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Robotic-Assisted Virtual Field Trips: A System Architecture for Bridging Classroom Learning and Real-World Construction Environments

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Traditional construction field trips are integral to construction education, providing students with firsthand exposure to real-world job sites. However, these visits are often hindered by logistical, safety, and accessibility challenges that limit their feasibility and effectiveness. This paper proposes integrating robotic-assisted virtual field trips to overcome these challenges. We examine the limitations of both traditional and existing virtual field trips and explore the potential of robotic systems such as aerial drones and ground robots for construction education. Recognizing the importance of authentic learning experiences, we propose a comprehensive system architecture grounded in Situated Learning Theory. This architecture integrates technological, pedagogical, and compliance considerations to bridge classroom learning with real-world construction environments. The proposed approach aims to enhance students' learning experiences by providing authentic contexts and engaging them in real-world tasks through a community of practice, while ensuring safety and regulatory compliance. A preliminary pilot study demonstrated the feasibility of the proposed architecture. Initial testing confirmed that the robotic platform, real-time data transmission, secure access, and basic communication features performed as intended.

Keywords: Construction education, Robotic-assisted field trips, Virtual field trips, Situated Learning Theory

Introduction

Field trips are a key component for supporting classroom learning in construction education. Visiting construction sites provides students with real-world exposure to job sites, increases awareness of professionals’ roles, and enhances their understanding through firsthand observation (Seifan et al., 2020). When students participate in field trips, they have the opportunity to practice their spatial and visual cognitive abilities, which are vital for practical applications such as understanding complex construction processes and environments (Makransky & Mayer, 2022) and understand the multidisciplinary nature of construction projects and practices (Quinn et al., 2019).

However, conventional field trips (i.e., students physically travel to the construction site) pose various

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challenges. The inherent risks and dynamic nature of construction sites necessitate strict safety measures and detailed planning, which constrain the scope and practicality of educational field trips (Mills et al., 2006). Additionally, the logistical challenges of coordinating visits that align with the different construction phases while managing large groups of students and ensuring inclusive access for all learners (including those in online courses) pose significant limitations to implementing field trips (Wen & Gheisari, 2023). Institutional constraints, especially for universities located far from major construction hubs, result in missed opportunities for on-site learning (Eiris et al., 2022).
In response to these challenges, robotic technologies emerge as a promising solution. Robotic-assisted field trips have the potential to overcome these limitations by enhancing accessibility, ensuring safety, and providing real-time experiences. While virtual reality (VR) and augmented reality (AR) are state-of-the-art alternatives, they often lack the dynamic interaction and real-time realism that robotic technologies provide via multiple reality-capturing sensors that these platforms carry (AlGerafi et al., 2023). The platforms can bridge the gap by offering live-stream or remotely operated experiences that allow students to explore construction sites in real-time, interact with on-site professionals, and gain insights into current practices. A range of reality-capturing sensors such as, RGB cameras, depth cameras, and LiDAR, enable robots to deliver immersive and real-time experiences (Zhou et al., 2020). Building on these insights, this paper proposes a system architecture grounded in Situated Learning Theory to support robotic-assisted field trips into construction education. This proposed approach is intended to address traditional field trip challenges and extend capabilities of VR/AR-based approaches.

Literature Review

Traditional Field Trips in Construction Education

Traditional field trips are a foundational because they allow students to observe and engage with actual construction processes, materials, and technologies (Quinn et al., 2019). By physically being present on active construction sites, students enhance their spatial and visual cognitive abilities, which are vital for understanding complex construction activities and environments (Makransky & Mayer, 2022). Real-time interaction during these visits deepens students' understanding of the multidisciplinary nature of construction projects and strengthens the connection between theoretical knowledge and practical application (Sun et al., 2022). This immersive experience cultivates critical thinking and problem-solving skills, and prepare students for the challenges they will face as future construction professionals (Quinn et al., 2019). Despite their educational value, traditional field trips in construction education are increasingly challenged by a range of safety, logistical and institutional barriers. Safety risks are a primary concern due to the inherent hazards present on active construction sites. Strict safety measures and detailed planning are required to ensure student safety, which can limit the feasibility and frequency of these visits (Mills et al., 2006). Logistical challenges also arise in coordinating visits, such as synchronizing with specific construction phases, managing large groups of students, and arranging transportation (Eiris & Gheisari, 2018; Quinn et al., 2019). Large class sizes and restrictive academic schedules compound the difficulty of organizing field trips that are both meaningful and manageable (Sun & Gheisari, 2021). A survey by Eiris Pereira and Gheisari (2019) revealed that core subject areas in construction had minimal field trip integration, with many educators conducting only one or two field trips throughout their teaching careers. This limited exposure can lead to gaps in learning, particularly for online students who may miss out on hands-on experiences entirely (Elgewely et al., 2021). The lack of equitable access highlights the need for alternative methods to provide practical, real-world experiences in construction education.

Virtual Field Trips in Construction Education

The introduction of VR, AR, and 360-degree tours has introduced innovative approaches to construction education utilizing hardware such as head-mounted displays, motion sensors, and high-performance computing systems to render realistic 3D environments (Halder & Afsari, 2022). AR applications often utilize mobile devices or AR glasses to overlay digital information onto the physical world, while 360-degree tours rely on panoramic cameras and interactive platforms to present comprehensive views of construction sites (Chen et al., 2024). The implementation of these technologies in construction education has been explored extensively. For instance, Elgewely et al. (2021) integrated VR with Building Information Modeling (BIM) to create immersive classrooms that simulate real construction sites to enhances active learning and student engagement through gamification. AR has also been applied to improve communication and collaboration on construction sites. One of the primary benefits of virtual field trips is the increased accessibility they offer. Virtual Industry Visits (VIVs) utilized by Farrell (2023) showcased how educators and industry professionals could deliver interactive, documentary-like learning events remotely. However, despite these advantages, a significant concern is the lack of tactile and sensory experiences that physical visits provide. The gamified appearance of many VR environments can detract from the authenticity of the learning experience due to the absence of realistic textures and details. Technological limitations, such as low-resolution displays and VR-induced motion sickness, characterized by symptoms such as disorientation and dizziness, further hinder the effectiveness of virtual trips (Halder & Afsari, 2022). Furthermore, high-quality VR experiences demand stable and high-speed internet connectivity, which may not be readily available in all educational settings or remote construction site locations. The costs associated with procuring VR hardware, developing software, and ongoing maintenance can be prohibitive for institutions with limited budgets (Halder & Afsari, 2022). Moreover, both students and educators face a learning curve in becoming proficient with these technologies, requiring additional training and time that could detract from other learning objectives (Eiris & Gheisari, 2018).

Robotic Technologies, Types, and Applications in Construction Education

The integration of robotic technologies into construction education represents an innovative approach to enhancing learning experiences while addressing the limitations of traditional and virtual field trips. Robotics—including aerial drones, ground robots, and docked systems—offer dynamic, interactive, and immersive experiences that can significantly support construction education learning by providing students with real-time access to construction environments (Lee et al., 2023). Aerial drones (UAVs) provide comprehensive aerial views, offering unique perspectives valuable for understanding overall site layouts and logistics (Eiris et al. 2018). Integrating UAVs can enhance spatial-temporal reasoning and practical skills (Mutis and Antonenko 2022). Ground robots (wheeled, crawler, or legged robots) enable up-close, ground-level interaction and access to difficult or unsafe areas (Halder & Afsari, 2023). Applications include detailed inspections and simulations (Halder & Afsari, 2022; Sun et al., 2024). These robotic approaches facilitate remote observation and analysis of construction processes. Table 1 summarizes the comparative strengths and weaknesses of robotic-assisted field trips against traditional and VR/AR methods regarding key aspects like accessibility, safety, realism, interactivity, and cost.

Identified Gaps in the Existing Literature

Despite the promising advancements in utilizing aerial and ground robots within construction education, there is a noticeable absence of an integrated approach guiding their systematic implementation within the construction curriculum as method to support field trips. Existing research often focuses on isolated technological applications without integrating them into a broader course designs and learning outcomes (Jaselskis et al., 2015; Eiris Pereira et al., 2018; Halder et al., 2022;

Mutis & Antonenko, 2022; Sun et al., 2024). Moreover, considering the operational aspects associated with these technologies—such as real-time communication, data management, user interface, and adherence to regulatory and safety standards—is essential for their effective adoption in educational settings. Addressing these issues requires a strategic approach to embed robotic-assisted virtual field trips into educational practice, all while emphasizing alignment with instructional goals, structured delivery, and student engagement. In response to these identified gaps, this paper proposes a detailed system architecture for incorporating robotic-assisted virtual field trips into construction education. This architecture integrates technological, pedagogical, and compliance considerations, grounded in Situated Learning Theory, to enhance student learning experiences while overcoming the logistical, safety, and accessibility challenges of conventional methods.

Table 1. Comparison of Field Trip Methods

Key aspect	Traditional Field Trips	VR/AR Field Trips	Robotic Field Trip
Accessibility	Low (location, logistics) (Mills et al., 2006; Sun & Gheisari, 2021)	High (overcomes geographical barriers) (Farrell, 2023)	High (real-time access regardless of location) Lee et al. (2023)
Safety	High-risk (on-site hazards) (Mills et al., 2006)	Moderate-risk (VR-induced motion sickness) (Halder & Afsari, 2022).	Low-risk (remote operation) (Halder et al., 2024)
Realism	High (direct sensory experience) (Quinn et al., 2019)	Moderate to high (limited spatiotemporal context) (Eiris, Wen, et al., 2022; Halder & Afsari, 2022)	High (live feed from actual sites) (Halder et al., 2023)
Interactivity	High (direct interaction and communication in active construction site) (Eiris & Gheisari, 2018)	Low to high (from 360-videos to immersive VR/AR) (Chen et al., 2024; Ohueri et al., 2025)	High (real-time operation and interaction) (Halder et al., 2024)
Cost	High (e.g., travel, logistics) (Eiris & Gheisari, 2018)	Moderate to high initial investment, but lower operational costs (Halder & Afsari, 2022)	High initial investment, but lower operational costs (Halder et al., 2024)

Theoretical Foundation and System Architecture

The theoretical foundation of our proposed system architecture is based in Situated Learning Theory. This theory posits that learning is inherently context-dependent, with knowledge best acquired through active participation in authentic activities within a specific environment (Lave & Wenger, 1991). This theory emphasizes two critical aspects: *Authentic Contexts* and *Community of Practice* (Culatta, 2005). *Authentic Contexts* in construction education can be provided by using robotic-assisted virtual field trips to enable students to engage with active construction sites remotely. With the use of robotic technologies, students can observe live construction activities, analyze construction practices, and apply their theoretical knowledge to real-world scenarios. On the other hand, *Community of Practice* is facilitated through collaborative activities where students interact with instructors, peers, and industry professionals during virtual field trips. Real-time communication tools, supported by robotic systems, can allow students to participate in live Q&A sessions, engage in discussions, and share insights.

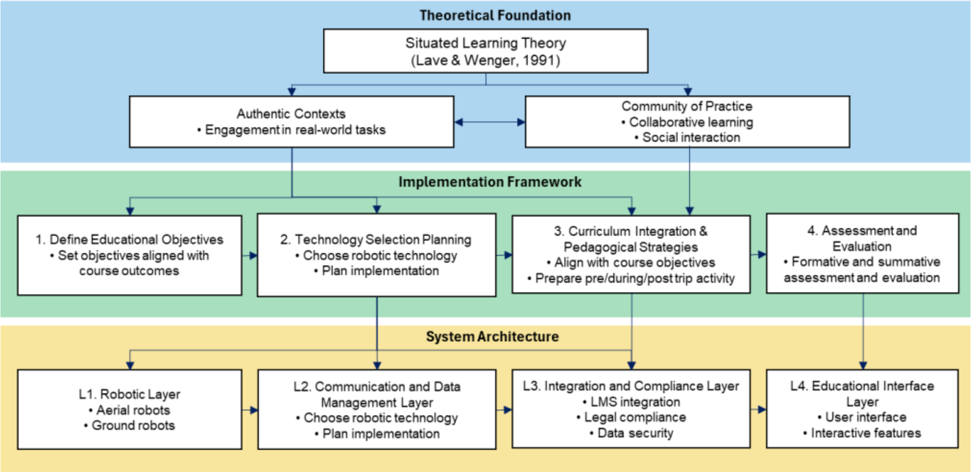


Figure 1 Overview of the proposed framework for robotic-assisted construction field trips: Situated Learning Theory (top), implementation framework (middle), and system architecture (bottom).

To translate the theoretical foundation into practice, a structured four-part framework for implementation is first proposed. Figure 1 illustrates how Situated Learning Theory informs a four-stage implementation framework, which in turn guides the design of the four-layered system architecture. *(1) Define Educational Objectives* involves setting objectives that align with course learning outcomes focusing on authentic engagement, classroom participation, and practical knowledge application. For example, in a course focusing on construction safety, objectives might include observing real-time safety protocols and evaluating compliance with OSHA standards related to fatal-four hazards and hierarchy of controls. *(2) Technology Selection Planning* involves selecting appropriate robotic technology for replicating real-world site experiences as well as planning for safety and regulatory compliance related to robotic operations. Several factors should be considered to ensure alignment with the educational objectives. A primary consideration is the nature of construction activities, as different phases and tasks require different vantage points. Aerial drones are suited for observing large-scale site layouts, while ground robots are suited for detailed inspections. Another key factor is the required level of detail, which dictates sensor choices. High-resolution RGB cameras are required for visual clarity, while thermal cameras may be used to enhance site inspections. Accessibility and maneuverability are important to ensure robots are able to access areas relevant to the learning objectives. The selected technology should support real-time interaction, immersive visuals and operational flexibility to enable targeted exploration and student-led inquiry. The implementation will also require planning for safety and regulatory compliance of robotic operations and technology infrastructure for reliable data transmission. *(3) Curriculum Integration & Pedagogical Strategies* involves integrating the robotic-assisted virtual field trips into the curriculum to align with existing instructional design. In this regard, aligning with course objectives and scheduling trips during specific construction phases ensures contextual relevance and enhances the learning experience. Pre-trip activities should provide foundational knowledge to prepare students. During the trip, interactive engagement, such as real-time Q&A sessions with site personnel, should be encouraged to promote active learning. Post-trip discussions and reflections should reinforce what was learned. Furthermore, pedagogical strategies should support discussions to foster collaborative learning and create a community of practice. *(4) Assessment and Evaluation* involves developing assessment methods that measure the effectiveness of the robotic-assisted virtual field trips in achieving the educational objectives. This includes formative and summative assessments, such as quizzes, reflective essays, or project reports based on the virtual field trip exercise. These assessment tools should help educators track students' progress, identify areas for improvement, and ensure that the learning outcomes align with the course objectives. This approach reinforces authentic participation and provides actionable feedback to enhance future iterations of the program.

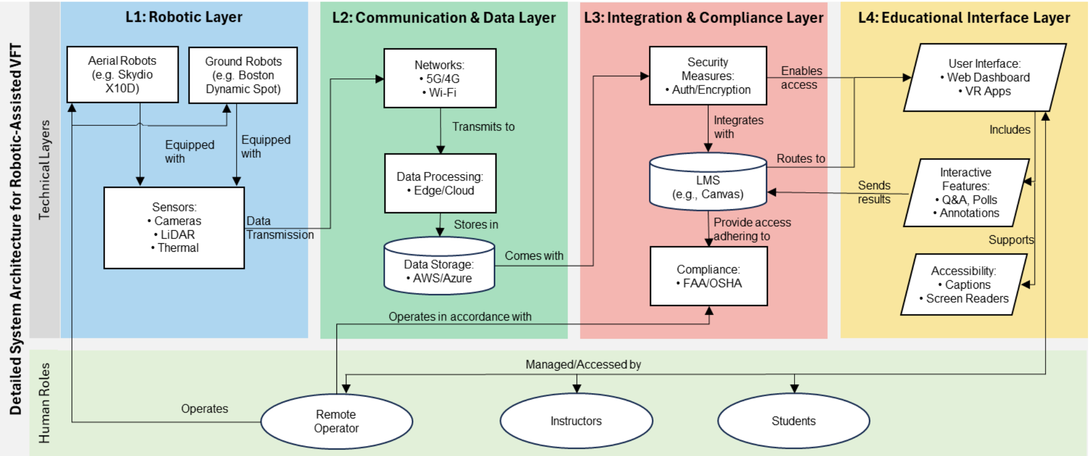
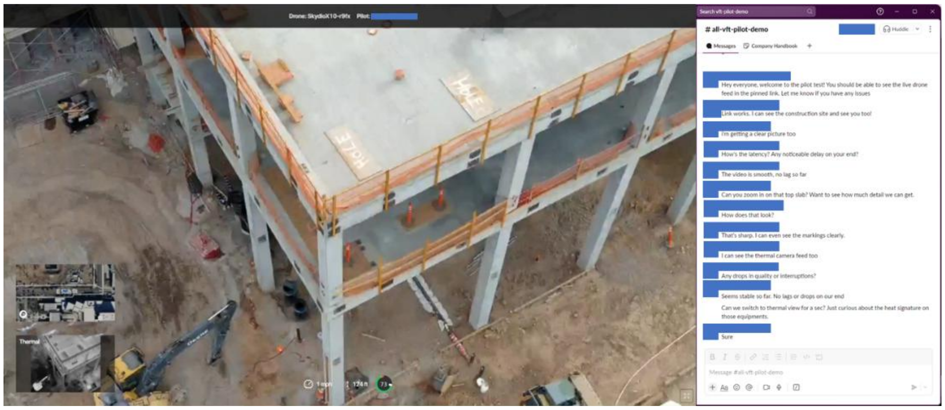


Figure 2 Detailed System Architecture for Robotic-Assisted Virtual Field, detailing the four technical layers (top) and the human roles (bottom).

To operationalize this theoretical framework, a system architecture comprising four integrated layers is proposed (see Figure 2). *(1) Robotic Layer* involves deploying robotic platforms with or without docking capability equipped with essential sensors for real-time data capture. Robotic platforms may utilize aerial drones (e.g., Skydio X10D) to observe macro-level site layouts, activity tracking, and spatial relationships between project components. Ground robots (e.g., Boston Dynamics Spot) may be used to navigate through construction environments for detailed ground-level observations. The choice of robot depends on course objectives and site conditions. The sensors and equipment include high-resolution cameras, LiDAR sensors, and thermal devices for visual and spatial data collection. A remote operator is responsible for controlling these robotic platforms and overseeing flight paths or navigation routes. *(2) Communication and Data Management Layer* manages data transmission, processing, and storage. Communication networks such as 5G/4G LTE and Wi-Fi enable data transfer from robotic platforms to processing units. The data processing systems may involve edge computing or cloud platforms to handle real-time data processing. Cloud storage (e.g. AWS S3, Azure Blob Storage) handle data storage for live (synchronous) or on-demand (asynchronous) learning activities. *(3) Integration & Compliance Layer* bridges the technological infrastructure with educational and regulatory frameworks. Cloud-based security features (encryption, multi-factor authentication) protect data integrity and user privacy. Learning Management System (LMS) integration (e.g., Canvas) provides centralized access to resources, schedules, and assessments. Compliance is maintained with FAA, OSHA, and university-specific data protection regulations. Instructors manage and access the content and configurations within this layer. *(4) Educational Interface Layer* is the user-facing layer that facilitates interactions between students, instructors and virtual field trip content. User interface may include web-based dashboards or VR applications for accessing live streams, controlling robotic viewpoints, and engaging with educational content. Interactive tools such as real-time Q&A sessions, annotations, polls and quizzes can be used to promote active learning and student engagement. Furthermore, accessibility options such as live captioning and screen reader may be used. Finally, students and instructors can access and manage content through user interfaces. Feedback and assessment data generated here loop back to the LMS for continuous system improvement. Students interact with the system primarily through this layer to access content and participate in the virtual field trip activities designed by instructors.

Preliminary Pilot Study

A pilot study (n=8) involving researchers from the University of Florida and Arizona State University was conducted to evaluate the feasibility of the proposed robotic-assisted virtual field trip framework in a real-world construction setting. The study focused on testing the core functionalities of each system layer. On-site personnel at the Tempe District Utility Plant construction site operated a Skydio X10 drone (L1: Robotic Layer) equipped with a high-resolution camera, zoom, and thermal imaging capabilities. The drone's video feed was transmitted in real-time via a 5G mobile hotspot connected to the Skydio cloud platform (L2: Communication and Data Management Layer), enabling remote participants from the Construction Management program at University of Florida to observe the site. Access to the live feed was secured through the Skydio cloud platform, providing a preliminary level of data protection (L3: Integration and Compliance Layer). While full integration with an LMS (e.g., Canvas) and a dedicated web-based dashboard are planned for future development, a Slack channel served as the initial interface for interaction (L4: Educational Interface Layer), allowing participants to request specific views and engage in text-based communication with the drone operator.



all-vft-pilot-demo [redacted]

[redacted]
Hey everyone, welcome to the pilot test! You should be able to see the live drone feed in the pinned link. Let me know if you have any issues

[redacted]
Link works. I can see the construction site and see you too!

[redacted]
I'm getting a clear picture too

[redacted]
How's the latency? Any noticeable delay on your end?

[redacted]
The video is smooth, no lag so far

[redacted]
Can you zoom in on that top slab? Want to see how much detail we can get.

[redacted]
How does that look?

[redacted]
That's sharp. I can even see the markings clearly.

[redacted]
I can see the thermal camera feed too

[redacted]
Any drops in quality or interruptions?

[redacted]
Seems stable so far. No lags or drops on our end
Can we switch to thermal view for a sec? Just curious about the heat signature on those equipments.

[redacted]
Sure

Figure 3 Pilot Interface Layer. (Left) View from the Skydio X10 drone including google map view and thermal camera view (Right) Sample interaction chat.

Discussion

Opportunities for In-Class, Hybrid, and Online Students

The proposed system architecture democratizes access to virtual field trips that benefits all three learning modalities – in-class, hybrid, and online students. In-class students gain a valuable supplement to traditional instruction, bypassing the safety and logistical limitations of physical site visits. Hybrid and online students, often excluded from such experiences, gain full access to live streams, interactive Q&A sessions, and annotation tools. Integration with the LMS further enhances accessibility by providing asynchronous access to recorded sessions.

Robotic Platforms and Sensors

The choice of robotic platforms (aerial drones or ground robots) and integrated sensors directly impacts the scope and quality of virtual field trips. Aerial drones can provide expansive overview of the site layouts and illustrate spatial relationships among project components. On the other hand, ground robots can offer detailed, close-up views of construction processes and equipment by navigating complex terrains and confined spaces. Advanced sensors (RGB cameras, LiDAR, thermal imaging) enhance data richness. However, limitations in sensor resolution, field of view, and environmental conditions might constrain observation of specific activities.

Safety and Security of Student and Site Data

Prioritizing student and data safety is paramount. Secure data transmission (5G/4G LTE, Wi-Fi) and cloud storage (AWS S3, Azure Blob Storage) incorporate robust cybersecurity measures to prevent unauthorized access. The Integration and Compliance Layer ensures adherence to all relevant regulatory standards, including FAA regulations for drone operations, OSHA safety guidelines, and university-specific data protection laws.

Limitations

While the proposed system architecture offers a comprehensive approach to integrating robotic-assisted virtual field trips into construction education, several limitations must be acknowledged. First, further empirical validation is needed to assess its real-world feasibility and effectiveness. The preliminary pilot study, while promising, had a limited sample size and utilized a temporary communication platform instead of a fully integrated LMS. Future research should focus on addressing these limitations through larger-scale studies that incorporate LMS, a dedicated web-based educational interface layer, and a more stable network infrastructure to minimize latency issues. Second, integrating various robotic platforms, sensors, and communication systems presents several technical challenges. Ensuring compatibility between hardware and software components, maintaining network connectivity in remote locations, and managing the large volume of data generated during virtual field trips require careful planning and execution. Furthermore, the limited battery life of robotic platforms may constrain the duration of virtual field trips or require frequent battery swaps to remain effective. Finally, the cost of acquiring robotic platforms, sensors, and supporting infrastructure can be substantial. Initial investment costs, along with ongoing operational costs such as product subscription, data storage fees, and insurance costs could limit applicability.

Conclusion

Advances in robotics and communication technologies have created new opportunities for enhancing construction education through robotic-assisted field trips. The use of these technologies directly addresses the logistical, safety, and accessibility issues that are inherent in traditional field trips. This paper proposes a system architecture that integrates technological, pedagogical and compliance for robotic-assisted virtual field trips for construction education. Grounded in Situated Learning Theory, the proposed architecture emphasizes authentic contexts and fosters community of practice that enables students to remotely engage with real-world construction environments and tasks. The proposed four-layered system architecture provides a comprehensive approach that integrates robotic platforms, communication and data management, regulatory compliance, and user-centric educational interfaces. This design bridges classroom learning with real-world construction sites while maintaining secure, regulatory-compliant interactions aligned with educational objectives. The preliminary pilot study, connecting University of Florida researchers with a live drone feed from Tempe District Utility Plant at Arizona State University provided initial validation for the proposed architecture and demonstrates its potential to enhance construction education. Future work will involve conducting a larger-scale study (n>30) in a classroom setting, utilizing the fully integrated system architecture including LMS integration. This expanded study will also incorporate formal assessment methods to evaluate the impact of robotic-assisted virtual field trips on student learning outcomes, engagement, and satisfaction.

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