgen et al. (2019) highlight the usability and effectiveness of VR in design education, demonstrating that VR enhances problem-solving activities for interior architecture and architecture students, making it a promising and complementary tool in basic design education. Bashabsheh et al. (2019) argue that VR facilitates a shift from teacher-centred to student-centred learning, enhancing students' interest and engagement. Kaarlela et al. (2022a) and Kaarlela et al. (2022b) propose digital twin-based virtual environments and teleoperation platforms for robotic training, utilizing XR to enhance the training experience, enable immersive teleoperation, and provide risk-free safety training. Ogunseiju et al. (2022) conclude that embracing MR as a pedagogical tool in construction education can be highly beneficial, and a well-designed and efficient MR environment is necessary for effective learning of sensing technologies in the construction industry.

THE COURSE CONTEXT

The project focuses on educational activities in study programs where hands-on design thinking is fundamental, like architecture, building technology, and product design studies. These programs involve courses where students use tangible tools and materials to develop, analyze, and present their ideas. They build physical models and prototypes to explore a design concept's spatial and material qualities and understand how a design would work in the physical world. These models are tools for students to think and interfaces of communication between fellow students and educators.

These courses often need exclusive spaces, like workshops or labs, to make these models through certain craftsmanship. It is challenging to make this type of learning activities blended because the current use of the existing facilities is not flexible enough and they do not allow remote access.

This project focuses on a course that introduces the students to architectural robotics. It is a 5-EC elective course in the Building Technology M.Sc. program. It is a hands-on course based on experiential learning and learning-by-doing. It integrates three components such as; (i) learning how to program and operate a robotic arm; (ii) developing and rationalizing a spatial design concept; (iii) making a scaled prototype of the design using the robotic arm.

Figure 1
A student project (Credits: A. Alsalhi, D. Aristizábal, A. Sadaphal).

The assignment challenges the students to make an architectural design that can be realized through the robotic assembly of discrete elements. They are asked to conceptualize an architectural idea, design discrete elements, devise strategies for assembly, and build scaled models using the robot. These stages unfold in a non-linear manner. The students revisit and modify the outcomes of different stages based on their evolving understanding of robotics and creative insights. It allows them to adapt and refine their design as they progress, fostering a more flexible and iterative design process. This is an exemplar of a reflective conversation with talking-backs between the designer and the material, a paradigm coined by Schön (1984). Based on the complexities of the architectural concept, structural performance, design of discrete elements, and assembly strategies, students need to program the robot to execute diverse complex movements. Figure 1 displays an exemplary student project.

Table 1
Course learning activities.

	Activity type	Objective	Space	Teacher Presence
1	Lecture	Understand robotics.	Classroom	Yes
2	Lecture	Develop offline robot programs.	Classroom	Yes
3	Tutoring	Operate the robotic arm.	Lab	Yes
4	Self-study	Operate the robotic arm.	Lab	No
5	Self-study	Develop a spatial design.	Studio	No
6	Critiques	Develop a spatial design.	Studio	Yes
7	Critiques	Build a prototype.	Lab	Yes
8	Self-study	Build a prototype.	Lab	No

Table 1 presents the main course activity types, their objectives, the type of space they need, and whether or not the teacher needs to be present for that specific activity.

The students first receive training on programming and operating the robot through its teach pendant using Polyscope (the software interface between the operator and the robot). Simultaneously, they develop computational designs using Rhino and Grasshopper (GH) software. Then, they use the visose/robots plugin in GH to develop the robotic assembly for their designs, simulate it, generate the robot program, and send it to the robot. This design-to-production workflow is one of the course learning objectives.

DEVELOPMENT OF THE HLE

The HLE is the blend of the existing robotic fabrication workspace and its digital twin through XR. The initial step involved developing a digital twin of the robot workspace. This was achieved by generating a responsive 3D model using Blender software, which was imported into Unity to construct the VR environment that mirrors the physical workspace. The review of Coronado et al. (2023) identifies commonly used and relevant software frameworks and tools used by the robotics community to integrate physical robotic platforms with virtual elements generated by game engines and concludes that the Unity game engine was the most commonly used platform and it presents a lower learning curve and requires fewer programming skills to build virtual worlds.

In this VR environment, the users can move the robot, configure settings, transmit output signals, and create programs. The immersive experience unfolds within the VR environment, affording users a lifelike 3D experience. This stands in contrast to the customary 2D representation on a computer screen.

The following step involved developing the hybrid environment by establishing mutual communication between VR, Polyscope, GH, and the physical workspace. Different methods were explored for this purpose.

Exploration 1: Integration with RhinoCommon API

This exploration aimed to integrate the design-to-production workflow into VR. The visose/robots plugin was customized to output a JSON object (J), including the robot program instructions. J was imported into Unity via RhinoCommon API. This method enables the program to be sent from GH to VR and the robotic arm simulation to be observed here. It allows users to move the robot in VR by gripping and moving a cube or manually adjusting the robot flange through handheld controllers. In both cases, the robot tracks a target (whether it is on the cube or the robot flange), which dynamically updates the program as the target's position changes. Despite the successful communication between GH and VR, latency was experienced. The processing of the J generator was considerably slow, potentially accounting for the latency

Exploration 2: Connection Through MQTT

This exploration aimed to test the usability of the Message Queuing Telemetry Transport (MQTT) protocol between VR and robot. The test was done using the virtual Polyscope (running on URSim Emulator Software) instead of the physical robot. An MQTT Connector Plugin (the trial version of MQTT Connector Professional URCap) was used to communicate between Polyscope and the MQTT Broker (Eclipse Mosquitto). A program was developed in URScript to generate the JSON objects received by the connector plugin. The MQTT broker facilitated communication with Unity through a dedicated library (M2MQTT for Unity).

A considerable latency between Polyscope and the MQTT Broker was observed with this method. It was assumed that the URSCript program was the cause of the delay in the messages sent to the MQTT Broker.

Exploration 3: Connection Through TCP

This exploration aimed to test the usability of the Transmission Control Protocol (TCP) between VR and the robot. TCP is free to use and already installed on the robot software. The test was done using both the virtual Polyscope and the physical robot. PolyScope inherently incorporates TCP, functioning via an Internet Protocol (IP) address (TCP/IP). A program was developed to translate robot software instructions into Bytes. Unity then receives and transforms these Bytes in the same way, ensuring synchronization with the robot.

This method enabled the connection between VR and virtual Polyscope. It also enabled mutual communication with the physical robot, allowing collaborative interactions involving two users: one interacting with the robot through VR and the other interacting with the physical robot. It also enabled live streaming from a camera at the physical workspace, allowing the user to see the robot's movements in a dedicated panel inside VR.

Exploration 4: Connection Through Web Server

This exploration aimed to test the usability of a web server to control and manage the traffic between multiple software and hardware (Figure 2). A web server was developed using JavaScript. It connects multiple virtual Polyscope users, the physical robot, the cameras, and the digital twin and makes it accessible through VR. The communication between the web server and Polyscope (both physical and virtual) is achieved through TCP. The cameras are developed using Raspberry Pi Cameras (Module 3). They monitor the physical workspace and live stream to VR through the web server. They communicate with the web server through Real-Time Streaming Protocol (RTSP). The live stream is shown on a specific screen in VR. A WebSocket protocol is used for the communication between the digital twin in Unity and the web server. Through this protocol, interaction with Polyscope through VR becomes possible, and the robot pose and camera can be transferred to VR. The user's interaction with Polyscope is achieved by using x11vnc, a Virtual Network Computing (VNC) server. It allows the user to interact with the Polyscope interface. Thus, the user uses the actual robot software to operate the robot, enabling accurate inverse kinematics calculations. Moreover, when multiple users are connected to the same workspace, they all see the same interface on their virtual teach pendant. The teach pendant control can be handed over with a button attached to the pendant. Eventually, the user interacts with the digital twin through a VR headset and controllers. However, interaction is possible through a standard computer setup as well. The use of a Web Server, as explained here, was observed to be functional for setting up the HLE, allowing smooth communication between physical and virtual environments.

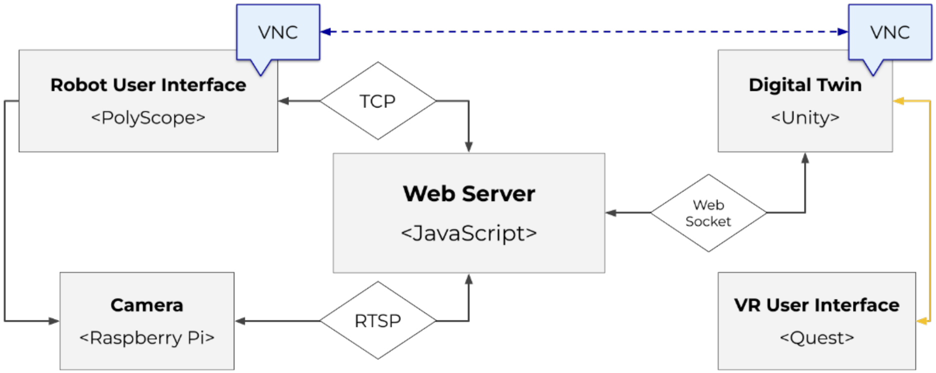

Figure 2
Connection through web server.

Evaluation of the Preliminary Use

A series of tests were conducted to empirically analyze the HLE's affordances and identify the need for its seamless integration into the course. The users had sufficient knowledge and skills in using the physical robot. They used and evaluated the hybrid platform and compared its use with the physical robot. They tried to; (1) Move the virtual robot using a standard computer setup; (2) Move a physical object using the robot by operating it in VR through a headset; (3)Repeat the 2nd operation while receiving instructions from another user physically at the robot workspace. These experiments demonstrated that the VR experience (Figure 3) is more intuitive, engaging, and realistic when compared to the standard computer setup. It facilitates enhanced robot observation from multiple angles, helping in a comprehensive 3D understanding of its operations. Using a VR headset makes it challenging to experience a sense of safety and move around physically in the room. While in VR, receiving feedback from a collaborator in the physical workspace proves reassuring when completing the operations. Effective collaboration between the physical and virtual environments requires a well-defined mode of communication. Finally, the sense of touch was absent in VR, a gap that can be restored by implementing tangible interfaces.

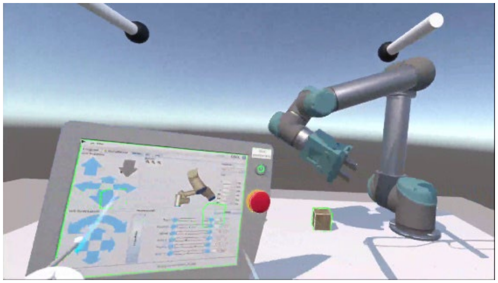

Figure 3
A screenshot from the workspace in VR.

THE USE SCENARIO

Eventually, the learning activities outlined in 3, 4, 7, and 8 in Table 1 will be practiced through the HLE. The HLE involves the standard Learning Management System (LMS), an Open Educational Resource (OER) Platform, The VR environment, and the physical lab. The LMS contains course management tools and materials, including communications, submissions, and assessments. Typical learning materials, including video tutorials and self-assessment tools, are hosted on the OER Platform.

The VR Environment provides two modes: Standalone and Connected. The Standalone mode includes game-like exercises that guide students through specific tasks (such as creating a designated toolpath or moving an object using the robot) aligned with the tutorials. Here, the students can use much time as they need to practice what they learned in the tutorials. It also allows them to experiment with the functionalities available in Polyscope and simulate the programs they made in GH. This mode can also be used collaboratively if a user sets up a web server and shares it with others.

The Connected mode is exclusively available to enrolled students with access on a schedule. It enables remote connection to the robot through VR. It is used to operate the robot, send programs to it, and monitor the workspace. It allows collaboration between several users, remote or on-site, while at least one on-site operator is needed. This mode can be used both for training and for actual prototyping phases.

DISCUSSIONS

The project's current challenges relate to network protocols. A local web server is used to communicate between VR and the physical robot. It is planned to host the web server on the campus network and make it available to (confirmed) users through the Internet securely. Additionally, accessing the HLE from outside the campus may reduce connection quality, particularly for users with limited bandwidth. To mitigate this issue, an additional layer of interaction control can be introduced between the remote operator and the physical robot. This layer can manage the data transfer sequences to lessen latency issues and improve safety in the physical workspace.

An additional potential challenge relates to equipment requirements. The optimal scenario requires VR headsets, which might not be accessible to all students. This project aims to minimize this issue by following OpenVR standards, enabling compatibility with devices from various vendors in the market. In the least favorable scenario, the platform remains functional without a headset. Then, users will access the platform via a standard computer, retaining full functionality but without the immersive VR experience.

A significant future research objective will involve incorporating tactile sensations into the VR experience. Integrating equipment like VR gloves and teleoperators can introduce the required tangible dimensions. Furthermore, adopting a multisensory and multimodal approach can provide substantial advantages, including a more immersive experience, a potentially improved feeling of safety, and more seamless collaboration between on-site and remote participants.

Enhancing collaboration between on-site participants and those engaging remotely also relates to structuring the learning exercises. Even within a multisensory and multimodal VR environment, achieving identical sensory experiences for remote and on-site participants will remain challenging. Hence, the learning exercises should include clarified strategies for effectively communicating information. This final challenge is more closely linked to the pedagogical approaches rather than the technological aspects. Eventually, the effectiveness of the HLE must be evaluated through workshops with students, following the theoretical framework presented.

CONCLUSIONS

This paper presents the theoretical framework and ongoing applied research regarding developing an HLE tailored for blended learning on robotics in design disciplines. The empirical analysis of initial project outcomes confirms that the acquisition of robot programming and operational skills can be sustained within a blended format by adopting an HLE that integrates the physical workspace with its digital twin in a VR environment.

As per the findings of this research, the most effective approach for establishing communication between VR and the physical robot is using the TCP protocol between platforms and managing the traffic through a custom web server. This choice for TCP is justified by its capacity to mitigate latency issues, cost-free nature, and integration within the existing robot software. The web server is utilized for easy communication between several platforms, including multiple users. With this method, multiple users can collaboratively participate in the learning activities, enabling a blend of on-site and remote engagement. The test use of a preliminary version demonstrated that it is intuitive, engaging, and offers a more realistic experience than the digital simulations on a standard computer setup. It has the potential to enhance remote learning by enabling improved observation of the robot's operations from various angles, similar to a real-world experience. It can facilitate effective remote collaboration, provided that the communication methods are defined and well-structured within the learning exercises.

Further system improvements can be achieved by incorporating tactile feedback through devices such as VR gloves or tele-manipulators alongside a multisensory and multimodal VR approach. This addition can further enrich the VR experience while reinforcing the user's sense of safety within the VR environment. Eventually, customized learning activities and pedagogical approaches are needed to integrate the HLE into education.

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