RoboSite: An Educational Virtual Site Visit Featuring the Safe Integration of Four-Legged Robots in Construction

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Abstract: The rise of robot use in the construction industry underscores the need to prepare the next generation of construction professionals for this technological shift. While knowledge about these robots is vital, understanding their operational mechanisms and the safety challenges they pose on construction sites is equally essential. However, implementing an effective robot-related curriculum in construction education is hindered by logistical and financial obstacles of bringing physical robots to classrooms. While traditional lecture-based instruction or videos may offer some assistance, their limited interactive capabilities severely constrain the extent to which students can be effectively trained in working with robots on real job sites. This research introduces *RoboSite*—a virtual site visit interface utilizing the immersive power of virtual reality, aiming to provide a safe and cost-effective learning platform. In this project, RoboSite was designed to facilitate trust and positive perceptions regarding four-legged robots while concurrently enhancing students' understanding of the applications, safety challenges, and preventive measures associated with such technologies in construction. The effectiveness of RoboSite was evaluated using repeated-measure experiment design and the results indicate that RoboSite offers a promising avenue to effectively enrich students' understanding and reduce their negative perceptions about diverse and unfamiliar scenarios. **DOI: 10.1061/JCEMD4.COENG-14779.**

Author keywords: Four-legged robots; Virtual site visit; Construction education; Safety; Quadruped robots.

Introduction

The construction industry is undergoing a transformative phase with the increasing adoption of innovative technologies aimed at improving safety, and productivity. One of the key technologies that holds significant promise is robotics, which has the potential to revolutionize the industry by addressing issues related to stagnant productivity and safety concerns. On-site robotic systems have shown remarkable potential in enhancing productivity by automating repetitive and labor-intensive tasks such as bricklaying, finishing, and rebar-tying, allowing human workers to focus on more complex activities that require their unique skills and capabilities (Madsen 2019). Automation and robotics can help lower project costs by enabling construction work to be carried out in adverse weather conditions (Dakhli and Lafhaj 2017; Iturralde et al. 2020). Robots can also help mitigate labor shortages and increase workforce access by allowing underrepresented groups of workers, such as disabled individuals who are unable to perform heavy labor, to engage in construction tasks (Balzan et al. 2020). Moreover, construction robots can perform hazardous and labor-intensive tasks, such as demolition, thereby reducing injuries and fatalities in an industry notorious for its dangerous work environment (Balzan et al. 2020).

In dynamic and ever-evolving construction settings, an ideal robot deployed on a construction site should possess the ability to execute multiple tasks under varying conditions while adapting to the changing work environment. Four-legged robots with symmetrical leg configurations and unrestricted mobility in all directions are well-suited for construction sites. These robots excel in operating in uneven, cluttered, and obstacle-laden construction environments, enabling them to climb multiple levels and navigate indoor spaces effectively. As a result, the prevalence of four-legged robots on construction sites have witnessed a notable surge in recent years (Safeea and Neto 2019). Many studies have examined training programs involving construction robots. For instance, research has focused on topics such as safe operation of construction robots (Adami et al. 2020) and enhancing construction workers' trust in robots (Shayesteh et al. 2022; Latikka et al. 2021). It is crucial for construction students, who may not possess expertise in construction safety and emerging technologies, to acquaint themselves with these emerging technologies. This familiarity will be essential for their success in future construction environments that are likely to be dominated by robots. To support learners' understanding and facilitate the advancement of construction automation, the training contents need to be reconsidered and advanced learning environments need to be developed and implemented.

In the current state of construction learning and training, traditional methods predominantly rely on lecture-based teaching and on-site visits to impart knowledge and practical experience to students (Adami et al. 2020). However, these approaches have their limitations, particularly when it comes to enhancing learners' conceptual understanding in complex and unfamiliar scenarios, such as the application of construction robots, which are not easily accessible through traditional classroom methods (Eiris et al. 2020). On-site visits have been considered beneficial as they provide students with the opportunity to observe construction robots in

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action within real construction environments. By witnessing the robots' functionality firsthand, students can better grasp their potential applications and gain valuable hands-on experience. However, despite these advantages, on-site visits also come with significant challenges (Eiris and Gheisari 2018). They involve inherent risks to the safety of students, especially in high-risk construction settings. Moreover, arranging on-site visits can be time-consuming and costly, requiring specialized equipment, trained supervisors, and experienced instructors to be present, which can be a significant burden on educational institutions (Miller and Parasuraman 2007). To address these limitations and challenges, there is a pressing need to explore alternative training and learning programs that can effectively enhance students' conceptual understanding without exposing them to undue risks or incurring exorbitant costs. Emerging technologies and innovative educational approaches hold the potential to bridge this gap.

In this study, we introduce RoboSite, an innovative virtual site visit that incorporates virtual reality (VR) technology to immerse students in virtual construction sites featuring four-legged robots. By expanding the possibilities of real-world construction environments, RoboSite creates immersive and interactive virtual spaces. Through this approach, we aim to inspire students, elevate their engagement, and foster a profound comprehension of complex and unfamiliar scenarios (Liu et al. 2021). RoboSite's remote accessibility adds further value, especially when dealing with constraints related to time, cost, and distance (Le et al. 2015). This feature allows students to experience virtual site visits from anywhere, breaking down geographical barriers and granting equitable access to valuable learning opportunities. The primary objective of this study is to evaluate the effectiveness of RoboSite as an educational tool in shaping students' attitudes and understanding regarding the use of four-legged robots in construction environments. Specifically, this research aims to investigate two key aspects: First, how RoboSite influences students' perceptions and attitudes toward the deployment of four-legged robots on construction jobsites. Second, the study seeks to assess how RoboSite contributes to students' development of knowledge, self-efficacy, and engagement with the subject of implementing these robots in construction settings. Given the specific focus of the study, the following research questions were formulated:

- Research Question #1: How does RoboSite impact students' attitudes toward four-legged robots on construction jobsites?
- Research Question #2: How does RoboSite contribute to students' understanding of the implementation of four-legged robots in construction, and what implications does RoboSite have on their self-efficacy and learning engagement?

To address the above research questions, the Unity engine was employed to construct RoboSite—an immersive and interactive construction site. The learning content was RoboSite was developed using comprehensive review of relevant literature. The platform was enhanced with several technical attributes, including a virtual instructor, situated and conceptual learning contexts, and intuitive user interfaces, integrated within the RoboSite Platform. To assess the impact of RoboSite on students' attitudes toward robots, their learning performance, and the usability of the system, a pre- and postassessment were conducted.

This paper first provides a background of four-legged robots in construction, virtual site visit in construction education, and student attitude toward four-legged robots. Following this, the paper discusses the research questions and outlines the research methodology. Subsequently, it provides an overview of the learning content generation and technical development of RoboSite. Finally, the paper presents the assessment results and discuss potential avenues for future research.

Related Works

Four-Legged Robots in Construction

The construction industry is grappling with a substantial shortage of skilled labor, making the integration of robots into construction work environments an inevitable solution. As technology continues to advance rapidly, the future of construction work will heavily rely on a collaborative partnership between robots and humans. Among the various types of robots gaining popularity in the construction industry, four-legged robots, also known as quadruped robots, are emerging as a preferred choice due to their mobility, stability, and flexibility (Afsari et al. 2021). Four-legged robots with symmetrical leg arrangements and the ability to move in any direction are ideal for construction sites and are more versatile than wheeled robots due to having more degrees of freedom (DoF) per leg (Halder et al. 2022). The locomotion control of four-legged robots enables stable movement over rough terrains, including walking over small obstacles, climbing stairs, which makes them be more suitable for the dynamic construction environment than wheeled or tracked robots relying on steering and the rotation of wheels or tracks for movement. Besides, the stability of four-legged robots is enhanced through polygonal support structures and the implementation of control laws designed to prevent falls, especially when the robot is moving or when external forces are applied. Although wheeled robots exhibit inherent stability due to constant ground contact, which simplifies the balance control in their programming, four-legged robots equipped with path planning technologies including control barrier functions and model predictive control algorithms (Ding et al. 2019) are ideally suited for moving in dynamic environments while maintaining safe foot placement and dynamic stability.

Given these benefits of four-legged robots, they are easily controlled and using sensors and robotic arms adapting for a wide range of construction applications, such as monitoring and inspection activities (Bellicoso et al. 2018; Safeea and Neto 2019). Several studies have demonstrated the effectiveness of four-legged robots in autonomously collecting 360° images using BIM-enabled automated reality capture and GPS technology, thereby reducing the manpower required for construction inspections (Afsari et al. 2021; Halder et al. 2022). In another monitoring-related study, a 3D LiDAR-equipped four-legged robot has been proposed to monitor scaffolding operations from a safety perspective by capturing 3D point cloud data of scaffolds (Kim et al. 2022). The ability of these robots to traverse and scan job sites more frequently than humans enhances the effectiveness of inspection and monitoring processes, generating digital replicas that facilitate qualitative and quantitative assessments. Furthermore, four-legged robots have been envisioned for tasks such as material and tool transportation and assisting in the building process (Sun et al. 2023). As four-legged robotic technology continues to advance, such applications are poised to become commonplace in construction.

The increasing deployment of four-legged robots in construction will result in increased interaction between human workers and such robots on the jobsite. However, such interactions pose potential safety risks and accidents resulting from technical defects, breakdowns in communication between humans and robots, and unintended contact between robots and workers or objects on the site (Kim et al. 2017). Studies have highlighted safety concerns regarding human-robot interactions in shared workplaces, with physical injury to humans being a primary challenge. Falls, for example, are the leading cause of work-related deaths in construction (NIOSH 2021), and the introduction of four-legged robots to construction sites could exacerbate this issue (Sun et al. 2023). Factors such as collisions between robots and workers at elevated heights, as well as robotic navigation failures in detecting precise walking paths, can contribute to such incidents robots, various measures have been proposed. Controls can be implemented to eliminate or substitute hazards completely, isolate workers through engineering controls (e.g., safety fences or barricaded areas), implement administrative controls (e.g., updated work procedures and safety guidelines), and ensure the use of appropriate personal protective equipment (PPE) such as hard hats, safety glasses, steel-toed shoes, and safety gloves when working with four-legged robots (Morris and Cannady 2019; Sun et al. 2023).

Despite the continuous research efforts focusing on the applications, safety challenges, and countermeasures associated with four-legged robots in construction, there is still a significant gap in effectively disseminating this knowledge to prepare future construction professionals. This study addresses this gap by proposing a virtual construction site environment populated with four-legged robots.

Virtual Site Visit in Construction Education

Virtual site visits have immense potential to address the challenges in construction education and significantly impact students' learning outcomes and attitudes (Wang et al. 2022). A virtual site visit entails a multimedia simulation of a remote location that allows students to observe and engage with site-specific information using electronic devices. As a few examples, virtual site visits have been employed to enhance students' understanding of construction-related disciplines (Shen et al. 2012), improve comprehension of building structures and materials (Eiris et al. 2022), and develop design review skills (Kandi et al. 2020). Notably, Zhang et al. (2017) developed a virtual construction site that enabled students to freely explore the virtual site and receive instant feedback. The study demonstrated that virtual site visits enhanced students' understanding of complex structures, provided better access to multiple construction sites, offered convenient and flexible learning opportunities, and supported safer site visits. Furthermore, several studies have highlighted the potential of virtual site visits to enhance construction students' social interactions (Le et al. 2015), problem-solving abilities (Eiris et al. 2022), higher-order thinking skills (Le and Park 2012), critical thinking (Kandi et al. 2020), and memory for spatial layout (Ferguson et al. 2020).

Previous studies have explored the effectiveness of incorporating virtual site visits in construction education for various learning and teaching purposes. While an increasing body of evidence highlights the benefits of using virtual site visits as an alternative approach in construction education, there remains a scarcity of research that focuses on construction robot education using virtual site visits. More specifically, the four-legged robots, their high acquisition, operation, and maintenance costs for individual construction programs and academic institutions, coupled with safety concerns related to direct student interaction with them, can be prohibitive factors in using them in the classroom. This study offers a well-defined workflow and instructional content design that can serve as a valuable resource for educational institutions or instructors planning to incorporate construction robots into construction education programs.

Furthermore, the preceding section addressed the potential safety challenges presented by the use of robots in construction and discussed the necessity of implementing appropriate measures to mitigate various hazards. It is imperative for students or future construction workers to be adept at accurately evaluating and avoiding these risks. However, demonstrating the consequences of such hazards to students in a real-life setting is scarcely feasible without endangering their safety. To bridge this educational gap, this study presents RoboSite, a novel virtual site visit platform that leverages the capabilities of Virtual Reality (VR) technology to offer an immersive interaction with four-legged robots within construction environments. The system permits students to navigate a virtual construction site through computers, enabling them to witness and interact with a variety of human-robot collaboration scenarios. This interaction is facilitated by the use of computer screens, headphones, keyboards, and mouse, thus obviating the need for exposure to physical site dangers. The integration of the RoboSite system into construction education serves as a proactive measure to ensure that students are well-prepared to work alongside robots in real-world construction settings, equipped with the knowledge to maintain safety standards and prevent accidents.

Student Attitude toward Four-Legged Robots

The potential of construction robots to revolutionize the construction industry by addressing concerns such as stagnant productivity and safety issues has been well-established (Madsen 2019). However, the adoption of these technologies is often hindered by the reluctance of construction students and workers to fully embrace them, leading to negative attitudes. Research has indicated that fostering a culture of trust and positive perceptions regarding the capabilities and dependability of new technologies is pivotal in encouraging higher adoption rates within the construction sector (Schia et al. 2019). Furthermore, as robotic technologies become more integrated into construction sites, human-robot interaction intensifies, necessitating a fundamental level of trust in these novel technologies. Hence, enhancing the attitudes of construction professionals and future workers toward robots in construction is of paramount importance.

Construction robots straddle diverse fields, including computer science, engineering, mathematics, statistics, and psychology. This multidisciplinary nature equips them with the ability to learn from historical data and past experiences, effectively performing tasks that conventionally demand human cognitive processes (Hild and Stemmer 2007). However, the intricate amalgamation of these disciplines can inadvertently exacerbate concerns among users and potential users of this new technology, raising apprehensions about operational intricacy and potential risks. Addressing this, Latikka et al. (2021) emphasized the need for advanced technologies to ensure transparency and interpretability, thereby mitigating human bias. In the realm of robotics, learning or training agents are equipped to offer explanations for robotic actions and the underlying rationale.

Various studies have explored the utilization of virtual site visits to enhance trust and cultivate positive attitudes toward robotics and automation in construction contexts. For instance, Adami et al. (2020) undertook research using a virtual learning environment, enabling trainees to remotely operate construction robots and gauge the level of trust in the robots. Nonetheless, prior research primarily centered on providing virtual or in-person training modules focusing on the accurate and safe operation of these robots in construction scenarios. A limited amount of research has delved into the potential of virtual site visits as an educational tool for enhancing construction students' understanding of robots within construction sites. RoboSite aims to cultivate trust and positive perceptions regarding these robots while concurrently enriching students' comprehension of safety challenges and countermeasures when engaging with such technological entities in construction environments.

Methods

This study highlights the importance of integrating four-legged robots into construction curricula by designing and developing a virtual site visit focused on the utilization of these robots in construction. The virtual site visit, called RoboSite, offers a safe and cost-effective learning opportunity for construction students. This paper specifically delves into the creation of content requirements for RoboSite, leveraging the immersive capabilities of virtual reality to provide an engaging experience for students while minimizing potential risks and expenses.

To answer these questions, this study follows a three-step research methodology: (1) learning content generation, (2) RoboSite development in VR, and (3) user-centered assessment (see Fig. 1).

Learning Content Generation

In this study, a set of specific learning objectives was defined to guide the attainment of educational learning goals of the RoboSite. These objectives and associated content were developed drawing from prior training materials focused on the subject of human-robot collaboration in construction. For instance, Cheng et al. (2022) created a 360° video designed to train construction workers about the safety challenges posed by drones. This training emphasized key objectives, including the definition of drone, its applications in construction, potential safety issues, and measures for the secure integration of drone in construction sites. Given the similarity in the learning goals related to introducing emerging technology in construction, the RoboSite learning objectives were formulated as follows:

- Learning objective #1: Define four-legged robots and discuss their benefits, challenges, and integrated technologies.
- Learning objective #2: Discuss four-legged robot applications in construction.
- Learning objective #3: Discuss potential safety challenges of four-legged robots on construction jobsites.
- Learning objective #4: Discuss potential countermeasures for the safe integration of four-legged robots on construction jobsites.

The development of learning content was informed by an extensive literature review encompassing various aspects, including four-legged robots in construction (Afsari et al. 2021; Halder et al. 2022; Kim et al. 2022), human-robot collaboration in construction (Sun et al. 2023), safety regulations in construction as outlined in established publications (Morris and Cannady 2019; OSHA 2022), and potential risks associated with robots in construction (Sun et al. 2023; Zhu et al. 2023).

To cover learning objective #1, popular robot types in construction were introduced first and then an introduction to four-legged robots was discussed with a focus on their definition and history, benefits, challenges, and technologies integrated in them. The learning content topics pertaining to learning objective #1 can be found in Table 1.

In order to address learning objective #2, various applications of four-legged robots in construction were addressed, such as

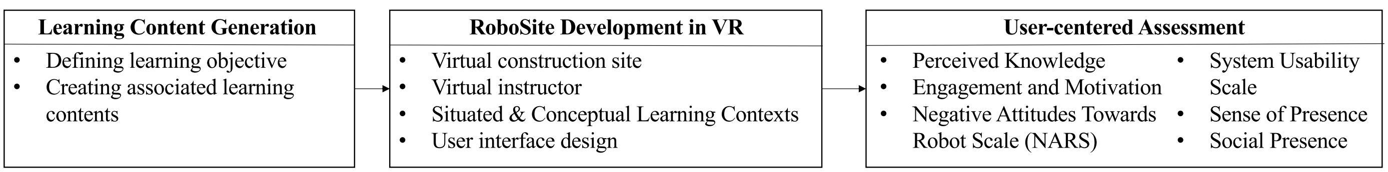

Fig. 1. Research methodology.

Table 1. Learning objective #1 and related learning contents

Learning objective	Learning topics	Learning content summary
(#1) Define four-legged robots and discuss their benefits, challenges, and integrated technologies.	Construction robot types.	• Wheeled robots. • Legged robots. • Climbable robots. • Aerial robots.
	Four-legged robots' definition and history.	• Definition: a four-legged robot, also known as a quadruped robot, has four legs or limbs and follows the gait patterns of quadruped animals. • History: This study traces the evolution of four-legged robots, beginning with the initial four-legged walking mechanism developed in the 1870s, and progressing to contemporary four-legged robot platforms commonly used today.
	Benefits of four-legged robots.	• High adaptability in dynamic and constantly changing work settings. • Mobility and stability of locomotion • Versatility
	Challenges of four-legged robots.	• Technical challenges associated with working in the harsh jobsite environment • Economic implication due to high capital investment • Safety challenges for human workers collaborating with such robots.
	Technologies integrated into four-legged robots for navigation.	• Navigation: GPS for precise location identification, LiDAR for mapping the terrain and detecting obstacles around the robots, and AI technologies to enhance the stability of the robot during both standing and movement. • Data collection: laser scanners and 360° cameras for capturing the reality of jobsites, sensors for collecting precise information tailored to specific tasks, and articulated robotic arms for carrying out physical tasks.

Table 2. Learning objective #2 and related learning contents

Learning objective	Learning topics	Learning content summary
(#2) Discuss four-legged robot applications in construction	Monitoring and inspection.	• Four-legged robots can capture the construction jobsite condition using 360° camera and laser scanner. The scanned information can be used for a wide range of inspection and monitoring types of work from progress monitoring to safety inspection.
	Material and equipment delivery.	• Four-legged robots can transport materials and tools on job sites. Workers can summon the robot to retrieve the toolbox from a truck using its robotic arm and then return it to the workers
	Other applications.	• Four-legged robots can use their robotic arms to lay bricks and turn on/off switches or valves.

monitoring and inspection, delivery of materials and equipment, and other relevant uses. The learning content topics for learning objective #2 are displayed in Table 2.

To address learning objective #3, an introduction to the safety challenges of four-legged robots was provided. This was achieved through discussing potential physical risks, attentional costs, and psychological impacts of integrating such robots in the construction domain (Sun et al. 2023), where each category was introduced using a learning scenario. The learning content topics for learning objective #3 are depicted in Table 3.

Finally, to cover learning objective #4, a series of countermeasures were suggested to address the potential hazards discussed in the previous learning objective. It should be noted that the Occupational Safety and Health Administration (OSHA) currently lacks specific regulations or technical guidelines pertaining to the secure integration or utilization of four-legged robots on construction job sites (OSHA 2022). Consequently, the hierarchy of controls (HoC) framework, as defined by the National Institute for Occupational Safety and Health (NIOSH 2019), was chosen as the operative model to propose a suite of countermeasures geared toward mitigating the potential hazards entailed in human interaction with such robots on construction sites. Reducing hazard exposure requires correctly following the hierarchy of controls, beginning with eliminating or substituting the hazard and only ending with implementing personal protective equipment (PPE) if no better solution can be found (Morris and Cannady 2019). The details of these countermeasures to achieve learning objective #4 are shown in Table 4.

RoboSite Development

This section will provide a detailed discussion on the development of various aspects of RoboSite platform components. Fig. 2 shows the process of RoboSite development.

- *Virtual Construction Site*: The environments where the virtual site visit occurs.
- *Virtual Instructor:* Acting as conversational guides, a virtual avatar helps students navigate through the visit while addressing the learning objectives.
- *Situated and Conceptual Learning Contexts:* Integrating learning contexts that require communicating real-world learning scenarios or explaining conceptual learning content.
- *User Interface:* These interface elements enable users to interact with the virtual site visit and learning material and navigate within the construction site environment.

Table 3. Learning objectives #3 and related learning contents

Learning objective	Learning topics	Learning content summary
(#3) Discuss potential safety challenges of four-legged robots on construction jobsites.	Physical risks.	• Falling risk: the robot or its payload falling from higher levels due to errors • Caught-in between: the risk of body part getting caught in/between moving parts of robots • Struck-by incident: the risk of being struck by a moving robot or its components, such as robotic arms.
	Attentional costs.	• As a recent addition to the job site, the presence of a robot can lead to virtual and cognitive distractions.
	Psychological impacts.	• Anxiety and acute stress may arise due to the monitoring of robots on job sites.

Table 4. Learning objective #4 and related learning contents

Learning objective	Learning topics	Learning content summary
(#4) Discuss potential countermeasures for the safe integration of four-legged robots on construction jobsites.	Elimination.	• It is the most effective strategy by physically removing the four-legged robots from construction sites.
	Substitution.	• Four-legged robots can be replaced with other equipment or humans that do not pose a risk.
	Engineering controls.	• Isolating people from hazards that cannot be eliminated or replaced, such as putting physical barriers around workers who are working in close proximity to robots.
	Administrative controls.	• Implementing safety precautions or guidelines for workers to follow when working with or around robots.
	Personal protective equipment.	• Using appropriate personal protective equipment (PPE) such as hard hats, safety glasses, steel-toed shoes, and proper safety gloves when working with four-legged robots.

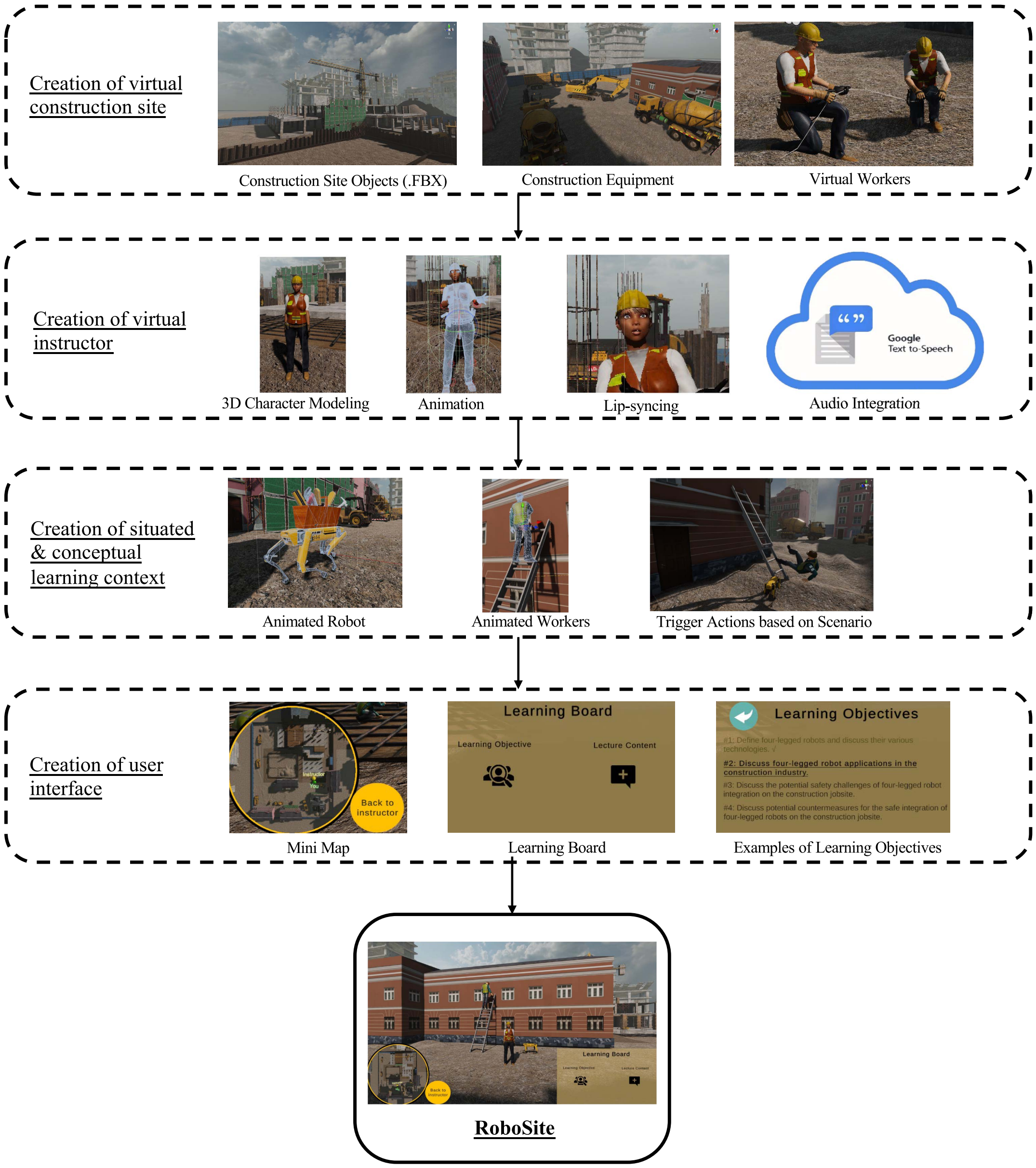

Fig. 2. The process of RoboSite development.

Virtual Construction Site

The virtual construction sites were modeled in VR using the Unity game engine. The building information models of construction workplaces were used to create virtual buildings to preserve the spatial accuracy of the simulated site. 3D models of different construction entities, such as temporary structures, scaffolding, and construction debris, were added to the site [Fig. 3(a)]. The other elements of a typical construction site, such as construction material stockpiles, dust, uneven ground, safety signage, and temporary lighting, were also added to the virtual site. Relevant virtual construction vehicles and equipment were placed based on the training requirements [Fig. 3(b)]. These were programmed to move along predefined paths (mimicking actual movement patterns observed in real construction sites and performing similar tasks). Avatars of virtual construction workers were also added to execute various tasks to mimic actual construction sites and to present possible safety risks associated with interacting with four-legged robots [Fig. 3(c)].

Virtual Instructor

The virtual instructor leads the students through the exploration of virtual construction site visits while providing them with on-site learning opportunities related to the four-legged robots. Unity game engine was utilized to design the 3D character model, harnessing its capacity to capture a spectrum of nonverbal cues such as distance, body orientation, movement, and gestures (Fig. 4). These behaviors have been identified as catalysts for social interactions, enhancing communication between speakers and audiences (Salem and Earle 2000). Moreover, Baylor (2005) highlighted that students exhibit better knowledge transfer when agents adopt realistic appearances, especially when portraying expert roles in unconventional ways. The researchers exercised complete creative control over the physical attributes (gender and ethnicity) and narratives of the 3D characters, facilitating the creation of avatars that function as akin or pertinent role models for the intended recipients. In the development of pedagogical agents, gender, ethnicity, and the authenticity of virtual agents bear significance. Consequently, a realistic 3D

Fig. 3. Virtual construction site development: (a) importing the construction site as an.FBX file into unity; (b) adding construction equipment to the construction site; and (c) adding virtual workers to the construction site.

Fig. 4. Virtual instructor development process.

representation of an African American female construction professional was selected as the virtual instructor for RoboSite. The selected virtual instructor's gender and ethnicity also serve to promote the representation of females and minorities within the construction industry (Herrmann et al. 2016).

To instill appropriate gesture animations, the built-in Animator asset within Unity was employed and seamlessly integrated with the 3D character model. Prior research attests that incorporating both verbal and nonverbal elements heightens the sensation of virtual presence, fosters interpersonal interactions, and elevates user satisfaction (Wen and Gheisari 2021). Gesture assignments for the virtual instructor (e.g., head shaking, greetings, single-hand raises, expressions of surprise, and shrugging) were contingent on the learning content to articulate emotions and amplify authenticity.

The audio for the instructional voice of the virtual instructor was generated using the Google Cloud text-to-speech API (Google Cloud 2023) based on the learning content developed previously for the learning objectives. These voiceovers possess an authentic and expressive quality, featuring natural pauses during the speech to enhance students' comprehension of the instructor's emotional nuances throughout the learning activities. To ensure a consistent focus on the instructional content and facilitate adherence to the virtual instructor's guidance, 3D sound settings were adopted, allowing the audio volume to decrease as the distance between users and the instructor increased.

To create a more natural and realistic virtual instructor, lip-syncing and facial animations were created. Lipsync Pro (Rogo Digital 2023) was used to create facial animations and core mouth shape corresponding to the words from the audio source while controlling the facial expressions and eye contact of the virtual instructor.

Situated and Conceptual Learning Contexts

For the situated learning scenarios, the virtual instructor presents learning content on construction scenarios that are contextually relevant. Lave and Wenger (1991) underscored the significance of situated learning, emphasizing the interplay between learning and the social context in which the learning takes place. This approach enables students to achieve profound comprehension and heightened engagement by applying their knowledge in a contextually rich learning environment. In the context of RoboSite, a virtual construction site with virtual workers, equipment, and four-legged robots was generated to replicate construction tasks and realistic working conditions outlined in the learning materials. As students engage with these scenarios, the virtual instructor covers the corresponding learning materials. Students would follow the virtual instructor to learn fundamental concepts of four-legged robots and to observe different situated interactive learning scenarios in the virtual construction site. This approach was consistently employed throughout the training session to cover all the learning objectives of the RoboSite experience without subjecting the trainees to any genuine risks, ensuring a controlled and secure learning environment (Fig. 5). For example, in learning objective #1, an various construction robots (e.g., drones, wheeled robots, climbable robots, and four-legged robots) with integrated animations were strategically positioned within the construction sites to demonstrate their respective characteristics and potential applications [Fig. 5(a)]. In learning objective #2, five situated learning scenarios were used to present the primary applications of four-legged robots in construction [Fig. 5(b)]. Within these scenarios, two interactive scenarios per application were designed to illustrate the construction environment both before and after the integration of four-legged robots for (1) monitoring and inspection and (2) material and equipment delivery. The fifth scenario showcased the capability of four-legged robots to (3) lay brick and operate switches and valves using their robotic arms. This approach allowed students to comprehend and draw comparisons regarding the distinct advantages of four-legged robots when applied in construction sites, in contrast to traditional worksites without such robots. In learning objective #3, five

(a) (b) (c) (d)

Fig. 5. Examples of situated learning scenarios for each learning objective: (a) example for learning objective #1; (b) example for learning objective #2; (c) example for learning objective #3; and (d) example for learning objective #4.

situated scenarios were presented to highlight virtual construction workers engaging in diverse collaborative tasks with four-legged robots on the construction sites while highlighting the potential safety risks that may arise when working with or in close proximity to four-legged robots [Fig. 5(c)]. These scenarios depict both the occurrence and consequences of these risks on construction sites. Finally, in learning objective #4, five situated learning scenarios were used to demonstrate the efficacy of safety measures in mitigating potential risks associated with the presence of four-legged robots in construction [Fig. 5(d)].

Beyond extensively utilizing situated learning scenarios, the virtual instructor also incorporated a display board as a means to introduce topics and explain nonsituated conceptual materials. The deliberate integration of the display board aimed to create an experience that closely resembled traditional classroom instruction, a format with which trainees are already well-acquainted (Usoh et al. 2000). This strategic approach was selectively deployed in instances necessitating the exploration of nonsituated conceptual content, including subjects like the technologies of four-legged robots [Fig. 6(a)], types of hierarchy of controls approaches [Fig. 6(b)], and personal protection equipment [Fig. 6(c)].

User Interface

Users must interact with the virtual site visits both to comprehend potential actions and to specify the tasks they want the system to undertake (Miller and Parasuraman 2007). The user interfaces for RoboSite (Fig. 7) comprised a main virtual site window, enabling students to navigate the environment using their mouse and arrow keys on their keyboards. On the lower-right side of the user interface, a learning board allowed students to check the learning objective corresponding to the presented content, as well as lecture content related to the objective, offering additional explanations. On the lower-left side of the interface, a 2D Map was available, enabling students to visualize their own location and the virtual instructor's position on the site. This 2D Map facilitated students' spatial understanding of the environment, complementing the 3D representation and aiding in visualizing the layout and organization of the space to support their learning process (Dalgarno and Lee 2010). Lastly, a *Back to Instructor* button was included to help students return to the virtual instructor. While students were encouraged to follow the virtual instructor during the site visit, they could also freely explore different locations on the virtual construction sites. This button acted as a valuable tool for students, enabling them to easily teleport to the vicinity of the instructor in case of disorientation or if they found themselves distant from the virtual instructor.

Finally, RoboSite was compiled as a standalone system version, specifically for the Window platform with an x86_64 architecture. To run RoboSite, a PC with a minimum of 520 MB of RAM is required. Users can download the RoboSite package onto their Windows PC and operate the application independently of an internet connection.

Assessment Procedure and Measures

A repeated-measure design was used in this study, which involved assessments in pre- and post-RoboSite virtual site visit experience (Fig. 8). This section will further discuss the assessment procedure

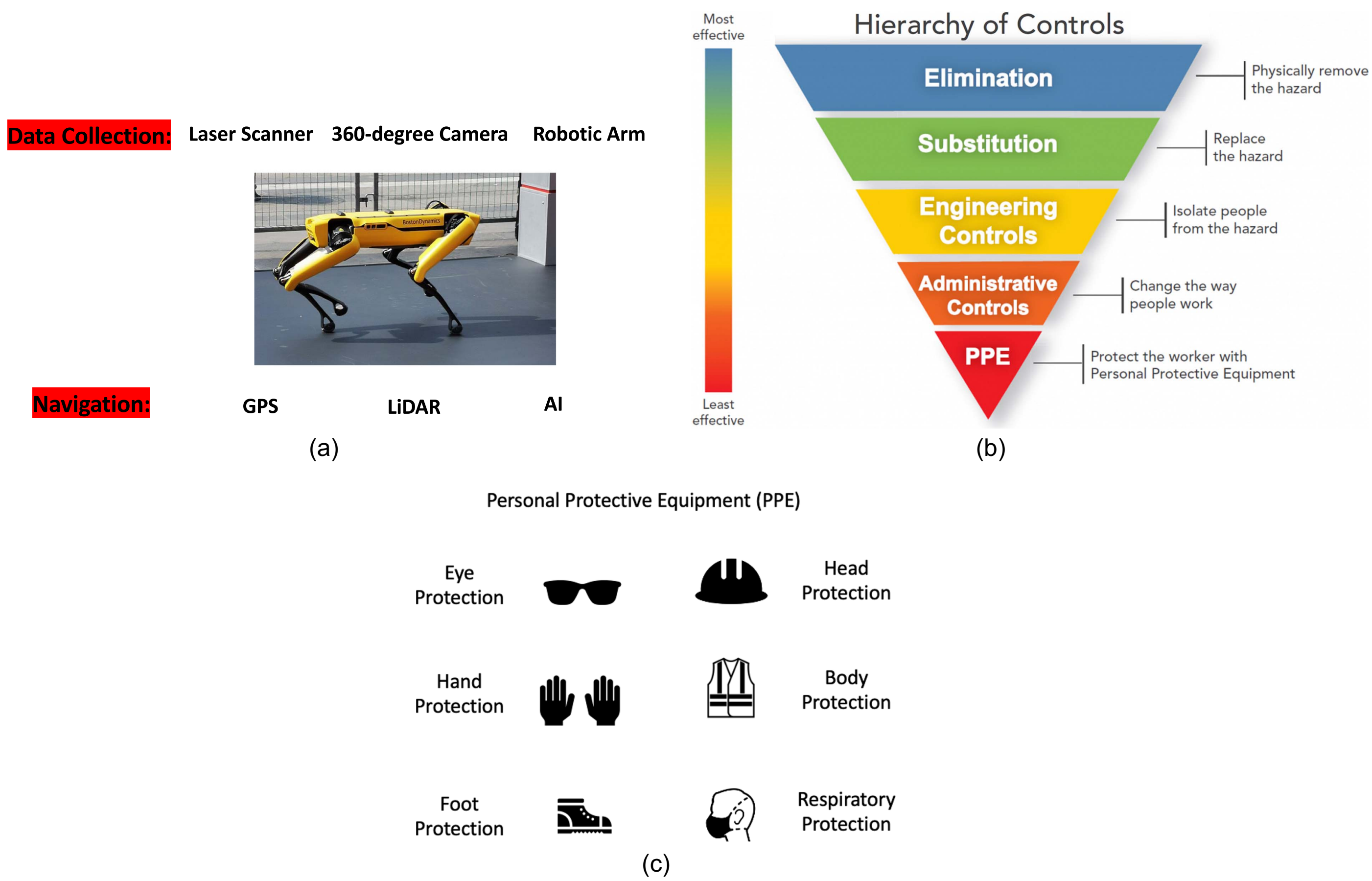

Fig. 6. (a)–(c) Examples of using a display board for conceptual learning. [Image (a) courtesy of Wikimedia Commons/Saggittarius A.]

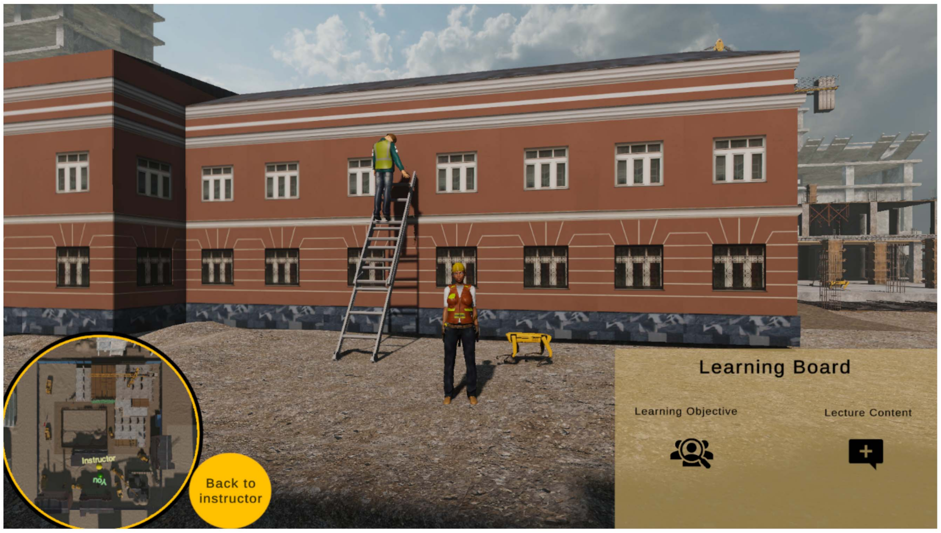

Fig. 7. RoboSite user interface.

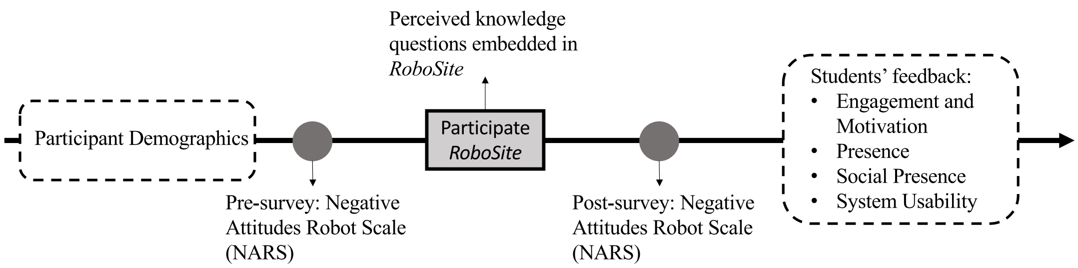

Fig. 8. RoboSite assessment procedure.

of this study and the measures employed within each step of the assessment process.

Participating students first reviewed the consent form, which discussed the study protocol reviewed and approved by the University of Florida Institutional Review Board (IRB# 16445). Participants then responded to a demographic survey, and a pre-RoboSite Negative Attitude toward Robots Scale (NARS) questionnaire. After the virtual site visit, the NARS questionnaire was repeated to assess any changes in the students' attitudes toward construction robots (Research Question #1).

- *Negative Attitudes Toward Robot Scale (NARS)* was utilized to gauge whether students generally hold a positive or negative attitude toward robots (Joosse et al. 2013). This scale comprises 12 questions presented on a five-point Likert scale. The central emphasis of this scale lies in assessing the degree to which individuals might exhibit hesitancy in interacting with robots. This hesitation serves as an indicator of negative attitudes not only toward engaging with robots but also toward the societal impact of robots and the emotions experienced during interactions with them.

During the virtual site visit, students responded to a set of questions to evaluate students' understanding, self-efficacy, and engagement concerning the incorporation of four-legged robots in construction (Research Question #2).

- *Perceived Knowledge*: A series of pop-up quiz questions was designed to evaluate users' comprehension levels during the virtual site visit. These questions encompassed diverse facets of the four learning objectives on topics such as four-legged robots, their applications, safety challenges, and mitigation measures. These questions were additionally employed to ensure that students remained engaged throughout the virtual site visit and remained attentive to the learning content conveyed by the virtual instructor. Table 5 shows detailed assessment questions.
- *Self-efficacy and Engagement*: Post the RoboSite experience, student self-efficacy and engagement were assessed through an adapted version of the Lee et al. (2016) survey. This modified survey encompassed a set of nine questions utilizing a five-point Likert scale. Self-efficacy pertains to students' belief in their academic aptitude, while engagement serves as a mediator in the correlation between intrinsic and extrinsic motivation and student achievement.

Finally, various surveys on Presence, Social Presence, and System Usability were conducted to evaluate the usability and feasibility of the RoboSite virtual site visit experience.

- *System Usability Scale (SUS)* is a validated series of ten questions on a five-point Likert scale developed by Bangor et al. (2009) to gauge users' perceived usability of a system in a unidimensional manner. SUS has been previously employed to evaluate technology acceptance in e-learning contexts (Sun et al. 2022). Within this study, the SUS will be utilized to evaluate the user experience's quality, specifically by assessing its effectiveness (i.e., users' ability to complete tasks using the system), efficiency (i.e., users' resource consumption during task performance), and satisfaction (i.e., users' responses to the system's performance).
- *Sense of Presence*: The efficacy of virtual environments in captivating and motivating users is frequently associated with the concept of presence. Presence is characterized as "the subjective

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Table 5. Assessment questions in perceived knowledge

Learning objective	Assessment questions
(#1) Learn about four-legged robots, their benefits, challenges, and integrated technologies	1. What are four-legged robots also called? (A. Quadruped robot; B. Wheeled robot; C. Drone; D. Climbable robot) 2. What are the benefits of four-legged robots in the construction industry? (A. High adaptability; B. Incredible mobility and stability of locomotion; C. High versatility; D. All of the above) 3. What are the technologies that four-legged robots use to navigate autonomously on construction sites? (A. GPS; B. LiDAR; C. AI; D. All of the above)
(#2) Discuss four-legged robot applications in construction	4. How can four-legged robots facilitate construction work? (A. Reducing the work duration; B. Reducing worker movements on the site; C. Increasing the work productivity; D. All of the above) 5. What technology might four-legged robots use for inspection and monitoring type of applications? (A. Laser scanner; B. Robotic arms; C. GPS; D. All of the above)
(#3) List the safety challenges of four-legged robots on construction jobsites.	6. What types of risks do four-legged robots pose to humans? (A. Physical risks; B. Attentional cost; C. Psychological impacts; D. All of the above) 7. Which of the following statements is NOT True? (A. Four-legged robots' fast or sudden movements may impact human workers' respiratory and vision health; B. Four-legged robots cannot distract us when we are working on height; C. The feeling of being watched by four-legged robots can increase the likelihood of an accident; D. Fast-moving legs of four-legged robots can cause physical risks)
(#4) Discuss potential precautions to minimize safety challenges of four-legged robots on construction jobsites	8. What is the most effective strategy to avoid the hazards posed by four-legged robots? (A. Elimination; B. Substitution; C. Engineering Control; D. PPE) 9. Which of the following statements is an elimination strategy? (A. Replacing a four-legged robot by a drone for collecting data; B. No using any robot at all; C. Using a caution tape to keep workers away from the path or four-legged robot; D. Always wearing safety gloves when working with robot)

experience of being in one place or environment, even when one is physically situated in another" (Witmer and Singer 1998). To assess users' level of presence, a validated five-point Likert-scale questionnaire developed by Usoh et al. (2000) was adopted. A higher Likert-scale value on the presence questionnaire indicates a stronger sense of spatial presence, engagement, and realism.

- *Social Presence*: The notion of social presence pertains to the degree to which students perceived themselves to be present with the virtual instructor during the RoboSite experience. This perception encompasses both an initial awareness and the ability to focus attention while comprehending both the content and emotional aspects of the encounter (Bulu 2012). To quantify social presence within this study, the social presence survey tool devised by Harms and Biocca (2004) was employed. This survey comprises eleven statements that students assess on a five-point Likert scale.

Results and Discussion

A total of 56 students (15 females and 41 males) participated in this study, as detailed in Table 6. The subjects included 27 undergraduate students and 29 graduate students, with a significant portion holding backgrounds in construction management or civil engineering (82%). Furthermore, a substantial majority (86%) had some practical experience in the construction industry. The majority of participants exhibited either limited or some degree of familiarity with construction robotics (74%) and four-legged robots (86%). Moreover, slightly over half of the subjects demonstrated a fair or competent level of familiarity with VR, accounting for 54% of the respondents. Within this section, an in-depth discussion will be presented regarding the outcomes yielded by the various measures assessed throughout the RoboSite virtual site visit experience.

Negative Attitudes toward Robot Scale (NARS)

NARS questionnaire was utilized to gauge whether students generally hold a positive or negative attitude toward four-legged robots and how the RoboSite experience might have affected their attitude (Research Question #1). The assessment of normality was conducted using the Shapiro-Wilk test (Shapiro and Wilk 1965) and the result showed that the data follows a normal distribution ($p > 0.05$). Consequently, a paired-sample t-test was conducted to compare the means and detect statistically significant distinctions between the NARS scores (Table 7) obtained prior to and after the RoboSite encounter (Pre-RoboSite and Post-RoboSite). In this study, the overall NARS score (Nomura et al. 2007) reduced significantly subsequent to students' participation in the RoboSite virtual site visit experience (Pre-RoboSite: 2.74 and Post-RoboSite: 2.53). This significant decrease indicates a notable reduction in negative attitudes toward these robots after engaging with RoboSite.

More specifically, participants declared that their feelings of unease significantly decreased when given jobs to work with four-legged robots (Statement #1; Pre-RoboSite: 2.32 and Post-RoboSite: 2.07) or when confronted with the idea that these robots had real emotions (Statement #3; Pre-RoboSite: 3.55 and Post-RoboSite: 3.11). Participants also indicated a significant reduction in their apprehension about working extensively with four-legged robots (Statement #6; Pre-RoboSite: 3.29 and Post-RoboSite: 2.91) and concerning the potential dominance of these robots in future society (Statement #8: Pre-RoboSite: 2.98 and Post-RoboSite: 2.57). Participants presented a significant reduction in their discomfort toward these robots (Statement #12: Pre-RoboSite: 2.52 and Post-RoboSite: 2.27).

Both before and after experiencing the RoboSite, participants indicated a neutral stance regarding the idea of such robots or artificial intelligence making judgments about things (Statement #2; Pre-RoboSite: 2.57 and Post-RoboSite: 2.36). Participating students also reported that they would not feel very nervous when

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Table 6. Demographics of the participating students

Parameters	Category	Number (Percentage)
Gender	Females	15 (27%)
	Males	41 (73%)
Educational level	Undergraduates	27 (48%)
	Graduates	29 (52%)
Educational background	Construction management	31 (55%)
	Civil engineering	15 (27%)
	Others (e.g., landscape, architecture)	10 (18%)
Experience in construction industry	No experience	8 (14%)
	Less than 6 months	15 (27%)
	6 months to 1 year	10 (18%)
	1 to 2 years	11 (20%)
	Over 2 years	12 (21%)
Familiarity with construction robotics	None	20 (36%)
	Some knowledge of	21 (38%)
	Fair	11 (20%)
	Competent	4 (6%)
Familiarity with Four-legged robots (aka Quadruped)	None	30 (54%)
	Some knowledge of	18 (32%)
	Fair	7 (13%)
	Competent	1 (1%)
Familiarity with virtual reality (VR)	None	9 (16%)
	Some Knowledge of	17 (30%)
	Fair	22 (39%)
	Competent	8 (15%)

Table 7. Results for students' negative attitudes toward robot scale

Statements on students' attitudes	Pre-RoboSite	Post-RoboSite	
Likert Scale: strongly disagree (1)—(5) strongly agree	Mean (SD)	Mean (SD)	p-value
#1: I would feel uneasy if I was given a job where I had to use four-legged robots	2.32 (0.96)	2.07 (0.76)	0.03**
#2: I would hate the idea that four-legged robots or artificial intelligence were making judgments about things	2.57 (1.13)	2.36 (0.75)	0.12
#3: I would feel very nervous just standing in front of a four-legged robot	1.86 (1.03)	1.86 (0.77)	1.00
#4: I would feel uneasy if four-legged robots really had emotions	3.55 (1.17)	3.11 (1.04)	0.01**
#5: Something bad might happen if four-legged robots develop into living beings	3.52 (1.22)	3.23 (0.83)	0.07
#6: I feel that if I depend on four-legged robots too much, something bad might happen	3.29 (1.14)	2.91 (0.94)	0.00**
#7: I am concerned that four-legged robots would be a bad influence on children	2.64 (1.02)	2.55 (0.99)	0.34
#8: I feel that in the future, society will be dominated by four-legged robots	2.98 (1.21)	2.57 (0.97)	0.01**
#9: I feel that in the future, four-legged robots will be commonplace in society	1.95 (0.80)	1.88 (0.83)	0.48
#10: I would feel relaxed talking with four-legged robots[a]	2.95 (1.02)	2.88 (1.01)	0.58
#11: If four-legged robots had emotions, I would be able to make friends with them[a]	2.68 (0.99)	2.63 (0.93)	0.57
#12: I feel comfortable being with four-legged robots[a]	2.52 (0.85)	2.27 (0.67)	0.01**
Overall:	2.74 (1.17)	2.53 (0.98)	0.00**

Note: ** p-value < 0.05.
[a]Statements 10, 11, and 12 are worded positively.

merely standing in front of a robot (Statement #3; Pre-RoboSite and Post-RoboSite: 1.86). Participants expressed the belief that something negative might occur if such robots developed into living beings (Statement #5; Pre-RoboSite: 3.52 and Post-RoboSite: 3.23), yet they maintained a neutral position concerning such robots would have a bad influence on children (Statement #7; Pre-RoboSite: 2.64 and Post-RoboSite: 2.55). Participants shared the sentiment that such robots would become commonplace in society in the future (Statement #9; Pre-RoboSite: 1.95 and Post-RoboSite: 1.88). Additionally, participants indicated their neutrality regarding feeling at ease while talking with such robots (Statement #10; Pre-RoboSite: 2.95 and Post-RoboSite: 2.88) and the prospect of forming friendships with such robots if they possessed emotions (Statement #11; Pre-RoboSite: 2.68 and Post-RoboSite: 2.63).

In light of these findings, it becomes apparent that the participants' perceptions and attitudes toward robots underwent subtle shifts after their engagement with RoboSite. The convergence of neutral positions on various aspects, such as robots' judgment capabilities, ease of interaction, and their potential societal presence, might underscore a prevailing cautious optimism toward robotic technology. This suggests that while familiarity with robots and their applications can alleviate initial unease, certain concerns regarding robots' evolving roles and potential influences persist. Overall, the results imply an evolving acceptance of robotics within the construction landscape, indicating the importance of ongoing education and awareness initiatives in shaping constructive attitudes toward the integration of robots in future work scenarios.

Perceived Knowledge and Student Self-Efficacy and Engagement

A set of questions pertaining to perceived knowledge, alongside a self-efficacy and engagement survey, were employed to evaluate students' understanding, self-efficacy and engagement concerning the incorporation of four-legged robots in construction (Research Question #2). On average, students accurately answered 80% of the assessment questions, indicating a high success rate in providing fundamental understanding regarding the application of four-legged robots in construction. The result is comparable with other studies exploring using of VR system on learning outcomes in construction education. Moreover, one student provided feedback stating, "Great training alternative! It covered the application, challenges, and protective measures that could be used to prevent four-legged robots from creating hazardous situations."

Regarding the impact of RoboSite on students' self-efficacy and engagement, the overall score (Average of Statements #1 to #9) was 4.05, signifying that students achieved a high level of self-efficacy and engagement during the RoboSite virtual site visit (See Table 8). In terms of student self-efficacy with RoboSite, it was evident that students strongly concurred with the notion that RoboSite substantially enhanced their self-efficacy, as they felt confident in mastering the knowledge provided (Statement #1; Mean: 4.18) within RoboSite, were able to comprehend almost all the tasks (Statement #2; Mean: 4.02) presented in RoboSite, and managed to grasp the learning material even when the tasks within RoboSite were challenging (Statement #3; Mean: 4.05).

In terms of student engagement with RoboSite, their consensus was that they devoted attention to all the learning activities within RoboSite (Statement #4; Mean: 3.86), did not experience boredom while acquiring knowledge (Statement #6; Mean: 3.25), had a moderate liking for their presence in RoboSite (Statement #7; Mean: 3.48), and employed self-questioning strategies to ensure comprehension of newly learned concepts (Statement #8; Mean: 3.45). Additionally, students reported a lack of perceived trouble during their RoboSite experience (Statement #5; Mean: 4.13). It is noteworthy that students expressed neutral sentiments toward Statement #9, indicating that they neither agreed nor disagreed with the idea of revisiting RoboSite if they faced difficulties in understanding the content (Statement #9; Mean: 2.95). Students also raised some concerns regarding the utilization of RoboSite and similar computer-aided training methods in the open-ended section of the survey. One student's perspective underscored this, stating, "I rarely use computer-aided training to acquire new knowledge; I still rely primarily on in-person learning and reading." Clearly, students' perceptions about computer-aided training and their familiarity with such methods hold the potential to significantly influence their engagement and motivation during virtual site visits.

Collectively, these results offer a compelling insight into the efficacy of RoboSite as an innovative tool for enhancing students' understanding, engagement, and self-efficacy in the context of four-legged robots in construction. The significant levels of self-efficacy and engagement demonstrated during the virtual visit reflect RoboSite's successful translation of theoretical concepts into experiential learning. The open-ended feedback from students further validates its comprehensive approach in addressing various aspects of robot integration. While the neutral stance on revisiting the content for clarification highlights a potential area for refinement, the overall impression from these results is positive and illustrates the potential of RoboSite in helping students develop understanding, self-efficacy, and engagement concerning the four-legged robot implementation in construction.

Usability and Feasibility of RoboSite VR Environment

System Usability Scale (SUS): In this study, the overall SUS score amounted to 75.38, signifying a level of system usability ranging from *Good* to *Excellent* (Bangor et al. 2009). A detailed analysis of individual statements was performed to gather deeper insights into the system usability (see Table 9). Respondents indicated a somewhat strong willingness to frequently use the system (Statement #1; Mean: 3.54) and found it very easy to use (Statement #3; Mean: 4.18). The integration of various functions within the system was notably seamless (Statement #5; Mean: 4.04), and most participants believed that the system's usage could be learned quickly by a wide range of users (Statement #7; Mean: 4.07). Additionally, participants expressed a high level of confidence in using the system (Statement #9; Mean: 4.30). Notably, the system was perceived to be devoid of unnecessary complexity (Statement #2; Mean: 1.91), and participants generally disagreed on the need for technical assistance to operate the system (Statement #4; Mean: 2.07). Similarly, the system was not seen as inconsistent (Statement #6; Mean: 2.02), awkward to navigate (Statement #8; Mean: 2.00) or requiring extensive prior knowledge for operation (Statement #10; Mean: 1.98). Furthermore, students' qualitative remarks supported these

Table 8. Results for students' self-efficacy and engagement

Statements on self-efficacy and engagement Likert scale: strongly disagree (1)–(5) strongly agree		Mean (SD)
Self-efficacy	#1: I'm sure I can become really good at the knowledge taught in the RoboSite	4.18 (0.11)
	#2: I'm sure I can figure out almost all the work in the RoboSite	4.02 (0.12)
	#3: Even though the work in the RoboSite is hard, I can learn it	4.05 (0.12)
Engagement	#4: I pay attention to all of the learning activities in the RoboSite	3.86 (0.13)
	#5: I get in trouble in the RoboSite[a]	4.13 (0.13)
	#6: I feel bored when I'm learning this knowledge[a]	3.25 (0.15)
	#7: I like being in the RoboSite	3.48 (0.13)
	#8: When I learn new knowledge on the RoboSite, I ask myself questions to make sure I understand what I am learning about	3.45 (0.14)
	#9: If I do not understand what I learn in the RoboSite, I go back and watch it over again	2.95 (0.16)
	Overall:	4.05 (0.05)

[a]Statements 5 and 6 are worded negatively.

Table 9. Results for system usability scale (SUS)

Statements on system usability scale (SUS) Scale: strongly disagree (1)–(5) strongly agree	Mean (SD)
#1: I think that I would like to use this system frequently[a]	3.54 (0.11)
#2: I found the system unnecessarily complex	1.91 (0.12)
#3: I thought the system was easy to use[a]	4.18 (0.12)
#4: I think that I would need the support of a technical person to be able to use this system	2.07 (0.15)
#5: I found that the various functions in the system were well integrated[a]	4.04 (0.12)
#6: I thought there was too much inconsistency in this system	2.02 (0.13)
#7: I would imagine that most people would learn to use this system very quickly[a]	4.07 (0.12)
#8: I found the system very awkward to use	2.00 (0.14)
#9: I felt very confident using the system[a]	4.30 (0.10)
#10: I needed to learn a lot of things before I could get going with this system	1.98 (0.16)
Overall SUS (Bangor et al. 2009):	75.38

[a]Statement 2, 4, 6, 8, and 10 are worded negatively.

findings. For instance, one student remarked, "I found RoboSite to be very user-friendly and well-designed, despite not being particularly adept with technology." However, some students reported encountering technical challenges that necessitate further refinement. For example, one user noted, "the mouse is not centered on the screen, which makes it slightly difficult to use." Presently, mouse movement controls both the field of view and interaction with user interfaces, leading to difficulties in maintaining the cursor at the screen's center. Addressing this design concern could involve implementing a more suitable control and movement system, such as adjusting the field of view when right-clicking while reserving mouse movement solely for interacting with user interfaces.

Sense of Presence: Participants in RoboSite reported a moderately high sense of being present at the construction site (Statement #1; Mean: 3.63) and also demonstrated a somewhat stronger sense of being on the construction site than elsewhere (Statement #3; Mean: 3.41) (Table 10). Furthermore, participants sometimes felt that the construction site within RoboSite was genuinely real (Statement #2; Mean: 2.88). They also held neutral perspectives on whether RoboSite resembled a place they visited or merely images they observed (Statement #3; Mean: 2.89) and expressed neutral perceptions of actually being present on the construction site (Statement #5; Mean: 2.89). Considering the overall sense of presence, participants collectively reported a relatively neutral sense of presence within RoboSite (3.14), somewhat consistent with findings from other studies exploring the impact of virtual environments in educational contexts (Ferguson et al. 2020). Qualitative insights on presence in the virtual site visit were also shared by some participants. For instance, one user commented, "I felt that RoboSite was a good depiction of the construction site and I felt that I had good presence in the game." However, certain participants identified limitations that diminished the sense of presence during the virtual site visit, such as "When the instruction is walking, it looks unreal as the instructor's feet do not touch the ground." This concern may stem from a restricted number of components within the integrated animation database, resulting in less lifelike movements for the virtual instructor and other virtual workers and equipment on the site. To address this, more intricate animation development should be pursued, although careful consideration of the time investment required for virtual development is crucial. It should be noted that earlier research indicates that higher fidelity in the virtual environment does not necessarily correlate with heightened learning outcomes and engagement (Eiris et al. 2021). Thus, achieving an appropriate level of fidelity that aligns with the learning objectives of the virtual site visit should be a focal point, while also taking into account the developmental demands of such a virtual environment.

Social Presence: The overall social presence score (3.78) indicates that students agreed on feeling connected to the virtual site visit throughout the experience (see Table 11). Regarding the initial awareness facet of social presence, it is evident that students strongly concurred with the idea that RoboSite effectively establishes initial awareness. Students also strongly agreed that they noticed the virtual instructor (Statement #1; Mean: 4.57) within RoboSite, its presence was apparent to them (Statement #2; Mean: 4.52), and it captured their attention (Statement #3; Mean: 4.16). Concerning the aspect of attention allocation within the realm of social presence, students demonstrated a neutral or relatively low level of agreement. Their responses indicated a neutral consensus when it came to being easily distracted from the virtual instructor amidst other activities during the virtual site visit (Statement #4; Mean: 3.02) or when the virtual instructor struggled to maintain their undivided attention (Statement #6; Mean: 2.96). Students also indicated a moderate level of focus on the virtual instructor

Table 10. Results for sense of presence

Statements on sense of presence	Likert scale	Mean (SD)
#1: Please rate your sense of being on a construction site	Not at all (1)–(5) very much	3.63 (0.13)
#2: To what extent were there times during the RoboSite when the construction site was the reality for you?	At no time (1)–(5) Almost all the time	2.88 (0.16)
#3: When you think back about the RoboSite, do you think of a construction site more as images that you saw or more as somewhere that you visited?	Image as I saw (1)–(5) somewhere that I visited	2.89 (0.17)
#4: During the time of the RoboSite, which was strongest, on the whole, your sense of being in a construction site or elsewhere?	Being elsewhere (1)–(5) being on a construction site	3.41 (0.16)
#4: During the time of the experience, did you often think to yourself that you were actually on a construction site?	Not very often (1)–(5) very much so	2.89 (0.18)
Overall:		3.14 (0.07)

Table 11. Results for social presence

Category	Statements on social presence Scale: strongly disagree (1)–(5) strongly agree	Mean (SD)
Initial awareness	#1: I noticed the virtual instructor in the system	4.57 (0.66)
	#2: The virtual instructor's presence was obvious to me	4.52 (0.74)
	#3: The virtual instructor caught my attention	4.16 (1.08)
Attention allocation	#4: I was easily distracted from the virtual instructor when other things were going on[a]	3.02 (1.14)
	#5: I remained focused on the virtual instructor throughout our interaction	3.32 (1.16)
	#6: The virtual instructor did not receive my full attention[a]	2.96 (1.13)
Content comprehension	#7: The virtual instructor's thoughts were clear to me	4.39 (0.62)
	#8: It was easy to understand the virtual instructor's learning contents	4.37 (0.70)
	#9: Understanding the virtual instructor was difficult[a]	4.30 (0.93)
Affective comprehension	#10: The virtual instructor's emotions were not clear to me[a]	3.02 (1.20)
	#11: I could describe the virtual instructor's feelings accurately	2.95 (1.24)
	Overall:	3.78 (1.19)

[a]Statements 4, 6, 9, and 10 are worded negatively.

throughout the virtual site visit (Statement #5; Mean: 3.32). These slightly diminished levels of agreement in terms of attention allocation can be attributed to the abundance of elements in the virtual construction sites, including construction equipment, operational robots, and construction personnel, all of which could potentially serve as distractions. Students also offered qualitative feedback noting technical challenges that occasionally diverted their attention from the instructor's narratives. One student mentioned, "the instructor sounded a bit robotic, and I sometimes got distracted due to the monotonous tone." The instructor's audio was generated using the Google Cloud text-to-speech API, and this aspect could be enhanced by incorporating recordings of a human voice or exploring more realistic audio solutions. Concerning the facet of content comprehension of social presence, it is evident that students firmly concurred that the virtual instructor effectively facilitated their understanding of the learning content in RoboSite. Students found the virtual instructor's thoughts to be lucid and coherent (Statement #7; Mean: 4.39), and the virtual instructor's narrative contents were easily graspable for them (Statement #8; Mean: 4.37). Students also expressed that comprehending the virtual instructor's communication posed no significant difficulty (Statement #9; Mean: 4.30). In terms of attention allocation within the realm of social presence, students displayed a neutral level of agreement, indicating that they neither agreed nor disagreed on their ability to understand the virtual instructor's emotions (Statement #10; Mean: 3.02) or accurately describe its feelings (Statement #11; Mean: 2.95). Students' qualitative comments further highlighted that the virtual instructor's expression of emotions was not adequately pronounced. For instance, a student mentioned, "the virtual instructor's gestures and facial expressions are repetitive, sometimes not matching the story she is narrating." The instructor's animation package in Unity encompasses 21 gesture animations, yet these gestures may lack realism when compared to those of real humans.

In summary, RoboSite system utilized virtual reality technology to offer a promising platform for students' immersive experiences. Its system's usability scores predominantly range from *Good* to *Excellent*, underscoring its intuitive design and user-friendly interface. Nevertheless, student feedback identified certain technical issues, particularly related to the control system, suggesting areas for future refinement. The immersion items, including the sense of presence and social presence, were moderately positive. While there is a potential to enhance the fidelity of the virtual environment for a deeper immersive experience, it is essential to balance this with the time and resources required for development. Notably, prior research suggests that ultrahigh fidelity does not necessarily lead to enhanced learning or engagement. Thus, the objective should be to strike a balance, ensuring the virtual environment's fidelity complements the learning goals without imposing undue development demands.

Implications for Research and Practice

The findings of this research indicate that RoboSite can be a valuable as an instrumental tool in the construction curriculum, shedding light on four-legged robots' utility and mitigating students' concern. The virtual site visits facilitated interactions with a virtual instructor and empowered students to navigate the environment autonomously, bolstering their understanding of four-legged robots and their self-efficacy and engagement. Incorporating multimedia learning strategies in the virtual site visits stimulated active student participation, leveraging diverse verbal and visual contexts to conceptualize the learning content. Moreover, developed using Unity, the virtual site visits were accessible through personal laptops, obviating the need for real-world site exposure. The user interfaces were intuitively designed, ensuring swift and straightforward system navigation for students. Overall, these findings contribute to establishing a clear workflow for designing and deploying virtual site visits and the instructional strategies pertinent to construction robots. It offers an effective alternative when opportunities for learning about cutting-edge technology, like construction robots, are limited or unavailable.

Although the study specifically targeted four-legged robots, the content within RoboSite could be customized to reflect the diverse types of construction robots, ranging from fundamental definitions and applications to the intricacies of safety challenges and their respective countermeasures. The technical development in this paper provided a guide for educators and researchers pursuing the creation of virtual site visits in construction. Furthermore, the assessment indicated that the RoboSite are effective in building trust and improving perceptions of construction robots, thereby enhancing learners' understanding of robotic technologies in construction. Such findings suggest that the approach used in RoboSite could be effectively replicated or adapted for educating students about a wider array of robotic technologies in the construction industry.

Conclusion and Future Research

This study developed the RoboSite system, integrating the immersive capabilities of virtual reality to offer safe and cost-effective learning opportunities. RoboSite was designed to facilitate trust and positive perceptions regarding four-legged robots while enhancing students' understanding of the applications, safety challenges, and countermeasures associated with such technologies in construction. The effectiveness of the developed RoboSite was evaluated using a repeated measures experiment involving 56 participants. The findings revealed a significant reduction in participants' negative perceptions and attitudes toward four-legged robots after they engaged with RoboSite. Furthermore, the positive outcomes in perceived knowledge and the survey of self-efficacy and engagement underscore the potential of RoboSite in facilitating students' understanding, self-efficacy, and engagement concerning the deployment of four-legged robots in construction. The overall usability scores ranged between *Good* and *Excellent*, indicating the system's user-friendliness, though some technical issues related to the control system of RoboSite might impact its ease of use. Participants also reported a relatively neutral sense of presence within RoboSite, with the overall social presence score suggesting that students felt consistently connected to the RoboSite virtual site visit experience. However, it is important to note that there were specific research and technological challenges encountered in implementing these virtual site visits, which should be taken into consideration.

The sample lacked diversity, with most participants having minimal to moderate knowledge about construction robots and four-legged robots in particular. The instructional contents and methodologies might not be suitable for students who have with an advanced understanding of these robots. To address this educational gap concerning robots in construction, it is imperative to devise instructional content and strategies that cater to broader learners. Thus, our sampling strategy represents the limitation of this research. Future studies should consider collecting data from a larger and more diverse group of students with varying levels of familiarity with construction robots and four-legged robots. Nevertheless, this experimental investigation provided valuable insights into the use of virtual site visits in construction education. Additionally, this study focused solely on four-legged robots as the learning target to assess learning performance and the system's effectiveness in improving students' attitudes toward robots in construction. Despite this constraint, the findings offered a foundational perspective on the application of the RoboSite system as an instructional resource. Further studies would expand the scope to include a wider variety of robots and educational scenarios, thereby broadening the applicability and impact of such virtual learning environments in construction education.

In terms of technological challenges, one limitation of this study was the reliance on desktop VR, which can be addressed and further explored by utilizing more immersive methods for experiencing the VR content. For example, the use of cost-effective and user-friendly VR headsets, such as Google Cardboards, could be explored to enhance the immersion of RoboSite system. Another limitation of the study was related to the accessibility of the RoboSite system. Students were required to download a sizable program file package on a laptop or PC, coupled with the system's slightly elevated hardware requirements for optimal graphic rendering. Some participants expressed concerns about the prolonged download times, particularly in regions with limited internet bandwidth. Feedback also indicated that the virtual instructor's speech and movement was perceived as slow, potentially due to hardware limitations. Future research should consider a platform-agnostic approach, enabling access to virtual site visits across diverse devices. For example, Mozilla Hubs, a virtual social platform known for its device-agnostic features and minimal hardware and software prerequisites, has already shown promise in the realm of virtual site visits for construction education (Sun et al. 2022).

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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