Work in Progress: VR-based Robotics Training for AEC Industry

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***Abstract*—This paper introduces the Intelligent Learning Platform for Robotics Operations (IL-PRO), a Virtual Reality (VR) system designed to enhance robotics training in the Architecture, Engineering, and Construction (AEC) industry. IL-PRO addresses the growing need for effective training methods as the AEC sector adopts robotic automation. The system integrates VR technology with game-assisted learning, combining online multimedia lessons for theory with immersive VR tasks for practical skills. Developed iteratively using Design-Based Research principles, IL-PRO incorporates realistic robot simulations and progressive task complexity. The VR environment, built in Unity, aims to enhance engagement, motor coordination, and spatial awareness in robotics training. While future goals include AI-driven personalized instruction, this work-in-progress focuses on VR curriculum development and implementation. The paper concludes by discussing future directions, including curriculum expansion and cross-institutional adoption, to establish new benchmarks in innovative robotics education for the AEC industry.**

Keywords—curriculum, AEC training, robotics, virtual reality, immersive learning, artificial intelligence

I. Introduction

The Architecture, Engineering, and Construction (AEC) industry is undergoing a significant transformation driven by the increasing adoption of robotic automation processes. This shift demands a workforce equipped with the necessary skills to operate and maintain these advanced technologies.

In recent years, Virtual Reality (VR) technology has emerged as a transformative educational tool, offering immersive and interactive experiences that traditional teaching methods cannot replicate [1]. This is particularly pertinent in teaching robotic arm operations, where safety, manual skills, and spatial awareness are essential [2,3]. Traditionally, training roboticists requires extensive hands-on practice, which can be costly and poses inherent risks. VR simulations address these challenges by enabling students to develop and refine their skills in a controlled, immersive environment without the hazards associated with real-world equipment [4]. By simulating industrial robotic arm operations, VR enhances motor coordination, spatial awareness, and reaction times [5].

Empirical evidence supports the effectiveness of VR in educational settings. A comprehensive literature review [6] demonstrated that VR enhances knowledge acquisition and spatial ability in training settings. Additionally, VR allows students to visualize and interact with complex 3D objects, deepening their comprehension and retention [7].

However, despite these advantages, many educational fields have been slow to adopt VR technology. Kraus et al. [8] note that most colleges and universities specializing in architecture, engineering, and construction have been hesitant to fully integrate advanced digital learning tools, particularly extended reality (XR) technologies, into their curricula. Those that have adopted such tools have generally done so on a limited scale.

This paper introduces the Intelligent Learning Platform for Robotics Operations (IL-PRO), an immersive learning system that integrates VR and game-assisted learning to teach robotic arm operations. The platform aims to enhance the learning

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process through engaging and interactive VR simulations [9,10]. While IL-PRO's long-term goal is to integrate AI models for tracking student performance and providing personalized instruction, this work-in-progress paper has a more specific focus. It primarily addresses the development of the VR curriculum and the creation of immersive learning experiences for training students in the AEC industry.

II. Project Background

IL-PRO is driven by several key objectives aimed at enhancing the design, methodologies, and learning theories of technology-mediated educational environments. It focuses on developing an Adaptive Intelligent Learning System (AILS) that integrates advanced technologies to track and analyze student performance. AILS are frameworks that aim to optimize the learning process for each learner. They build on domain knowledge, instructional information, and learner data to analyze and assess learning patterns. AILS's capacity for prediction and decision-making regarding the learner's progress enables customized content delivery, alternative learning paths, targeted advice, and timely feedback, all based on data-driven insights [11,12,13]. According to Adam, implementing AILS in educational settings is leading to significant improvements in student engagement, comprehension, and retention rates [14].

A central component of IL-PRO is the development of a VR environment designed to facilitate comprehensive data collection on student performance through telemetry and speech data. This data is analyzed using multimodal Machine Learning (ML) and Natural Language Processing (NLP) algorithms to assess comprehension levels and automate the delivery of tasks and feedback. IL-PRO employs a VR-based game-learning approach to boost engagement, motor coordination, and spatial awareness. Students interact with simulated robots and input devices to solve task-based challenges, structured like game levels with increasing complexity. This design systematically builds their knowledge, skills, and confidence in robotic operations by providing progressively challenging tasks.

III. Methodology, Methods, and Data Collection

In this project, we have employed a mixed methods approach to develop and evaluate our VR training curriculum. Our research design was primarily guided by Design-Based Research (DBR) principles [15], complemented by user-centered design [16] and iterative prototyping methodologies. Following DBR protocols, we engaged in iterative cycles of design, implementation, analysis, and refinement. Each design prototype was examined and evaluated in situ with diverse student groups [17,18], allowing for continuous improvement based on real-world testing and feedback.

For the software development aspect, we implemented an Agile methodology [19], organizing our work into short, iterative sprints. This approach enabled rapid prototyping, and frequent iterations based on user testing and stakeholder feedback, aligning well with our DBR framework. The Agile method facilitated close collaboration between our research team, developers, and end-users, ensuring that our VR training system remained responsive to both educational goals and user needs throughout the development cycle [20].

Our methodology incorporates AI-driven analytics to enhance adaptive learning. We developed modular VR tasks focusing on specific robotics skills. ML and NLP models analyze user performance data [21], dynamically adjusting task difficulty and recommending personalized learning paths. This approach enables a flexible learning experience tailored to each student's needs [22], with built-in bias mitigation techniques [23]. Our data collection framework incorporated multiple methods: 1) Telemetry data captured user interactions, task completion times, and error rates [24,25]; 2) Think-aloud protocols provided insights into users' thought processes [26,27]; 3) Pre-and post-assessments measured knowledge acquisition and skill development [28]; and 4) Usability testing sessions evaluated UI intuitiveness, simulation realism, and user experience [29].

This comprehensive approach, combining DBR, user-centered design, Agile development, and AI-driven adaptivity, provided a robust framework for creating an engaging and personalized VR learning experience for robotics education in the AEC industry. The integration of these methodologies allowed us to maintain a balance between rigorous research practices and flexible, responsive software development throughout the project lifecycle.

IV. Immersive Training Curriculum

The curriculum is structured into two complementary components to optimize both theoretical understanding and practical skill development for robotics. Initially, students engage with a series of online multimedia lessons designed to establish a foundation in essential robotics concepts. These lessons cover critical topics such as robotics operation and safety, kinematic chains, jogging commands, reference frames, and end-of-arm tooling. By delivering foundational knowledge online, the curriculum allows students to progress at their own pace, ensuring a comprehensive grasp of theoretical principles necessary for advanced, hands-on applications. Each online lesson is interactive and self-paced, featuring clearly defined learning objectives and key terminology. Animated examples demonstrate the practical application of these concepts in robotics, enhancing comprehension (Fig.1). Completion of these multimedia lessons is a prerequisite for advancing to the next phase of the curriculum, ensuring that students are well-prepared with the necessary theoretical background.

Upon mastering the theoretical content, students transition to the second component of the curriculum, which involves immersive, task-oriented activities within the VR environment. This phase allows students to apply their acquired knowledge in a controlled and interactive setting, where they can practice motor skills, enhance spatial awareness, and gain hands-on experience with robotic systems.

To evaluate student performance within the VR tasks, a comprehensive assessment strategy is employed. After each VR activity, students participate in the "Think Aloud" exercise, verbalizing their strategies and thought processes used to complete the task. This reflective practice offers valuable insights into their problem-solving approaches and cognitive engagement. Additionally, students respond to targeted questions designed to assess their understanding and ability to apply the concepts learned in practical scenarios. This

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combination of immersive task performance and reflective assessment provides a nuanced evaluation of student learning within the adaptive learning system.

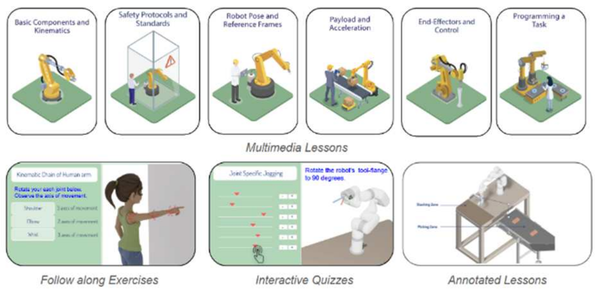

Fig. 1. Captures from Multi Media Lessons, including follow along exerciese and interactive quizes.

V. VR Learning System Design and Development

The creation of IL-PRO has been a comprehensive process that spanned from initial conceptualization to iterative development and refinement. This section outlines the key stages in designing and implementing our VR-based robotics education system for the AEC industry.

A. *VR Learning System Design*

Our design process began with the creation of a comprehensive Game Design Document (GDD) that outlined the core objectives, mechanics, and user experience of the VR learning system. This document served as a roadmap for development, detailing the educational goals, interaction systems, and progression structure of the robotics training modules. The GDD included wireframes and storyboards for key interactions and UI elements, providing a visual guide for the development team. To maximize accessibility, we made the strategic decision to develop the system for both the HTC Vive and Oculus Quest platforms. This cross-platform approach required careful consideration of each device's unique capabilities and constraints, leading to a flexible design that could adapt to different control schemes and processing powers. Throughout the design phase, we conducted regular expert reviews with educators and professionals to ensure the system would meet real-world training requirements in the AEC sector.

B. *VR Learning System Development*

We utilized Unity 2021 LTS as our primary development platform, leveraging its robust VR capabilities and extensive asset library. This agile methodology allowed us to rapidly prototype, test, and iterate on features, ensuring our immersive environments accurately simulated real-world robotics operations while remaining responsive to user feedback and requirements. Realistic robot simulations were achieved by integrating the BioIK Asset for Unity3D, allowing for accurate representation of robotic arm movements and interactions.

Following our modular design, we developed a series of VR tasks, each focusing on specific robotics skills. These tasks were designed to progressively increase in complexity, systematically building students' knowledge and skills. To support adaptive learning, we are in the process of implementing ML and NLP models to analyze user performance data [21], enabling dynamic adjustment of task difficulty and personalized learning paths.

The user interface has been developed with a focus on intuitive navigation and interaction. We have implemented interactive tooltips, voice guidance, and clear visual cues to enhance the user experience within the VR environment. A comprehensive data collection framework has been integrated to capture telemetry data, record think-aloud protocols, and conduct pre- and post-assessments.

The result of this comprehensive design and development process has yielded an engaging VR robotics training platform, now being utilized for large-scale user testing, with the foundation in place to begin incorporating AI-driven adaptivity in future iterations. By combining cutting-edge technology with sound pedagogical principles, IL-PRO represents a significant advancement in VR-based educational tools for the AEC sector.

VI. VR Student Experience

The VR component of the curriculum begins with students downloading and installing a custom executable file, providing access to the immersive learning environment. Upon entering the virtual space, students are guided through a comprehensive navigation tutorial. This tutorial is designed to familiarize them with essential VR interactions, including teleportation for movement, object manipulation techniques, and menu navigation for accessing various modules and settings (fig 2).

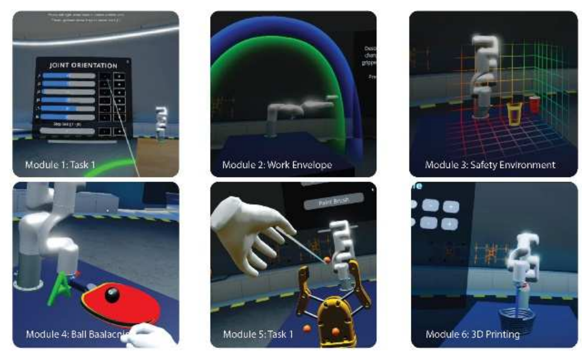

Fig. 2. Captures from IL-PRO's six VR modules.

This onboarding process serves a dual purpose: ensuring a smooth transition from theoretical learning to hands-on practice, while allowing students to immediately engage with VR in robotics education. To reinforce these skills, a dedicated demonstration area is provided. Here, students can practice their newly acquired VR abilities with interactive tooltips and voice guidance, enhancing their comfort and proficiency in the virtual environment. Once acclimated, students proceed to the main interface where they can select and initiate specific robotic tasks. Each task is accompanied by clear, step-by-step instructions, and the system actively monitors student progress throughout the exercise. Upon task completion, students engage in the "Think Aloud" exercise, verbalizing their thought processes and decision-making rationale. This metacognitive approach allows the system to evaluate their performance comprehensively. Following this evaluation, the system provides personalized feedback. Students receive either positive reinforcement for successful actions or constructive guidance on areas requiring improvement. This tailored feedback loop is crucial for reinforcing correct techniques and addressing skill gaps.

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VII. Conclusion & Future Work

The integration of VR into robotics training represents a significant advancement in educational technology, offering hands-on experience in a controlled environment while enabling scenarios impossible to replicate in real life. Our project builds on the effectiveness of a VR-based curriculum for enhancing both theoretical understanding and practical skills in robotics, combining online multimedia lessons with immersive VR tasks and AI-driven adaptive learning. This approach positions robotics programs at the forefront of educational innovation, potentially setting an example for other STEM disciplines [30].

Future work will focus on expanding the curriculum to include more advanced robotic operations, enhancing AI functionalities for personalized learning, conducting long-term impact studies, and refining the VR environment based on user feedback. We also aim to develop strategies for cross-institutional adoption, establishing this approach as a benchmark for innovative robotics education. By pursuing these directions, we strive to create a more engaging, effective, and accessible learning experience for future roboticists, with potential implications for other technical disciplines in higher education.

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