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RESEARCH

XR as a unifying layer for robotic and heavy machine control in construction

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Abstract
Construction workflows remain fragmented across design, robotic fabrication, and heavy machine operation, with each domain relying on separate interfaces that limit integration and operator accessibility. This paper proposes Extended Reality (XR) as a unifying interaction layer that bridges these domains by combining spatial augmentation, real-time telemetry, and an architecture designed to incorporate IFC-based construction data into a coherent operator interface. We present two prototypes involving a precise robot and heavy machinery. User studies demonstrate that XR-based interfaces improve spatial understanding and lower the entry barrier for inexperienced operators compared to conventional controls. We further identify latency, calibration stability, and haptic feedback as the key technical boundaries that currently constrain XR's effectiveness in these settings, providing a concrete design agenda for future development. Together, the prototypes demonstrate that a shared XR layer can meaningfully connect robotic fabrication and heavy machine teleoperation, offering a foundation for more integrated human–machine workflows in construction automation.

Keywords Extended reality · Robotic control · Heavy machine control · Human–robot interaction · Construction robotics · Training and safety

1 Introduction

Construction increasingly relies on two distinct classes of machine operation, robotic fabrication and heavy machine teleoperation, which contribute to the same workflows yet remain separated by incompatible interfaces, data representations, and interaction paradigms. Robotic fabrication systems have been developed primarily for structured, controlled environments (Chea et al. 2020), while heavy machine interfaces have evolved independently around operator-in-the-loop teleoperation (Lee et al. 2022; Westerberg et al. 2008). Robotic systems depend on calibrated, high-accuracy control in structured environments (Bock 2015), while heavy machinery operates in dynamic outdoor settings requiring continuous human oversight and real-time feedback (A survey on teleoperation 2007). Despite sharing a common construction context, neither domain currently benefits from a unified interaction layer that connects design data, machine state, and operator intent. This fragmentation has direct consequences: operators must navigate incompatible systems, design information rarely reaches the machine interface in a usable form (Li et al. 2024). As construction processes become more automated and data-driven, the absence of a shared spatial interface between robotic and heavy machine systems becomes an increasingly costly gap (Muñoz-La Rivera et al. 2025; Oesterreich and Teuteberg 2016).

Extended Reality (XR) has been explored independently in both domains (Su et al. 2023; Failed 2025), but no unified framework has been proposed that treats both as part of a single spatial interaction problem. By merging digital

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models, real-time telemetry, and spatial feedback into a coherent operator interface (Dunston and Wang 2005), XR offers a candidate layer for bridging these domains. The system architecture is designed to incorporate IFC-based construction data as a means of connecting design intent directly to on-site machine control (Wu et al. 2021), establishing a foundation for tighter integration between digital models and physical operation.

Following Milgram et al. (Milgram et al. 1995), XR is understood as a continuum from fully virtual to fully physical environments, with Mixed Reality (MR) occupying the intermediate space where digital and physical content coexist. Both prototypes operate within this MR region, and the term XR is used throughout as an umbrella covering this spectrum. This paper investigates XR as a unifying spatial interaction layer by implementing and evaluating two prototypes: an XR interface for controlling an industrial robotic arm on-site, and an XR teleoperation framework for a mini-crane integrating telemetry, camera feeds, and safety overlays. Across these contrasting scales, we ask:

RQ1: How can XR function as a shared spatial interaction layer that connects robotic fabrication and heavy machine teleoperation across different operational contexts?

RQ2: How do XR-based interfaces compare to conventional controls in terms of operator spatial understanding and accessibility for inexperienced users?

2 Related work

This section reviews XR research across two domains that have developed largely in parallel: precision robotic control and heavy machine teleoperation (Su et al. 2023; Chen et al. 2024; Hu et al. 2025). Despite operating within shared construction workflows (Zhang et al. 2022), each domain has produced distinct XR interaction approaches shaped by differences in scale, precision requirements, and operational risk (Xu et al. 2024). We further examine existing XR interaction taxonomies to assess whether current classifications can support a unified interaction layer spanning both domains (Milgram et al. 1995; Suzuki et al. 2022). Together, these threads reveal a gap that motivates the present work: no existing framework treats robotic fabrication and heavy machine teleoperation as part of a single spatial interaction problem.

2.1 XR for precision robotic control

The integration of XR into robotic control has been driven by the need for more intuitive interfaces in remote and hazardous operational contexts. Su et al. (Su et al. 2023) provided a broad review of XR enhanced robotic systems, demonstrating that combining virtual, mixed, and augmented reality into teleoperation workflows improves operator spatial awareness and reduces the cognitive demands of dexterous manipulation tasks. Within construction specific contexts, Xu et al. (2024) demonstrated that mixed reality can enhance robot arm control for dexterous manipulation, showing that spatial overlays of robot state and target geometry reduce operator error compared to conventional pendant interfaces. Suzuki et al. (2022) offers a taxonomy of AR enhanced human–robot interaction that organizes existing approaches by interface modality, feedback type, and degree of operator autonomy establishing a classification framework relevant to evaluating where construction robotic interfaces currently sit and what remains unaddressed.

Despite these advances, most XR robotic interfaces have been developed and evaluated in laboratory or manufacturing settings rather than on construction sites. Bock (2015) notes that construction automation has followed a different trajectory from manufacturing robotics, with on-site conditions introducing variability that structured robotic workflows are not designed to accommodate. This gap between controlled robotic XR research and the realities of construction deployment remains largely unaddressed in the literature.

2.2 XR for heavy machine teleoperation

Heavy machine teleoperation presents a distinct set of challenges from robotic control, including dynamic outdoor environments, variable terrain, and the need for continuous operator-in-the-loop oversight (Lee et al. 2022). Early work by Westerberg et al. (2008) demonstrated that virtual environment teleoperation of hydraulic forestry cranes could improve operator performance by providing spatial context beyond what direct line of sight affords, establishing a precedent for XR enhanced heavy machine interfaces. More recent work by Chen et al. (2024) shows a development of a mixed reality-based hazard prevention system for heavy machinery operators, using spatial overlays to deliver predictive motion cues and safety warnings in real time, demonstrating that XR can meaningfully enhance situational awareness in dynamic construction environments. Wu et al. (2024) presented a unified framework linking ROS and Unity to enable mixed reality assisted path planning for demolition robots.

Extending into training scenario context, Balamurugan et al. (2025) showed that XR-based simulation of heavy equipment operation reduces onboarding time and improves operator confidence compared to conventional training methods. Hu et al. (2025) provided a broader review of robotic teleoperation of construction machinery, identifying sensing, feedback latency, and operator situational awareness as the primary technical boundaries constraining current systems. Across this body of work, a consistent finding emerges: XR

improves spatial understanding and lowers the entry barrier for inexperienced operators, but latency, calibration stability, and limited haptic feedback remain unresolved constraints (Dunston and Wang 2005; Chen et al. 2024; Hu et al. 2025).

2.3 The use case for a unified XR interaction layer

Robotic XR interfaces prioritize precision and spatial correspondence between digital models and physical targets (Lee et al. 2022; Xu et al. 2024). While heavy machine XR interfaces prioritize situational awareness and safety overlays under dynamic conditions (Lee et al. 2022; Chen et al. 2024). These differences are real, but both domains share a construction context in which design data, machine state, and operator intent must be coordinated in space and time. Dunston and Wang (Dunston and Wang 2005) identified early that mixed reality in construction requires bridging digital models and physical environments, yet full lifecycle BIM integration with automated systems remains an open problem with design information rarely reaching machine interfaces in actionable form (Zhang et al. 2022). While BIM and XR have been integrated in isolated cases, no unified framework connects IFC-based construction data to operational machine control across different system types (Wu et al. 2021).

3 Methodology

3.1 Research approach and prototype strategy

This research follows a comparative case study approach based on two XR prototypes developed for different construction machine contexts. This approach was chosen to examine whether XR can function as a shared spatial interface across machine classes that are typically treated separately in both research and practice. Rather than forcing both cases into an identical task or evaluation structure, the study compares them at the level of interaction design, operator support, and the use of digital task information.

3.2 Shared MR interaction layer and design rationale

Both prototypes share a common architectural foundation defining the shared MR interaction layer. Unity serves as the development and runtime platform for both systems, deployed to a Meta Quest 3 headset in standalone mode. Machine communication is handled via MQTT, providing a lightweight messaging protocol suited to construction site network conditions.

Both systems incorporate a three-dimensional digital model of the respective machine, enabling real-time visualization of machine state within the operator's spatial field of view alongside a HUD layer overlaying telemetry, target indicators, and status information. Camera feed integration fuses live visual data with virtual spatial overlays on a shared coordinate frame, supporting depth judgment and spatial alignment across both contexts.

The prototypes' framework also additionally incorporates IFC-based construction data alongside the machine's digital model, represented as a URDF and OBJ format. The IFC model of the construction site in Aachen (Kirner 2026) with building element is converted into Linked Building Data format using a converter (GitHub. 2026) for fast information querying, and an inverse kinematics algorithm is embedded into the robot model for control. Figure 1 illustrates the full system architecture.

3.3 Prototype 1: MR interface for industrial robotic arm control

Prototype 1 implements an MR interface for controlling an industrial robotic platform, represented in this study by a KUKA IONTEC KR70 R2100 industrial robotic arm, mounted on a continuous track mobile platform, enabling on-site deployment beyond fixed laboratory settings. The prototype instantiates the shared XR interaction layer described in Sect. 3.2 as a standalone Unity application deployed to a Meta Quest 3 headset, removing the dependency on an external computer during operation.

Spatial anchors establish a stable coordinate frame between the digital interface and the physical environment, replacing fiducial markers and enabling digital content to share a global coordinate frame with the physical workspace. A ZED camera mounted at the robot end effector streams visual data to a local computer running an AI model for steel beam recognition, with the resulting segmented video relayed to the headset via WebSocket. Figure 2 shows the described communication and system architecture framework for the robot.

The operator interaction follows a simulation and confirm sequence: the user selects a target object, such as a screw or structural element, and a simulated robot trajectory is visualized through the MR device before any physical motion is executed. Upon confirmation, target position and motion command are sent to the robot via MQTT. Joint motion is visualized in real time during execution, giving the operator continuous spatial feedback throughout the task. IFC-based building data are integrated into the framework as an architectural feature to contextualize target objects within the broader construction model as shown in Fig. 1.

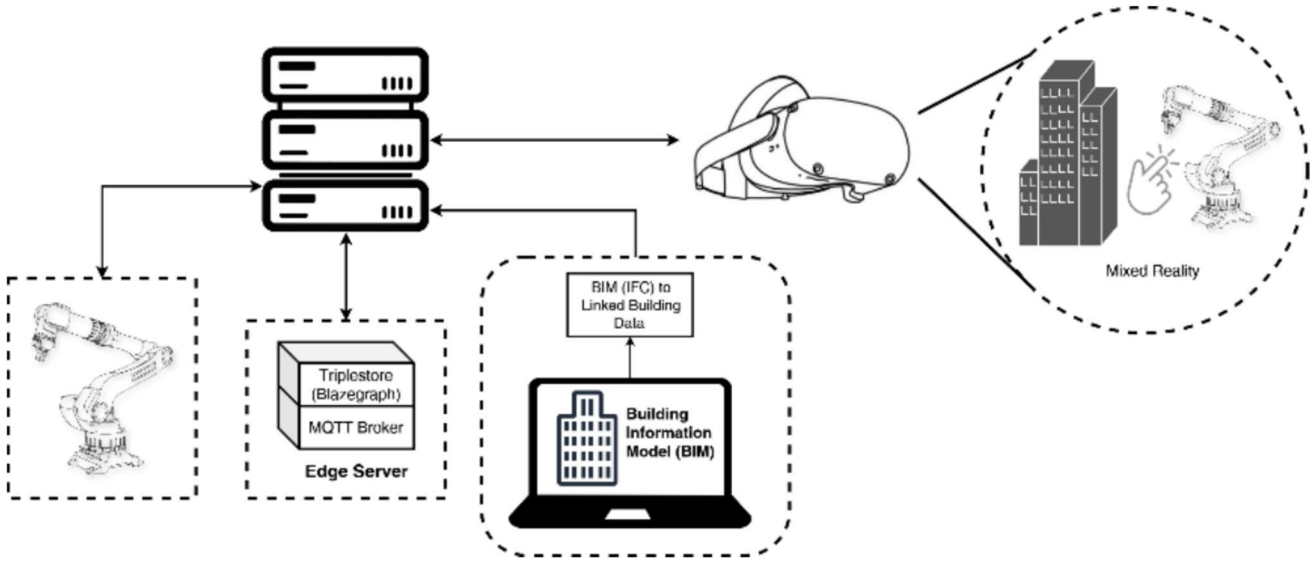


Fig. 1 System architecture of the communication system between HMD, machines, and data information

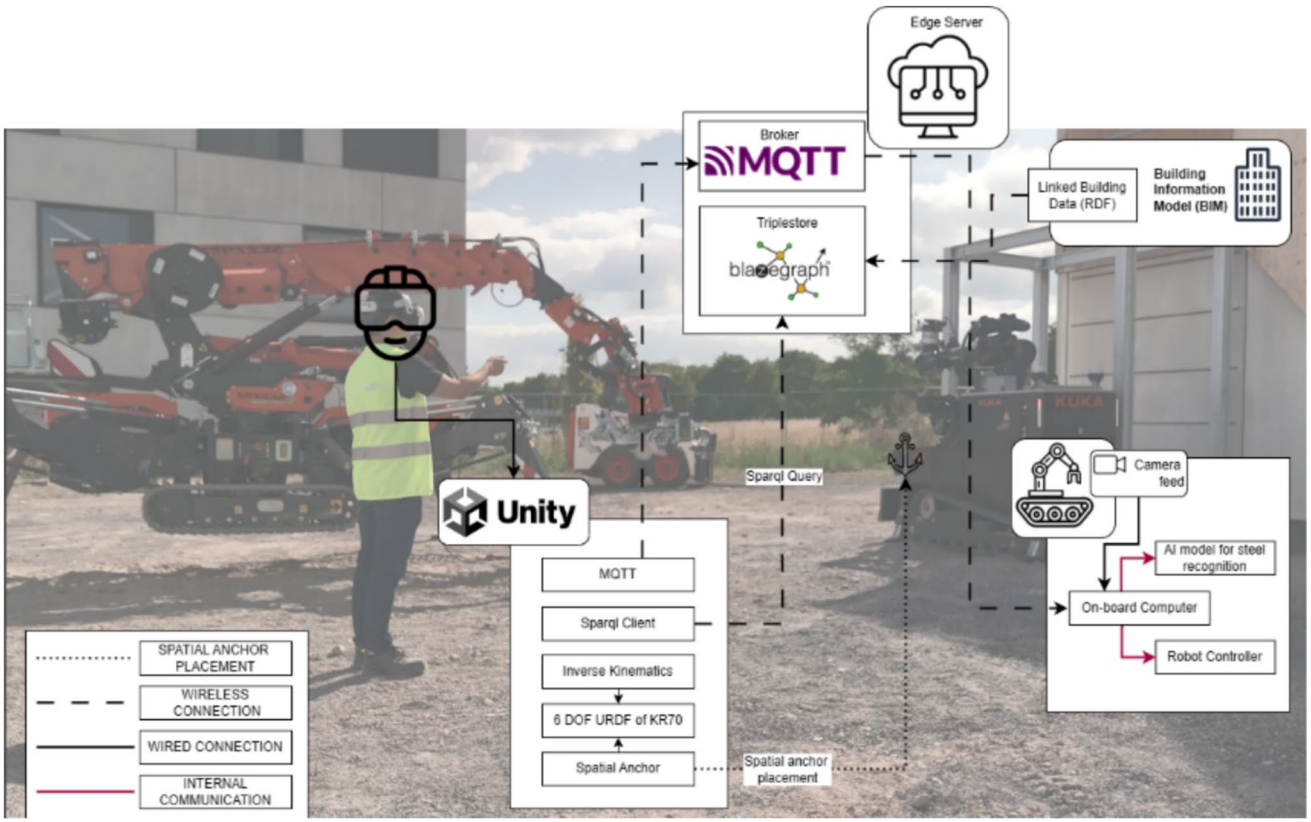


Fig. 2 Overview of the system architecture for the proposed frameworks for robotics

3.4 Prototype 2: MR interface for heavy machine teleoperation

Another standalone application is developed in Unity and deployed to Meta Quest 3, allowing users to operate the system directly through the headset without reliance on an external computer for visualization. In this prototype, a Jekko SPX532 mini-crane is used as the heavy machine

platform for MR-supported teleoperation in a construction-like environment. The MR interface combines real-time machine telemetry, live camera feeds, and spatial guidance cues within a single operator interface.

The system communicates with the crane through an MQTT-based pipeline. A Raspberry Pi mounted on the machine acts as the communication hub, relaying commands from the MR application through ROS2 and then to the crane control system via CAN-based communication. At the same time, a stereo camera mounted on the crane streams live video to the headset, while an external processing unit performs human detection and safety zone classification. The resulting warnings are returned to the MR interface and visualized as safety overlays.

In contrast to the robotic arm prototype, this system does not visualize a complete target pose or simulated machine trajectory. Instead, the MR interface supports the operator through a guidance-oriented heads-up display inspired by flight simulator HUD design principles. Pick-up and drop-off zones are queried from the IFC-based linked building data, following the same LBD conversion and querying mechanism described in Sect. 3.2. These zones are communicated to the operator through angular indicators, orientation-support compasses, and directional cues that visually reference the relevant zones within the queried working environment. This enables the operator to determine an appropriate navigation strategy while maintaining manual control of the crane. Although IFC-based zone querying was implemented in the prototype, it was not activated during the user study, which focused on the core XR interaction and guidance layer. The architecture remains compatible with the same LBD querying mechanism, allowing pick-up and drop-off locations to be derived directly from construction data in future evaluations. Figure 3 shows the system architecture and main components of the prototype.

3.5 User study design

Two separate user studies were conducted, one for each prototype. The robotic arm study involved six participants, while the crane study involved ten participants. Participants were divided into two groups: novice users with no prior experience operating the respective machine, and experienced users with direct hands-on experience with the traditional control system. For the robotic arm study, experienced participants had prior experience with robot programming and teach pendant operation. For the crane study, experienced participants had prior experience with crane operation and its standard controller.

Each participant completed both conditions sequentially, first using the traditional controller, then the XR interface. To reduce the effect of unfamiliarity with the traditional controller, novice participants were given a practice trial with

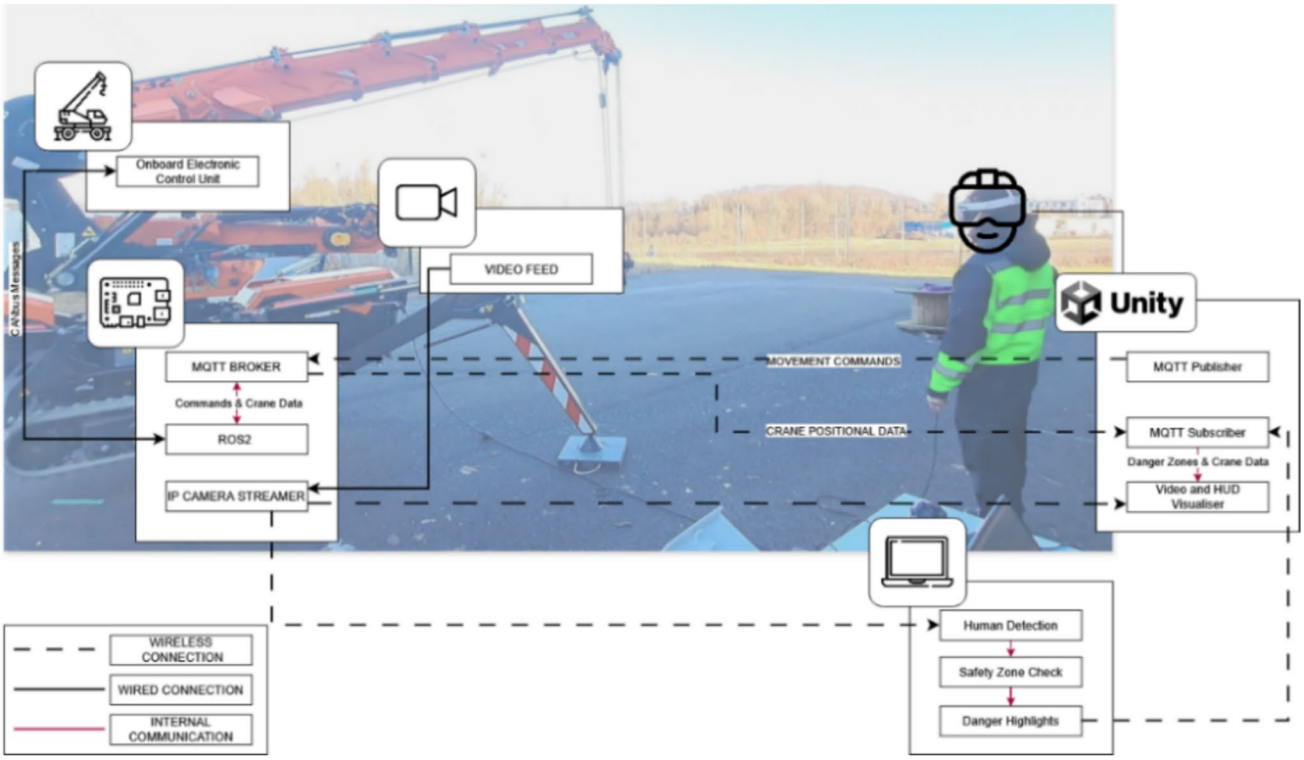


Fig. 3 Overview of the system architecture for the proposed frameworks for heavy machinery

the teach pendant before the recorded session began. No equivalent familiarization was provided for the XR interface, meaning any performance advantage observed under XR conditions cannot be attributed to prior exposure.

For Prototype 1, the task required participants to move the robotic arm to a target point with a specified rotation. For Prototype 2, participants operated the mini-crane on site using its standard handheld remote controller with physical switches and levers as the baseline condition, then repeated the equivalent task using the XR interface. The crane task required moving a suspended object from a start position to a target position using the hook.

Task completion time was recorded for all participants across both conditions and both prototypes. For the robotic arm, joint angles were recorded throughout each trial and the end effector transformation was reconstructed and visualized from this data, enabling qualitative comparison of movement paths across conditions and participant groups. Path efficiency was not formally measured. No standardized questionnaire was administered though informal observations and short conversations with participants following each session informed the qualitative interpretation of results.

4 Results

4.1 Results of the XR interface evaluation for robotic arm control

The robot arm evaluation examined task completion time and movement path across novice and experienced participants. The task required moving the robot from its home position to a predefined target frame located at the upper left corner of the structure, as shown in Fig. 4, with the goal position superimposed onto the physical robot.



Fig. 4 Positions of the real robot and hologram with AI-supported camera feed as seen through the HMD of the MR system

Under the pendant condition, participants controlled each joint independently to reach the target. Under the MR condition, participants pointed at the target region on the steel structure, reviewed a simulated robot path visualized through the headset, and confirmed execution. Task completion time and end effector trajectory were recorded for both conditions.

Figure 5 presents completion times across both conditions and participant groups. Experienced users completed the task faster with the pendant, achieving a mean completion time of 28.97 s compared to 65.90 s with the MR interface. Novice users showed the opposite pattern, with a mean completion time of 190.63 s using the pendant and 85.13 s with the MR interface. The standard deviation of completion times was substantially lower for novice users under the MR condition (9.97 s) compared to experienced users (24.51 s), indicating more consistent performance among less-experienced operators. These findings suggest that the MR interface lowers the entry barrier for novice users, while experienced users face an adaptation cost when transitioning from a familiar control system.

An example data of the movement paths reconstructed from recorded joint angles are visualized in Fig. 6, with pendant paths shown on the left and MR paths on the right. MR paths follow a smooth curved trajectory toward the target, consistent with continuous spatially guided motion. Pendant paths display a more segmented character, reflecting the axis-by-axis control logic of pendant operation. This difference was consistent across participant groups. Novice participants additionally reported greater difficulty achieving the required end effector rotation under the pendant condition, a challenge reduced under MR where the target orientation was spatially visualized.

4.2 Results of the XR interface evaluation for mini-crane

The crane evaluation examined task completion time and operational behavior across novice and experienced participants. Figure 7 presents completion times separated by experience level. Under the MR condition, mean completion time decreased by 9.33 s for experienced users and 11.68 s for novice users, while standard deviation decreased by 9.39 s and 5.31 s respectively, suggesting a tendency toward faster and more consistent task completion. This tendency appeared more pronounced for novice users, who relied on pass-through vision and spatial overlays to support depth and angle judgment during the placement task. Experienced users described the MR system as more beneficial for situational awareness through the HUD and camera-based warnings than for precise control, and identified response delays,

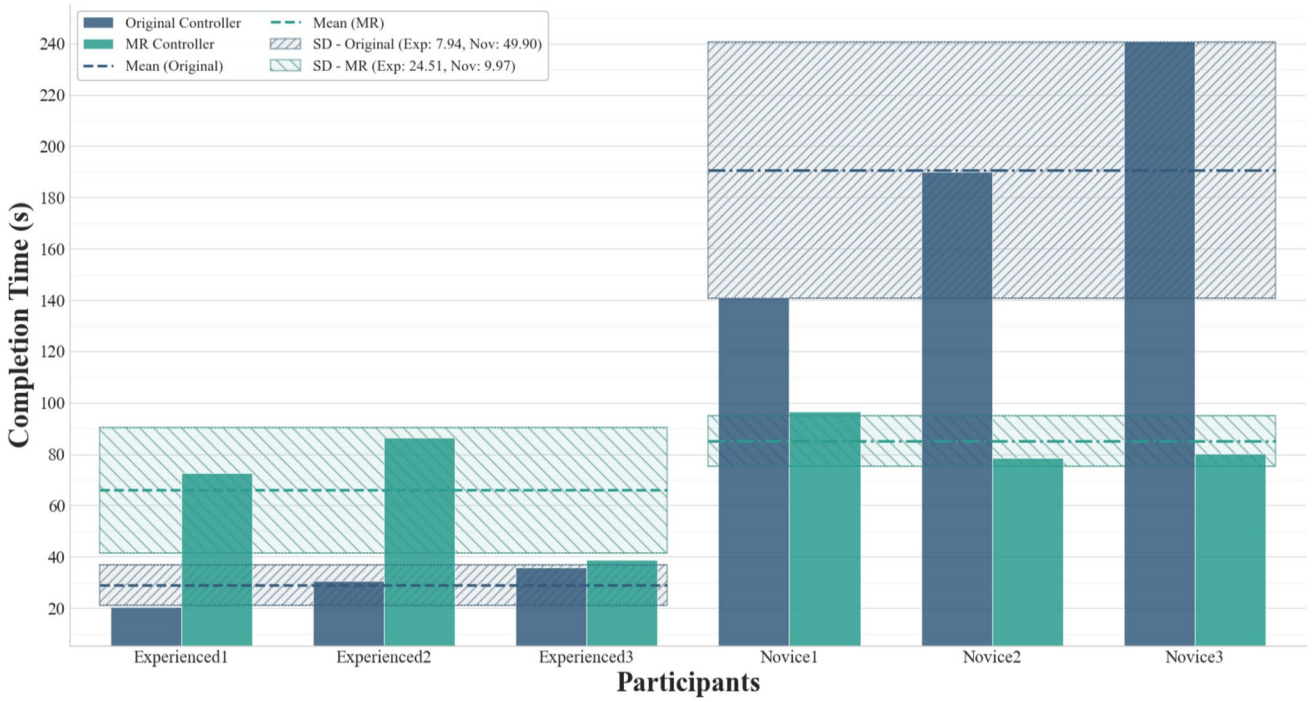


Fig. 5 Task completion time with standard deviation for Original Controller and XR Controller across expert and novice participants for the robot

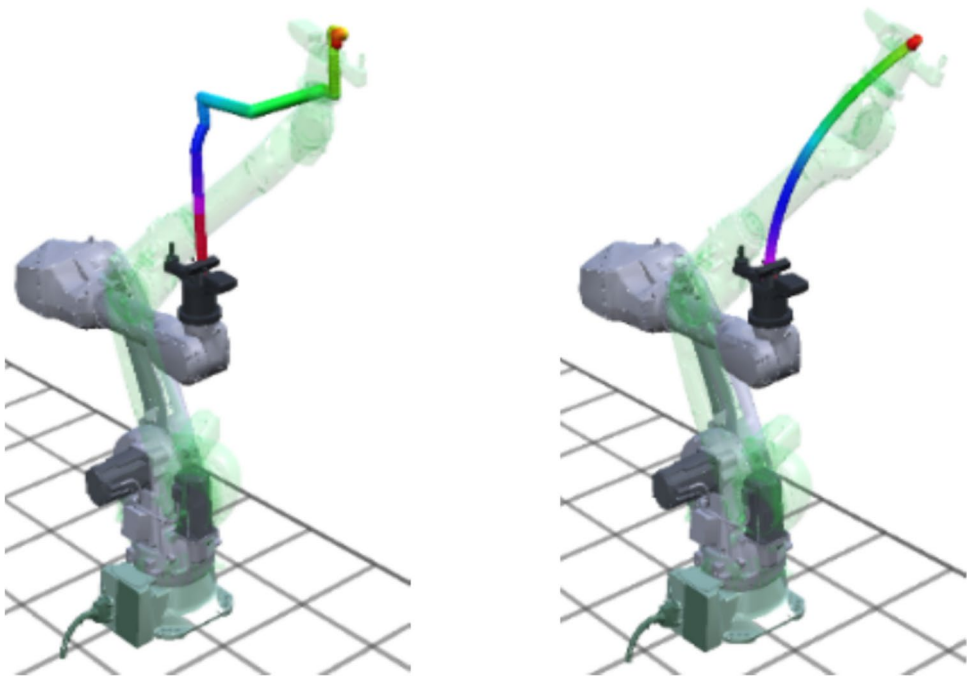


Fig. 6 Starting and end position using pendant (left) and MR (right) control, with the path visualized

auxiliary camera stream latency, and the absence of tactile feedback as recurring limitations.

Auxiliary camera stream latency, as seen in Fig. 8, was assessed using a capture-to-display test based on repeated binary luminance transitions (Jansen and Bulterman 2013). Delays ranged from 156 to 375 ms at baseline and from 125 to 375 ms under 10 Mbps network load. Under 50 Mbps load, latency became markedly less stable, ranging from

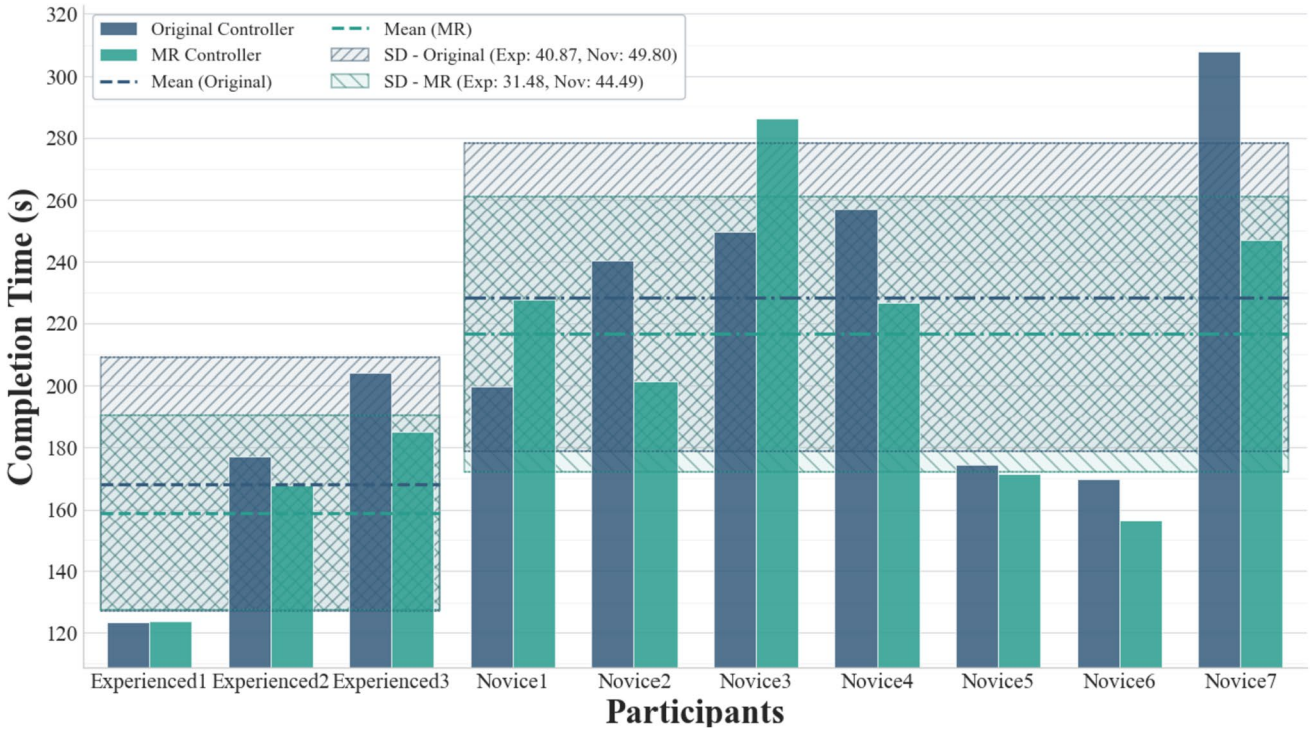


Fig. 7 Task completion time with standard deviation for Original Controller and MR Controller across expert and novice participants for the crane

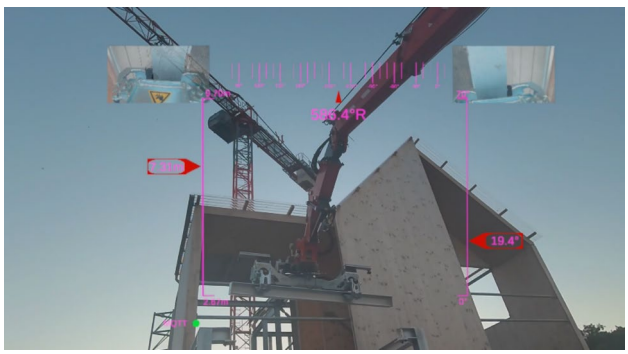


Fig. 8 MR operator view during crane control. The interface displays spatial overlays for crane position and movement, two auxiliary camera feeds for enhanced situational awareness. The HUD elements support long-distance alignment and monitoring during lifting

172 to 841 ms with a 95th percentile of 578 ms and a 99th percentile of 725 ms. Participant reports further indicated occasional lag spikes on the order of one second and, in the worst case, several seconds under connectivity issues. To address the associated safety risk, a watchdog mechanism was introduced to halt crane motion whenever no updated command was received within one second, preventing continued motion during communication dropouts.

Informal participant feedback suggested the system may be particularly useful for operator training and early familiarization with crane behavior. Given the small sample size, the results are treated as exploratory, with broader claims requiring larger participant groups and longitudinal assessment.

5 Discussion

5.1 Shared spatial architecture

Both prototypes demonstrate that XR can be structured as a shared spatial interaction layer connecting digital construction data, robots, and heavy machines, directly addressing RQ1. This common architecture using HMD as a central hub fusing machine telemetry, sensor data, and spatial overlays, shows that robot motions and crane maneuvers can be planned and monitored against the same physical environment within a single XR layer, advancing prior work by Dunston and Wang (2005) and (Wu et al. 2021) by spanning two fundamentally different classes of construction equipment rather than a single machine type. IFC-derived Linked Building Data was incorporated as an architectural feature in both prototypes and represents a direction for future validation.

5.2 Interaction patterns and performance

The user studies show that MR interfaces change the nature of operator interaction consistently across both prototypes, though with important differences between user groups, addressing RQ2.

For the robotic arm, the MR interface reversed the performance ranking between groups: experienced users were faster with the teach pendant (28.97 s vs. 65.90 s), while novice users were faster with MR (85.13 s vs. 190.63 s). Critically, novice standard deviation dropped from 49.9 s under the pendant to 9.97 s under MR, indicating that XR substantially reduced performance variability among less experienced operators. For the crane, mean completion time decreased under MR for both groups, differing from the robotic arm pattern. This difference is informative: the crane task involved continuous spatial navigation where MR overlays provide ongoing guidance, while the robotic arm task involved a single point to point motion that experienced users could execute from memory. This suggests XR provides the greatest benefit in tasks requiring continuous spatial judgment rather than recalled procedural sequences.

The slower experienced user result under MR for the robotic arm reflects an interface switching cost rather than a fundamental limitation. Experienced users had developed fluent motor routines with the teach pendant, consistent with teleoperation literature noting that operator expertise is interface specific and does not transfer directly across control modalities (Lee et al. 2022).

Path visualization revealed that MR paths follow smooth curved trajectories toward the target, while pendant paths display a segmented, linear character reflecting axis-by-axis joint control. This suggests XR shifts operators from a joint space to a task space mental model, a finding with direct implications for how MR robotic interfaces should be designed and evaluated.

5.3 Latency and technical constraints

Camera latency for the crane ranged from 156 to 375 ms at baseline, remaining within tolerable thresholds identified in teleoperation literature (A survey on teleoperating 2007; Chen et al. 2024). Under 50 Mbps network load, latency became markedly unstable, ranging from 172 to 841 ms with a 95th percentile of 578 ms, values that begin to undermine fine control and operator trust. Network load therefore emerges as a key variable requiring active management in real construction deployment.

For the robotic arm, the simulate-and-confirm interaction model decouples the interface from real-time latency constraints entirely. This architectural difference between the two prototypes is itself a design insight: where operational context permits a preview and confirm paradigm, XR robotic interfaces can sidestep latency as a critical constraint.

5.4 Contributions and design principles

This paper demonstrates that a shared XR spatial interaction layer is architecturally feasible across precision robotic fabrication and heavy machine teleoperation, and provides empirical evidence that MR reduces performance variability among novice operators across both domains. Latency, calibration stability, and interface switching cost are identified as the key boundaries constraining deployment, providing a concrete design agenda for future work.

Two transferable design principles emerge: first, centralize critical state information, target indicators, and safety cues in a compact HUD that preserves peripheral awareness; second, fuse camera imagery with spatial overlays on a shared coordinate frame to support depth judgment and alignment. These principles offer an initial framework for XR interface design across construction machine types and point toward future work on adaptive information hierarchies, multimodal feedback, and safety aware XR integration in real construction environments.

6 Conclusion

This paper investigated XR as a unifying spatial interaction layer across two distinct construction machine domains, precision robotic fabrication and heavy machine teleoperation. Two prototypes were implemented and evaluated: an XR interface for controlling a KUKA robotic arm and an XR teleoperation framework for a Jekko SPX532 mini-crane. User studies demonstrated that XR reduces performance variability among novice operators across both domains while imposing an interface switching cost on experienced users, and that the simulate-and-confirm interaction model used in the robotic prototype effectively sidesteps latency as a critical constraint. Together, the prototypes establish that a shared XR spatial layer is architecturally feasible across fundamentally different classes of construction equipment using a consistent pattern of head mounted display, ROS2/MQTT communication, and spatial anchoring. Latency, calibration stability, and haptic feedback remain the key technical boundaries for real deployment. Future work will address these constraints through larger participant studies, longitudinal evaluation, and validation of IFC-based construction data integration within the shared XR layer.

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