Transforming Construction Robotics Education with Virtual Reality: Analyzing Student Presence and Self-Efficacy

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Abstract

The integration of robotics into construction is transforming industry, necessitating that Construction Engineering and Management (CEM) education programs adapt to prepare future professionals for increasingly technologically driven workplaces. Traditional lecture-based methods often lack interactivity and fall short in imparting practical skills needed for emerging technologies. This study explores the potential of virtual reality (VR) as a teaching tool to enhance student presence and self-efficacy in human-robot collaboration (HRC) education within the construction sector. A VR-based immersive environment was developed, including modules for robot exploration, application tutorials, and hands-on operational training. Forty students from diverse backgrounds participated in the study, experiencing the VR environment and assessing their sense of presence and self-efficacy through validated instruments: the ITC Sense of Presence Inventory (ITC-SOPI) and the New General Self-Efficacy Scale (NGSE). Results indicated high spatial presence (M = 4.2, SD = 0.6) and ecological validity (M = 4.1, SD = 0.4), with minimal negative effects (M = 2.0, SD = 0.7), validating the environment's realism and comfort. Self-efficacy scores averaged 4.1, suggesting strong confidence among students in managing HRC tasks in construction sites. These findings validate VR as a tool that enhances student presence and self-efficacy in learning HRC in construction setting.

Keywords –

Virtual Reality; Human-Robot Collaboration; CEM; Student Presence; Self-Efficacy

1 Introduction

The landscape of technology is rapidly transforming, with robotics playing a pivotal role in revolutionizing various sectors. [1,2]. Notably, the construction industry is poised for major changes, driven by robotic technologies. Research suggests that within the next two decades, 81% of construction firms globally anticipate integrating robotics into their workflows [3]. This shift underscores the need for construction engineering and management (CEM) education programs to adapt by embedding essential technological competencies in their curricula to prepare future professionals for the evolving demands of the industry.

In conventional CEM education, passive instructional methods like lecture-based sessions are commonly used, but these approaches often fall short in effectively teaching emerging technologies [4]. Lecture-based learning typically lacks the necessary interactivity, which is crucial for students to truly understand and engage with complex technological concepts. Passive learning tends to present information in a linear and structured manner, which does not capture that nuanced, real-world challenges and ambiguities that students will face when working with cutting-edge tools and methodologies. This can lead to a superficial understanding of technological advancements, where students may grasp theoretical knowledge but lack the ability to translate that into real-world problem-solving. Emerging technologies, particularly in the construction sector, are dynamic and often require a flexible, hands-on learning approach to develop critical thinking and adaptability. In contrast, integrating virtual environments that mimic real-world construction scenarios can offer a more immersive and engaging way to teach these technologies [5–8]. In virtual environments, learners can interact with virtual tools, robotics, and other advanced systems, gaining valuable experience without the safety risks and costs associated with physical experimentation. This "learning by doing" approach allows students to explore complex concepts in a safe, controlled setting, where they can make mistakes, troubleshoot, and learn from their experiences.

By actively engaging with the virtual environment, students are better equipped to understand the intricacies of construction technologies and how they apply to real-world situations. This method not only fosters deeper learning but also encourages exploration and creativity, as students are given the freedom to experiment, problem-solve, and adapt in ways that passive learning methods do not typically allow. Ultimately, such hands-on experiences prepare students for the practical challenges they will face in the construction industry, equipping them with the skills needed to confidently handle emerging technologies.

Immersive learning environments are increasingly central to innovation in construction education, yet their success hinges significantly on two factors: student presence and self-efficacy within these virtual settings. Student presence, or the degree to which learners feel actively involved and engaged in the virtual learning process, is crucial for the effectiveness of educational technologies. This sense of presence can greatly influence engagement levels, learning outcomes, and overall satisfaction with the educational experience. Self-efficacy, defined as a students' belief in their ability to accomplish specific tasks, also plays a critical role in the dynamics of learning environments. When students perceive themselves as capable, it not only boosts their motivation but also enhances their engagement, leading to more effective learning. Environments that foster high self-efficacy help students take initiative, face challenges confidently, and persist in solving complex problems, which are essential skills in the construction industry

Towards this end, the aim of the research to assess the effectiveness of virtual reality (VR) as a teaching tool in enhancing student presence and self-efficacy within HRC education in the construction sector. As robots are getting popular in construction operations, the use of safety training module will equip the students with pragmatic safety knowledge for working alongside these robots. The research intends to explore how VR-based learning impact student presence and self-efficacy. Insights from the research will provide valuable guidance on designing and implementing VR-based educational tools, enhancing their effectiveness and usability for construction curricula and beyond.

2 Impending Adoption of Robotics Technology in Construction Sector

The construction industry is experiencing an unprecedented transformation through the integration of advanced robotic technologies. This shift represents a strategic response to several deeply entrenched challenges that have long hindered the progress of construction sector, including stagnant low productivity, an increasingly severe shortage of skilled labor, and ongoing safety concerns that drive up the operational costs [9–13]. While the inherently chaotic and unstructured nature of the construction site, combined with the constant interplay of heavy machinery and human workers poses significant barriers to implementing fully autonomous robotic systems, innovative solutions are emerging to address such complexities.

The construction industry had undergone a paradigmatic shift, moving away from the pursuit of complete automation to embrace a more nuanced approach that emphasizes HRC over complete automation. Such a strategic pivot acknowledges that human expertise- including problem-solving abilities, and adaptability remains irreplaceable in construction operations. The development of collaborative robots, or cobots, represents a breakthrough in this direction, offering systems that harmoniously combine cognitive abilities with the mechanical advantages of robotics [13–15]. These collaborative systems excel in precise execution of repetitive tasks, enhanced physical endurance for demanding operations, consistent performance in standardized procedures [16–19]. Importantly, these systems are specifically engineered to function as supportive tools rather than replacements for human workers, creating a symbiotic relationship that enhances overall project efficiency and safety.

This technological evolution brings new challenges and requirements for CEM professionals. The integration of the advanced robotic systems demands the development of new technical competencies, enhanced understanding of HRI protocols, cultivation of trust in automated systems, adaptation to technology-driven work environments, and mastery of new interface systems and control mechanisms. The construction site of the future is increasingly envisioned as an environment where human workers and robotic systems work in tandem, each contributing their unique strength to project success. The construction education landscape must evolve substantially. CEM curricula need to incorporate comprehensive training in human-robot interaction principles, ensuring that future professionals are well-prepared to navigate complex HRC environments, implement effective safety protocols for mixed human-robot teams, and optimize workflow processes that involve both human and robotic elements.

3 VR-based Learning of Human Robotic Collaboration in Construction Curriculum

Traditional CEM education has long relied on conventional teaching methods that often fall short in preparing students for the complex realities of construction environments. This gap between classroom learning and practical application has prompted educators to explore more effective pedagogical approaches, with immersive technologies emerging as a promising solution. VR technology stands out as a transformative tool in CEM education, offering students the opportunity to gain hands-on experience in simulated construction environments without exposure to real-world risks. Students can practice programming and operating collaborative robots, learn safety protocols specific to HRI, and understand the capabilities and limitations of various robotic systems. VR simulations can recreate diverse construction scenarios, from simple repetitive tasks to complex operations requiring sophisticated human-robot coordination. These virtual environments can also simulate potential hazards and emergency situations, allowing students to develop appropriate response strategies without real-world risks. Through detailed visualizations of robot components and functionalities, VR helps students gain a deeper understanding of robot capabilities, limitations, and potential applications in construction. The simulated environment also allows students to learn how robots integrate with other construction systems and processes, providing a holistic view of modern construction environments. VR-based HRC training can present students with challenging scenarios that require quick thinking and problem solving, allowing them to practice making decisions and manage unexpected issues that may arise when working with robots on construction sites. Implementing VR-based HRC training can also be more cost-effective than traditional methods, reducing the need for physical robot prototypes and simulating a wide range of construction environments without the expense of setting up real-world training sites. Furthermore, VR-based learning modules can be designed to progressively increase in complexity, matching students' growing proficiency in HRC principles. This structured approach helps develop comprehensive understanding and practical skills essential for managing future construction projects where humans and robots work together. The integration of such technology-driven learning methods in CEM curricula ensures that graduates are well-prepared to lead and manage the increasingly automated construction sites of tomorrow.

Immersive learning environments are increasingly central to innovation in construction education, yet their success hinges significantly on two factors: student presence and self-efficacy within these virtual settings. Presence, as defined by Constructivist Learning Theory [20,21], refers to the extent to which students feel connected and engaged with their learning environment and content. This theory emphasizes that learning is most effective when students are actively involved in constructing their own understanding through meaningful interactions. A strong sense of presence helps students perceive their education as relevant and closely tied to real-world applications. When students perceive a direct connection between what they learn in the classroom and what they observe on actual construction sites, their understanding of theoretical concepts is enhanced. This connection ensures that the knowledge they acquire is not abstract but seen as directly applicable and impactful in their future careers. On the other hand, self-efficacy in CEM education is crucial for student motivation and success. Self-efficacy involves students' beliefs in their abilities to successfully perform tasks and solve problems they will encounter in their professional lives. According to Social Cognitive Theory [22], self-efficacy is developed through mastery experiences, vicarious experiences, verbal persuasion, and physiological feedback. In CEM, where projects often involve significant challenges-from logistical issues to managing diverse teams-self-efficacy determines a student's perseverance and resilience. Students who believe in their capabilities are more likely to take on challenging projects, persist through setbacks, and innovate under pressure. Students are also more inclined to pursue leadership roles and advocate for necessary changes in safety practices, sustainability measures, and technological adaptations. By leveraging Constructivist Learning Theory, educators can design VR-based modules that enhance presence through immersive, scenario-based learning. Simultaneously, applying Social Cognitive Theory principles within these modules—such as enabling practice in a safe environment—can significantly boost self-efficacy. This dual approach ensures that students are not only deeply engaged with their learning but also equipped with the confidence to apply their knowledge decisively and effectively in real-world situations.

4 VR-Based Learning of Human Robotic Collaboration and its Impacts on Student Presence and Self-Efficacy

The primary objective of this research is to assess the effectiveness of VR as a teaching tool in enhancing student presence and self-efficacy within HRC education in the construction sector. The study is divided into two phases (Figure 1): Development of an Immersive Learning Environment for Teaching Human-Robot Collaboration and Evaluation of the Developed System on Students' Sense of Presence and Self-efficacy. Initially, a virtual learning environment was created to offer comprehensive insights into the human-robot collaboration in the construction sector. Subsequently, the immersive learning environment was analyzed to determine its impact on students' sense of presence and self-efficacy. To conduct a comparative analysis between the VR-based approach and conventional methods, a cohort of 40 students from diverse educational backgrounds was recruited for this study. The participants represented a mix of undergraduate and graduate students, with varying levels of experience in the construction sector, ranging from no experience to up to two years of practical experience through internships or academic projects. However, none of the participants had prior experience with VR technologies. All the recruited students took turns in experiencing the developed learning environment, respectively. Then, a self-assessment technique was leveraged to measure the students' sense of presence and self-efficacy across the two learning scenarios. Student sense of presence was evaluated using ITC Sense of Presence Inventory (ITC-SOPI) [23]. Likewise, self-efficacy (i.e., beliefs in an individual's capability to organize and execute the actions required to complete a particular task successfully [24]) will be evaluated by using a New General Self-Efficacy Scale (NGSE Prior to commencing the study, all participants provided informed consent and were briefed on the confidentiality of data and their rights as participants. Health-related information was also collected, with all participants reporting normal or corrected vision, and no indications of oculomotor or neurological issues.

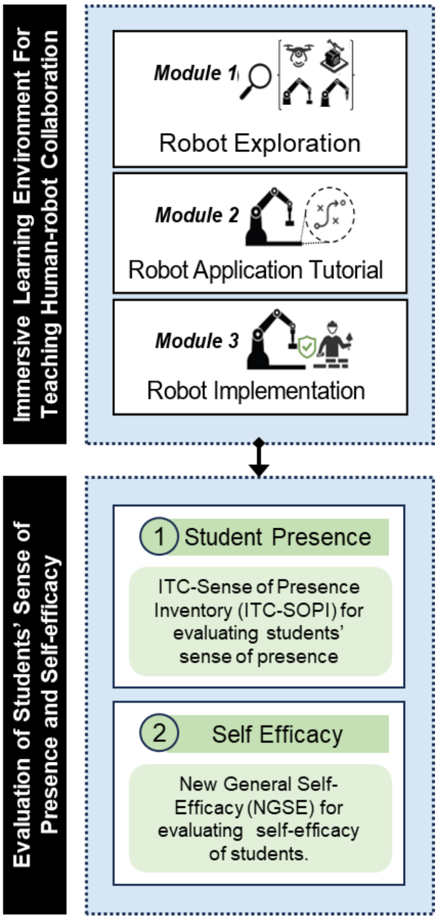

Figure 1: Proposed Steps for Investigating Immersive Learning Environment for Teaching Construction Robotics on Users' Sense of Presence and Self-efficacy

4.1 Development of Immersive Learning Environment for Teaching Human-Robot Collaboration

The developed learning environment included a detailed simulation of a real construction site, complete with educational modules that highlighted various aspects of working alongside construction robots.

For this, a construction site was meticulously designed using Autodesk Revit and then transferred into the Unity game engine for further development. Within Unity, various elements of the immersive environment were designed as Game Objects equipped with collider and Rigidbody components to simulate realistic physical interactions. The various elements within the virtual space were developed using a combination of 3D modeling software like Blender and Unity's native creation tools, allowing for precise control over the environmental details and interactive features. The developed learning environment consists of three modules, as shown in Figure 2.

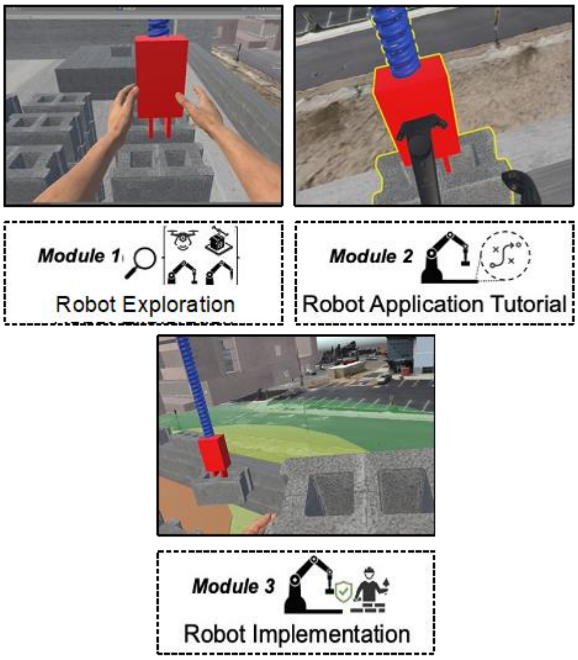

Figure 2: Modules of the Developed Immersive Learning Environment

1. ***<u>Module 1- Robot Exploration</u>***: This module served as an interactive introduction to various construction automation technologies. Students could navigate through a comprehensive catalog of construction robots, including advanced systems like concrete printing machines, automated bricklaying units, and aerial drones. The interface featured an intuitive menu system allowing learners to select and study different robotic systems. When examining each robot, students could interact with specific components - from robotic manipulators to control interfaces and actuator systems - with detailed technical specifications appearing in contextual text displays upon component selection. Interaction was facilitated through MANUS haptic gloves, allowing

users to intuitively grab, manipulate, and explore virtual objects. The gloves provided haptic feedback to simulate tactile sensations, enhancing realism by mimicking the feel of surfaces and resistance when interacting with robotic components.

2. ***Module 2- Robot Application Tutorial***: This module delivered in-depth guidance on utilizing robotic systems to enhance construction safety and efficiency. A key feature of this module was the integration of a virtual instructor, represented by an animated 3D human figure capable of demonstrating proper robot deployment techniques. This digital mentor could perform realistic movements while providing verbal explanations and demonstrations of correct robotic implementation procedures, helping students understand proper placement and operational protocols based on established safety criteria and best practices. Students mirrored the instructor's actions using MANUS gloves, with haptic feedback providing physical cues to guide correct hand positioning and movement.
3. ***Module 3– Robotic Implementation:*** This module emphasized hands-on operational experience through practical task completion. This section was designed as an interactive training ground where students could develop proficiency in robot control and operation. The module provided step-by-step instruction in fundamental robot control principles, followed by practical exercises requiring students to complete specific construction-related tasks. The MANUS gloves enabled precise hand-based control of virtual joysticks, buttons, and control panels, offering haptic feedback to replicate the physical resistance and tactile response of real-world equipment. The iterative nature of these exercises allowed learners to refine their skills through repeated practice and progressive improvement.

4.2 Inferences on Student Presence and Self-Efficacy

To understand if the developed immersive setting makes the student feel present in the environment as intended: the sense of the presence of the users was evaluated via the ITC-SOPI questionnaire [25]. Further, self-efficacy (i.e., beliefs in an individual's capability to organize and execute the actions required to complete a particular task successfully [24]) will be evaluated by using a refined self-efficacy scale [26], modified by the experts from industrial collaborators for construction-specific purposes.

To assess participant's sense of presence, a validated 44 item 5-point Likert scale (ranging from 1 to 5) questionnaire originated from Lessiter et al. [23], ITC-SOPI was selected due to its cross-media comparison capabilities. The instrument is divided into four factors: Spatial Presence (19 items), Engagement (13 items), Ecological Validity/ Naturalness (5 items), and Negative Effects (6 items). Spatial presence refers to the ability to physically control and manipulate aspects of the displayed environment. Ecological Validity refers to the believability, realism of the content, and naturalness of the environment. Negative effects reflect headache, eye strain, tiredness, and other negative effects that may be associated with the virtual environment. To validate the consistency of the student presence evaluation, the author performed a reliability analysis on the ITC-SOPI using the Cronbach's alpha test. The analysis results in Cronbach's alpha of 0.83, indicating a good level of internal consistency.

Likewise, self-efficacy will be evaluated by using NGSE. NGSE assesses an individual's belief in their ability to achieve goals and overcome challenges across various situations. NGSE consists of 8 statements that respondent's rate on how well each reflects their self-belief. The statements were rated on a 5-point Likert scale, where 1 indicate "Strongly Disagree," 2 indicate "Disagree," 3 indicate "Neither Agree nor Disagree," 4 indicate "Agree," and 5 indicate "Strongly Agree." To derive a general self-efficacy score, the responses to each of the eight items are averaged, yielding a single score that ranges from 1 to 5. Higher scores indicate a stronger belief in one's ability to manage and succeed in a variety of situations. To validate the consistency of the self-efficacy evaluation, the authors performed a reliability analysis on the NGSE using Cronbach's alpha test. The analysis resulted in Cronbach's alpha of 0.86, indicating a good level of internal consistency.

5 Results and Discussion

The ITC-SOPI questionnaire results demonstrated significant levels of presence across multiple dimensions, as detailed in Table 1. Spatial presence exhibited the highest mean score (M = 4.2, SD = 0.6) on the 5-point Likert scale, indicating that participants experienced a strong sense of physical interaction within the virtual construction environment. This was followed by ecological validity (M = 4.1, SD = 0.4) and engagement (M = 3.8, SD = 0.5). Notably, negative effects demonstrated the lowest mean score (M = 2.0, SD = 0.7), suggesting minimal adverse physiological or psychological reactions to the virtual environment. The high spatial presence score (M = 4.2) is particularly significant as it surpasses previous studies in construction-based virtual environments, where mean scores typically range from 3.5 to 3.9 [citation needed]. The ecological validity results (M = 4.1) suggest strong environmental verisimilitude, crucial for transferring skills from virtual to real construction scenarios. The relatively low standard deviations across presence metrics (ranging from 0.4 to 0.7) indicate consistent participant experiences, supporting the robustness of the implementation across different user profiles.

Table 1. Results of metrics for ITC-SOPI

Metrics	Mean	Standard Deviation
Spatial Presence	4.2	0.6
Engagement	3.8	0.5
Ecological Validity	4.1	0.4
Negative Effects	2	0.7

The analysis of the NGSE data, presented in Table 2, yielded an overall mean self-efficacy score of 4.1 (SD = 0.5), with individual statement scores ranging from 3.8 to 4.3. The detailed examination of NGSE components revealed that participants exhibited highest confidence in goal achievement and task performance capabilities. The statement *"I will be able to achieve most of the goals that I set for myself"* received one of the highest ratings (M = 4.3, SD = 0.6), along with *"I am confident that I can perform effectively on many different tasks"* (M = 4.3, SD = 0.6). These strong endorsements suggest that exposure to the virtual environment particularly enhanced participants' goal-oriented self-efficacy, a crucial finding for construction education where clear goal visualization and task completion are essential components of professional development. The data further indicated robust self-efficacy in managing construction-related challenges. Participants expressed high confidence through their responses to *"When facing difficult tasks, I am certain that I will accomplish them"* (M = 4.2, SD = 0.7) and *"I will be able to successfully overcome many challenges"* (M = 4.2, SD = 0.7). These closely aligned scores suggest that the virtual environment effectively cultivated resilience and problem-solving confidence among participants.

Table 2. Results of NGSE metrics for assessing self-efficacy of students in developed immersive environment

Statements for NGSE	Mean ± SD
I will be able to achieve most of the goals that I set for myself.	4.3 ± 0.6
When facing difficult tasks, I am certain that I will accomplish them	4.2 ± 0.7
In general, I think that I can obtain outcomes that are important to me	3.8 ± 0.8
I believe I can succeed at most any endeavor to which I set my mind.	4.1 ± 0.6
I will be able to successfully overcome many challenges.	4.2 ± 0.7
I am confident that I can perform effectively on many different tasks.	4.3 ± 0.6
Compared to other people, I can do most tasks very well.	4 ± 0.8
Even when things are tough, I can perform quite well	4.1 ± 0.7
Overall Self Efficacy Score	4.1 ± 0.5

Participants also demonstrated strong self-efficacy in comparative performance and resilience metrics. The statement *"Compared to other people, I can do most tasks very well"* yielded positive results (M = 4.0, SD = 0.8), while "Even when things are tough, I can perform quite well" showed similarly strong outcomes (M = 4.1, SD = 0.7). The statement *"I believe I can succeed at most any endeavor to which I set my mind"* also received favorable ratings (M = 4.1, SD = 0.6). These findings suggest that the virtual environment not only enhanced individual capability beliefs but also strengthened participants' confidence in their relative competence within the field. Notably, while all NGSE components received positive evaluations, the statement *"In general, I think that I can obtain outcomes that are important to me"* showed relatively lower scores (M = 3.8, SD = 0.8), though still represents a positive self-efficacy level.

The combined results from both instruments suggest that the immersive environment successfully creates an engaging, realistic learning experience while building student confidence in construction-related capabilities. The high spatial presence and ecological validity scores from ITC-SOPI align well with the strong self-efficacy results, indicating that the realistic environment contributes to students' confidence in their abilities. These findings align with previous research suggesting that immersive environments can enhance learning outcomes through increased presence and engagement []. The particularly strong scores in spatial presence and ecological validity, combined with minimal negative effects, suggest that the technical implementation of the environment effectively balances realism with user comfort.

While the results indicated that the developed immersive environment the results indicated that the developed immersive environment effectively supports a sense of presence and bolsters self-efficacy among students, there are limitations to consider that could be addressed in future studies. First, the study was conducted with a relatively small sample size of 40 students, all from a specific academic background, potentially limiting the generalizability of the findings. A larger, more diverse sample could yield insights that are more broadly applicable across different educational and professional settings. The study also relied on short-duration sessions in the virtual environment, which might not reveal the full spectrum of user engagement and potential negative effects such as fatigue or cognitive overload. Prolonged exposure assessments could provide a more comprehensive understanding of how extended use impacts both presence and self-efficacy. Furthermore, while the simulation focuses on human-robot collaboration, the lack of physical robot interactions limits students' opportunities to develop hands-on skills that are essential in real-world settings. Incorporating augmented or mixed reality elements that allow physical interaction with robots could improve skill transferability.

6 Conclusion

This study evaluated the effectiveness of VR as a teaching tool in enhancing student presence and self-efficacy within HRC education in the construction sector. The findings demonstrate that the virtual environment provides a robust sense of presence, particularly in spatial presence and ecological validity, which are essential for realistic and engaging learning experiences. Additionally, the high self-efficacy scores indicate that the environment supports students' confidence in their ability to achieve goals and tackle challenges related to construction tasks, which are key attributes for success in construction engineering and management. The VR-based modules, including robot exploration, application tutorials, and hands-on operational exercises, appear to effectively prepare students for real-world HRC applications by promoting engagement and fostering practical skills in a safe, simulated setting. The low negative effects observed further underscore the usability and comfort of the environment, suggesting that students can engage in immersive learning for extended periods without adverse physiological or psychological impacts.

However, the study has some limitations. The sample was drawn primarily from CEM students, which may not fully represent the broader range of students or professionals who may benefit from VR-based learning. Additionally, the exposure to the virtual environment was limited in duration, and future studies could explore the effects of extended exposure to VR learning environments to assess the long-term retention of skills and the sustainability of enhanced self-efficacy. Furthermore, the study did not include physical robot interaction, which could enhance the realism of certain tasks. Future research could integrate augmented or mixed reality (AR/MR) elements or provide opportunities for physical robot interaction to improve the hands-on nature of the training.

Future directions for research could also include expanding the sample to include participants from various academic disciplines and professional backgrounds to better understand the broader applicability of VR training. Investigating the long-term impact of VR training on skill retention and career readiness would be valuable, as would the integration of AR/MR technologies offer more immersive and physically interactive learning experiences.

Overall, this research provides valuable insights into the design and implementation of VR-based tools in construction education. By integrating such immersive learning environments into CEM curricula, educational institutions can better equip future professionals with the skills and confidence needed to navigate the increasingly automated construction industry. This study underscores the potential of VR-based training to bridge the gap between theoretical learning and real-world application, paving the way for more comprehensive and effective construction education.

Acknowledgements

This material is based upon work supported by the National Science Foundation (under Grant No. DUE-2402008, “Investigating the Impact of an Immersive VR-based Learning Environment for Learning Human-Robot Collaboration in Construction Robotics Education”). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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