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TELEOPERATION INTERFACES FOR COMPACT DEMOLITION ROBOTS: RESULTS OF A PILOT STUDY WITH CONSTRUCTION WORKERS

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Abstract

As teleoperated robots become more common on construction sites, human-robot interfaces must better support operators' sensory needs. This paper presents results from a pilot study comparing a proposed sensory-enhanced teleoperation interface for compact demolition robots with a standard teleoperation interface. Recommendations from demolition stakeholders informed the design of the sensory-enhanced interface, while the standard interface was based on commercially available teleoperated construction equipment. The goal of this study was to refine the sensory-enhanced interface based on user feedback. Ten construction workers tested the interfaces, and we measured their perceived usability, telepresence, and trust in technology.

Introduction

Increasing numbers of robots with varying levels of autonomy are being deployed at construction sites (Liang et al., 2021). Among these, teleoperated systems are used extensively because they keep workers out of hazardous environments. These technologies fundamentally change construction site dynamics as workers adapt to these machines. However, despite their adoption, many teleoperated systems have created a mismatch between workers' needs and the control requirements of human-machine interfaces (Kim et al., 2026).

This mismatch can result in increased mental workload, decreased situation awareness, ergonomic issues, and compromised performance and safety (Kim et al., 2026). In teleoperated contexts, interfaces aligned with operators' preferences may reduce physical and mental loads, increase operator comfort, performance, and safety. Despite these benefits, teleoperation interfaces still face multiple issues that complicate their broader use (Rea & Seo, 2022), and better user-centered interfaces for construction robots are needed (Rasheed et al., 2024).

In this paper, we compare two teleoperation interfaces for compact demolition robots: a standard and a sensory-enhanced interface. The standard interface was designed based on construction robots' teleoperation interfaces (e.g., Caterpillar Inc. (2022)). The sensory-enhanced interface was designed based on recommendations from demolition stakeholders to extend the capabilities of traditional systems (Rodrigues, Lucas, et al., 2025).

We conducted a pilot study to test the two interfaces and ensure participants could safely complete various tasks in an obstacle course. We gathered participants' subjective feedback on perceived usability, telepresence, and trust in technology. We also conducted semi-structured interviews to collect their opinions and suggestions on interface designs. These results helped refine the interfaces, the obstacle course, and the experimental protocol before the full study with a larger sample.

Literature Review

Teleoperation is widely used in construction robotics (Liang et al., 2021). Applications include teleoperated drones for site inspection, safety surveillance, and surveying (Albeaino et al., 2022); teleoperated heavy equipment (e.g., excavators, bulldozers) for hazardous and remote sites (J. S. Lee et al., 2022); and teleoperated demolition (Rodrigues, Becerik-Gerber, et al., 2025), among others (Hu et al., 2025). This widespread adoption stems from the unstructured and dynamic conditions of most construction sites, which still limit fully autonomous operations and require human perception and decision-making to interpret site conditions, assess risks, and adjust operations in real time (Kim et al., 2026). As a result, the effectiveness of teleoperation in construction depends on the quality of the operator-interface interaction and the availability of adequate sensory feedback.

Commercial teleoperation interfaces in construction commonly replicate manned equipment interfaces (e.g., Caterpillar Inc. (2022)). Operators use seats, joysticks, and pedals modeled after those found on manned machines (e.g., excavators), with camera views replicating cabin perspectives. While this approach leverages operators' familiarity with traditional systems, directly transferring interfaces from manned to teleoperated machines is not straightforward, as physical separation between operators and the site in teleoperation affects the quality, quantity, and type of sensory information operators receive (J. S. Lee & Ham, 2022). For equipment not operated from a cabin, this approach is infeasible, requiring the redesign of the human-machine interfaces rather than transferring traditional control schemes (e.g., H. J. Lee & Brell-Cokcan (2023)).

Over time, however, these interfaces are often improved through trial and error. Advancements in artificial intelligence (AI) and hardware have enabled assistive teleoperation technologies that support higher levels of robot autonomy, such as robots that adjust behavior to reduce operator workload (e.g., Liu et al. (2021)). AI has also enabled assistive features that fuse and simplify data, identify hazards, and support decision-making (Hong et al., 2020). Similarly, adaptive interfaces adjust the type, amount, and timing of the information operators receive, such as allowing manual or autonomous camera viewpoint switching (Xu et al., 2024). Many of these systems, however, are in early stages of development and have only been tested under laboratory conditions.

Introducing new robotic systems on construction sites has emphasized the need for user involvement in interface design. User Experience (UX) design has been instrumental in this process, supporting ideation, design, and refinement. By recognizing these needs, Rodrigues, Lucas, et al. (2025) proposed a framework to inform the design of sensory-enhanced teleoperation interfaces for construction machines through user engagement and testing. By engaging demolition professionals, the authors identified how operators in traditional demolition tasks use different sensory channels to monitor the robot, task, and environment, and gathered their suggestions for teleoperation interface designs. Drawing on these suggestions, we designed a sensory-enhanced teleoperation interface and tested it against a standard teleoperation interface typical in construction.

Methodology

Robot Description

This study employed a Brokk 120 DII demolition machine equipped with a Brokk BHB 155 hydraulic breaker (Figure 1). It is one of the most compact Brokk Inc. demolition machines, with dimensions of 2030 mm × 780 mm × 1250 mm and a maximum reach of up to 4300 mm.

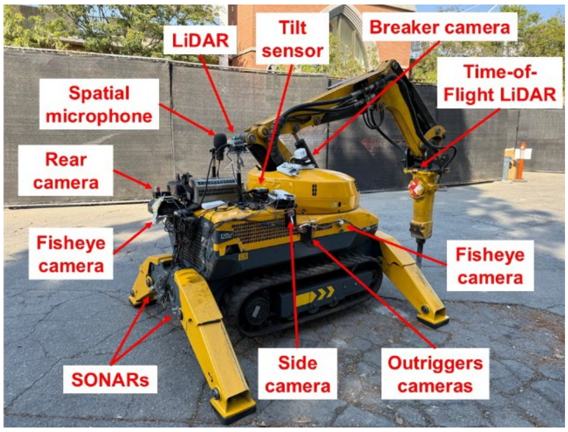

Figure 1. Brokk 120 DII sensor configuration.

Teleoperation System Architecture

Modularity

The teleoperation interfaces used modular designs to provide flexibility for testing and refinement. This approach allowed interface features to be added, removed, or adjusted based on user feedback. Various sensors connected to independent onboard computers and microcontrollers collected operational and site data, which was transmitted to a central computer that aggregated and relayed it via the user interfaces.

Communication Architecture

Communication between the robot and the teleoperation interfaces was enabled via a Wireless Local Area Network (WLAN) established with a single high-performance router in the obstacle course. The system combined the User Datagram Protocol (UDP) and the Web Real-Time Communication (WebRTC) protocol to ensure low-latency communication between the robot's onboard computers and the web-based interfaces.

The robot's onboard system included multiple Raspberry Pi 5 microcontrollers, wirelessly connected to a central minicomputer located inside the construction trailer, which aggregated data from the Raspberry Pi units and generated the web-based interfaces. A separate minicomputer installed on the robot, physically connected to a LiDAR sensor and a spatial microphone, provided real-time point clouds of the environment and environmental audio to the user interfaces. Finally, exocentric cameras installed throughout the obstacle course streamed external visual perspectives of the environment directly to the central minicomputer.

Control

The Brokk 120 DII demolition robot was controlled using the Brokk SmartRemote™ controller (Figure 2). This controller operates via radio communication and can control the robot at distances of up to 300 meters.

A deliberate design decision was made to maintain the robot's original hardware and software. Rather than modifying the robot's control system, an effort that would require an additional investigation, this study focused on augmenting operator situation awareness through external sensors and improved teleoperation interfaces.

Robot Sensors Configuration

Additional sensors were mounted on the robot and integrated with the teleoperation interface (Figure 1). Cameras were installed to provide egocentric views of the robot's front, rear, left, and right sides, its arm, and end-effector. Additionally, a bird's-eye view of the robot was provided using four fisheye cameras, offering operators an overhead perspective of its position and surroundings.

Several sensors were deployed to augment operators' spatial awareness. A tilt sensor measured the robot's pitch and roll. A LiDAR provided real-time point clouds of the environment, improving depth perception. Four robot-mounted sonar sensors measured distances to nearby objects as part of a proximity warning system for collision avoidance. A time-of-flight LiDAR measured distances from the breaker tip to demolition targets. Finally, a spatial microphone transmitted real-time environmental audio from the site to the teleoperation interfaces.

External sensors configuration

Several exocentric cameras were deployed throughout the obstacle course to provide external views of the robot to support localization and situation awareness. Two cameras were installed inside the trailer to capture the operators' postures and their usage of the interface.

User Interfaces

The user interface consisted of multiple TV screens, laptops, the Brokk SmartRemote™ controller, and a VR gaming chair equipped with vibration and rotation capabilities (Figure 2). The specific configuration of interfaces differed between the standard and sensory-enhanced interfaces. The user interface components were installed inside a construction trailer specifically adapted to accommodate the teleoperation interfaces and associated equipment. For the pilot study, this trailer was positioned adjacent to the obstacle course.

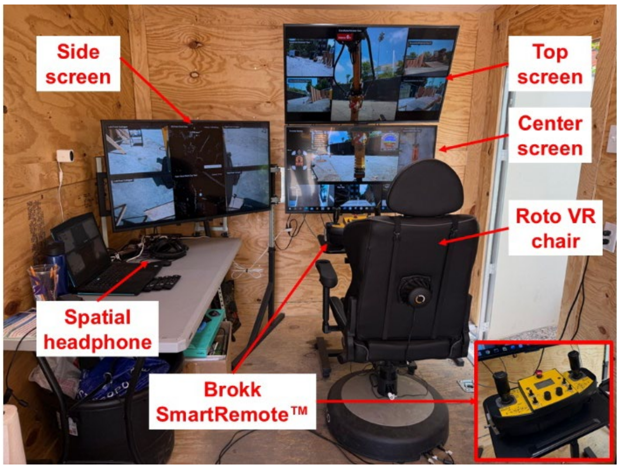

Figure 2. User interfaces inside the construction trailer. The inset shows a close-up of the Brokk SmartRemote™ controller.

Standard Teleoperation Interface

The standard teleoperation interface was designed based on the Caterpillar Cat® Command teleoperation interface (Caterpillar Inc., 2022), commonly used for heavy machinery such as excavators. This interface provided operators with multiple egocentric camera perspectives (i.e., front, rear, left, and right), exocentric camera perspectives, robot status information, environmental sound, and attitude data. In addition to the conventional design of the Caterpillar Cat Command interface, this implementation included a fixed camera to provide a continuous view of the robot's arm and end-effector.

Visual Feedback

Visual feedback (Figure 3) was presented on two vertically stacked 43-inch TVs. The center screen (Figure 3a) displayed four egocentric views: front, rear, left, and right. For the front and rear cameras, the interface also displayed grid lines to help operators estimate the robot's distance to objects. It also included an attitude indicator for the robot's roll and pitch, along with status information such as engine temperature, fuel levels, hydraulic system pressures, and maintenance indicators. The top screen (Figure 3b) presented four exocentric camera perspectives showing the obstacle course and an egocentric view of the robot's arm and breaker. All cameras used in the standard interface were fixed cameras with automatic focus.

Sound Feedback

The sound feedback system consisted of a headset and TV speakers, through which sounds captured by a microphone mounted on the robot were transmitted.

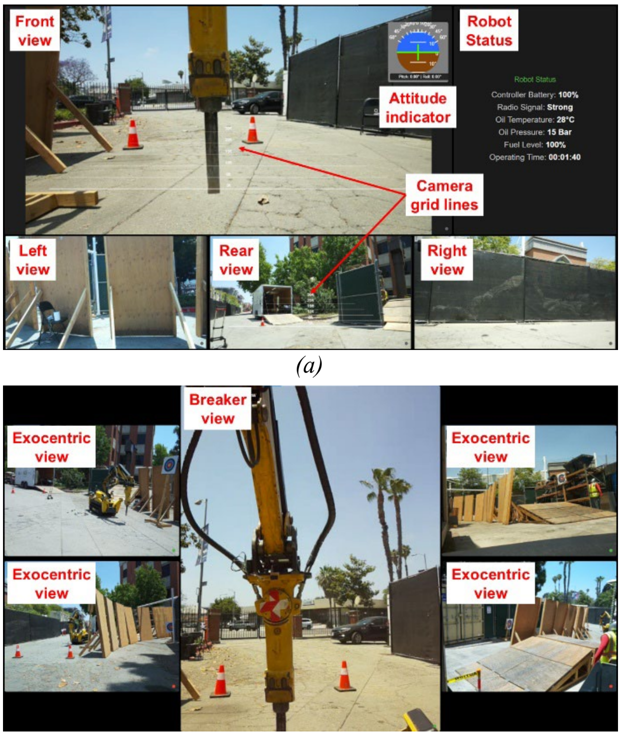

Figure 3. Standard teleoperation interface. (a) Center screen. (b) Top screen.

Sensory-Enhanced Teleoperation Interface

The sensory-enhanced teleoperation interface expanded on the standard interface by incorporating enhanced visual, auditory, and haptic feedback, alongside a proximity warning system to improve operator situational awareness. These inclusions were based on recommendations from demolition professionals during focus groups and preliminary testing of VR interfaces in a demolition tradeshow (Rodrigues, Lucas, et al., 2025).

Visual Feedback

The sensory-enhanced interface visual feedback (Figure 4) was presented through three 43-inch screens. The center screen (Figure 4a) displayed four egocentric robot views: front, rear, left, and right. The front and rear views included grid lines to help operators estimate distances. It also showed the robot with proximity warning arcs and distance indicators at each corner, providing real-time visual feedback from four sonar sensors. The screen also included a stitched bird's-eye view of the robot's surroundings from four fisheye cameras placed on the robot's sides, an attitude indicator for pitch and roll, and robot status information, including engine temperature, fuel levels, hydraulic pressures, and maintenance needs.

The top screen (Figure 4b) displayed four exocentric views of the obstacle course, an egocentric view of the robot's arm and breaker, and a distance indicator to the breaker tip. Finally, the side screen (Figure 4c) displayed four dedicated camera views, one for each robot outrigger. This screen also displayed two LiDAR point clouds (i.e., top and perspective views) to enhance operator depth perception and situation awareness. All cameras used in the sensory-enhanced teleoperation interface were fixed and equipped with automatic focus.

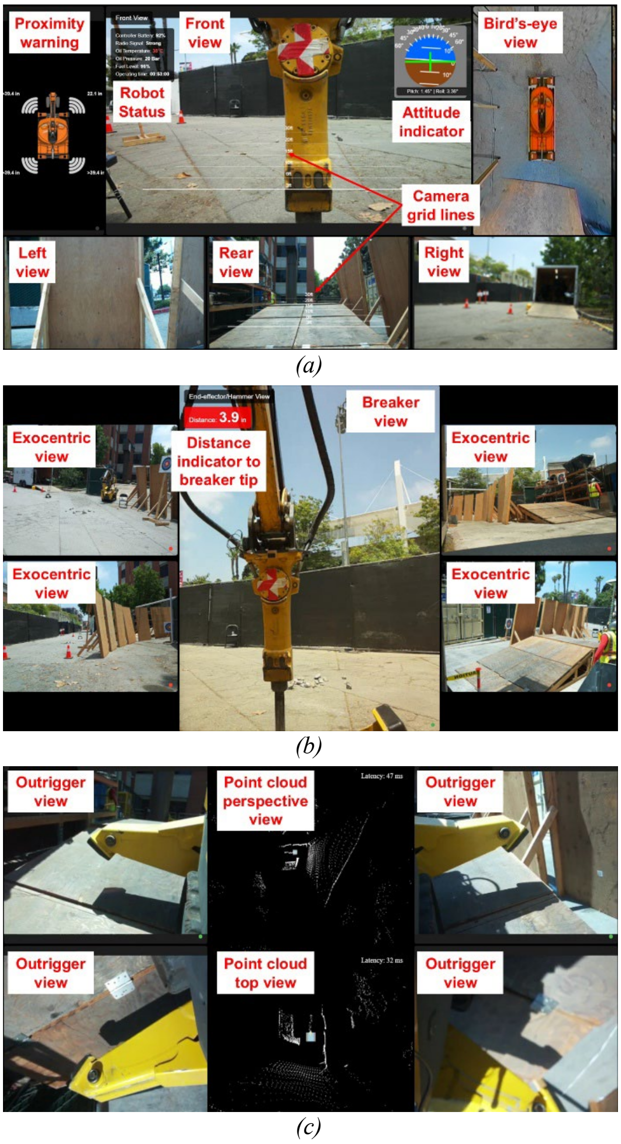

Figure 4. Sensory-enhanced teleoperation interface. (a) Center screen. (b) Top screen. (c) Side screen.

Sound Feedback

Sound feedback was delivered via a headset and the TV speakers, providing real-time environmental sound captured by a robot-mounted microphone. In addition, the sensory-enhanced teleoperation interface incorporated auditory alerts as part of the proximity warning system.

Haptic Feedback

The sensory-enhanced interface incorporated haptic feedback via a VR gaming chair (Roto VR chair) that vibrated (rumble) and rotated. Haptic feedback was used in the proximity warning system to provide vibratory alerts when the robot approached an obstacle.

Safety Mechanisms

The sensory-enhanced teleoperation interface included a proximity warning system using robot-mounted ultrasonic sensors to alert operators to potential collisions. Visual and auditory feedback were provided when obstacles were within 2 feet, while haptic feedback was activated at distances of 1 foot or less, with warning levels and frequencies increasing as distance decreased.

Additionally, the LiDAR point cloud highlighted moving objects such as people, vehicles, and equipment in red, thus enhancing operator awareness of dynamic elements.

Pilot Study

The objective of the pilot study was to identify opportunities for improvement before a full user study. The pilot also served to test the sequencing and timing of training and experimental tasks, verify the setup and functionality of the teleoperation systems, and ensure the safety of the obstacle course. By identifying potential challenges and opportunities before the user study, we aimed to minimize technical issues, enhance data validity, and avoid mid-study modifications that could introduce bias and compromise data comparability.

After providing informed consent, participants completed intake surveys that included demographics and baseline trust in technology and self-efficacy. We also recorded five-minute baselines for heart rate variability (HRV) and electrodermal activity (EDA) using an Empatica EmbracePlus smartwatch. Participants then underwent VR-based training in the Unity Game Engine, covering the robot's parts and controls, collision avoidance, worker safety, and safe operation on elevated and sloped surfaces. The VR training included three guided exercises focused on driving, arm positioning, and breaking concrete. Next, participants completed pre-experiment surveys assessing trust in technology, self-efficacy, state-trait anxiety, fatigue, musculoskeletal discomfort, and workload.

Next, participants received in-person training with the real robot, covering the Brokk SmartRemote™ controller, safe driving, arm operation, concrete breaking, and robot configuration for operations on ground and elevated surfaces. Then, participants went to the construction trailer to be introduced to their assigned teleoperation interface (standard or sensory-enhanced), with the researchers explaining its functions and features.

The experimental trial involved remotely operating the Brokk robot through a three-task obstacle course (Figure 5). The tasks included (1) driving in a flat open space while avoiding objects such as cones, construction tools, and concrete debris, and positioning the breaker on a target located above the robot, (2) driving in a constrained corridor while avoiding objects such as walls, utility pipes, and concrete beams, positioning the breaker on two targets located at the height of the robot, and demolishing part of a concrete beam, and (3) driving on sloped surfaces (ramps) and elevated surfaces (platform) while avoiding objects such as corridor walls, construction crane, and shelves, and positioning the breaker on a target located above the robot while the robot is on a sloped surface.

Throughout the trial, participants wore the Kexxu Eye eye-tracker to record gaze behavior and the Empatica EmbracePlus smartwatch to record HRV and EDA. After the trial, participants completed post-experiment surveys assessing trust in technology, self-efficacy, state-trait anxiety, fatigue, musculoskeletal discomfort, workload, situation awareness, telepresence, and system usability. Finally, they participated in a semi-structured exit interview to provide feedback on the interfaces.

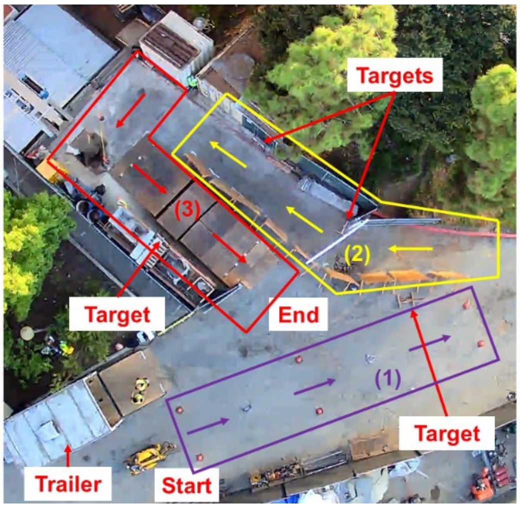

Figure 5. Obstacle course for the pilot study. (1) Open space. (2) Corridor. (3) Ramp.

Participants also completed a survey evaluating workstation features across different site conditions and tasks. Finally, participants assigned to the sensory-enhanced teleoperation interface completed a scenario-based evaluation, in which they read descriptions of demolition scenarios with varying site complexity levels and rated the importance of different sensory features under those conditions. The study protocol was approved by the Institutional Review Board (IRB) at the University of Southern California (USC) (Study ID: UP-24-01122).

Participants

We recruited 12 construction workers to test the two interfaces (*Table 1*). The first two participants were dismissed from the study due to technical issues with the WLAN and were not included in subsequent analysis. Participants were required to be construction workers fluent in either English or Spanish. Recruitment efforts included outreach to construction and demolition industry partners and site visits to construction projects at the USC University Park Campus (UPC). In addition, we employed snowball sampling by asking participants to refer the study to their colleagues.

Participants received compensation for their participation. Those who tested the standard interface completed a session that lasted up to 3.5 hours and received up to $380. Participants who tested the sensory-enhanced teleoperation interface completed a session that lasted up to 4.5 hours and received up to $450. The difference in duration and compensation was due to the scenario-based evaluation at the end of the experiment for the participants assigned to the sensory-enhanced teleoperation interface.

Pilot Study Results

Due to the small sample size of the pilot study, we did not perform formal statistical tests and group comparisons. Rather, we present descriptive statistics on the metrics for the effectiveness and usefulness of the interfaces. We also discuss our observations during the pilot study, the participant recommendations, and how they helped us refine the interfaces, the obstacle course, and the experimental procedures for subsequent studies.

Table 1. Demographic information of the participants (n=10) by experimental condition.

Characteristic	Category	Standard Interface	Sensory-Enhanced Interface
Gender	Male Female	5 0	4 1
Age	18-29 30-39 40-49	2 1 2	2 2 1
Preferred Language	English Spanish	4 1	5 0
Play Video Games	No Yes	4 1	1 4
Work Experience in Construction	None < 5 years 5-10 years	0 1 4	1 3 1
Demolition Experience	None < 5 years	3 2	4 1
Construction Machine Operation Experience	None < 5 years 5-10 years	2 2 1	4 1 0
Construction Machine Type	Excavator Crane Forklift Aerial lift	1 1 2 2	0 0 1 0
Teleoperation Experience	No Yes	5 0	5 0

Note: Totals may not equal 10 because participants could skip questions or select multiple choices.

Trust in Technology

Trust in technology was assessed at three time points: during the pre-VR training session, pre-experiment, and post-experiment. We used a modified version of the Trust Scale with 12 items (Jian et al., 2000), in which participants rated their trust, distrust, and familiarity with their assigned teleoperation interface. First, we reverse-coded the distrust items (items 1-5). Then, we used the average scores across the 12 items of the scale to determine each participant's trust in the teleoperated Brokk robot system. Final scores were in the range of 1 (not at all) through 7 (extremely). Figure 6 presents the means and standard deviations of the trust scores for each interface type and measurement time.

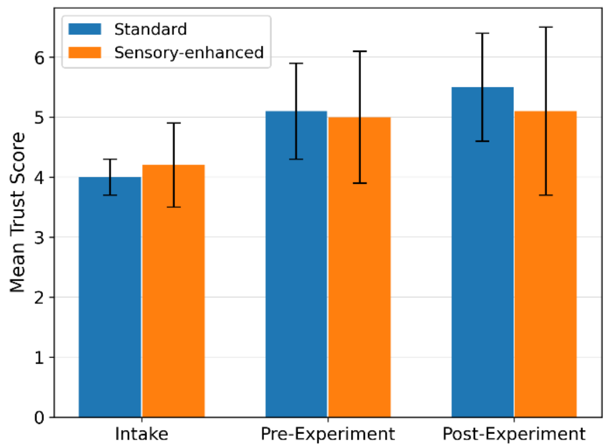

Figure 6. Mean trust scores by interface type and measurement time. Error bars represent ±1 standard deviation.

Usability of the Teleoperation Interfaces

The usability of the two interfaces was assessed using the System Usability Scale (SUS) (Brooke, 1996), a 10-item questionnaire in which participants subjectively rated each interface's usability, yielding final SUS scores ranging from 0 to 100. In usability testing, a commonly used threshold for SUS scores is 68 (Lewis & Sauro, 2018). Scores above 68 indicate above-average usability, while scores below 68 indicate below-average usability. Figure 7 presents the means and standard deviations of SUS scores for each interface type.

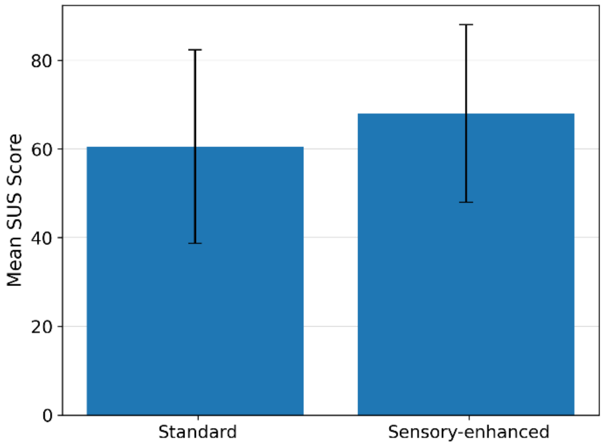

Figure 7. Mean SUS scores by interface type. Error bars represent ±1 standard deviation.

Telepresence

We used the 24-item Presence Questionnaire (PQ) modified by Robillard et al. (2002), based on the original instrument by Witmer & Singer (1998). Of the 24 items, we used 22, excluding the two optional haptic-sensation items, which were not applicable to our interfaces. We computed scores for overall presence (Total Presence) (items 1–19) and for the following presence subscales: Realism (items 3, 4, 5, 6, 7, 10, 13), Possibility to Act (items 1, 2, 8, 9), Quality of Interface (items 14, 17, 18), Possibility to Examine (items 11, 12, 19), Self-Evaluation of Performance (items 15, 16), and Sound (items 20–22). Items 14, 17, and 18 were reverse-coded before analysis. For each variable, scores were computed by summing the responses to the corresponding items and then normalizing by the number of items, so that all variables are in the 1-7 scale. Figure 8 presents the means and standard deviations of total presence scores and presence subscales scores for each interface type.

Refinements of the Interfaces

During the experiment and the exit interviews, participants provided feedback on the interfaces, training, and their experiences. Across both groups, users reported an initial learning curve to get accustomed to the controls. Sensory-enhanced interface users commonly reported improvements in usability over time, with one participant describing the interface as "very self-explanatory" and quick to learn. Conversely, standard interface users frequently reported persistent challenges with depth perception and camera-based navigation, particularly in narrow spaces or when approaching targets.

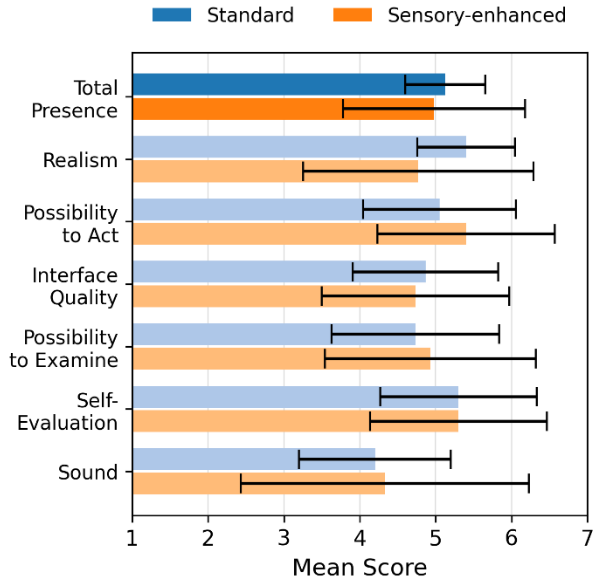

Figure 8. Mean total presence and presence subscale scores by interface type. Error bars represent ±1 standard deviation.

Both groups identified depth perception as a key limitation of the interfaces and suggested additional depth cues and visual overlays. Sensory-enhanced interface users reported positive reactions to the additional sensory feedback (e.g., extra views, sound, vibration), but some found it cognitively demanding to process information from multiple screens simultaneously. Similarly, standard interface users suggested additional visual representation of the arm's position to aid manipulation. Regarding training, participants from both groups valued the VR-based training, noting that it improved confidence during real robot operations.

When asked about interface features, some sensory-enhanced interface users reported ignoring or underutilizing certain features (e.g., point cloud and outrigger views), suggesting that these features require better integration or explanation. Several participants recommended adding automated tilt warnings, collision avoidance, and automated stops, especially for complex arm positioning tasks. While the interface's physical layout was generally well received, some participants from both groups noted that the number of screens could be overwhelming and suggested simplifying the interface to improve operational efficiency. In general, participants felt that the interface improved safety, but noted that its complexity and cognitive demands could reduce productivity and require extensive training due to the number of camera feeds and data streams presented.

Discussion

In this pilot study, we observed that participants' trust in the teleoperation systems increased over time, consistent with expectations as they gained familiarity through VR training and real-world robot operation, such as in Adami et al. (2022). Participants initially reported neutral trust levels prior to interface exposure (intake), which increased following VR-based training (Pre-Experiment) and further after operating the real robots (Post-Experiment). Importantly, this increase was observed for both teleoperation interfaces. These findings suggest that trust development may be more strongly influenced by interaction time and user experience than by interface design alone, at least in early stages of system exposure.

Regarding SUS scores, both interfaces were relatively close to the industry average of 68 (Lewis & Sauro, 2018), suggesting room for improvement. Another aspect of the pilot study that supports the usability of both interfaces is that all ten participants, five per interface, completed all three obstacle course tasks.

The presence scores suggest that participants experienced moderate to high levels of presence across both interfaces, with mean total presence scores in the upper half of the possible range. The presence subscales showed a similar pattern, with realism and possibility to act having relatively high scores, suggesting that participants felt able to interact with and influence the system. Next, interface quality and possibility to examine were slightly lower, but still above the midpoint of their respective score ranges, suggesting some limitations in these areas. Finally, the sound subscale yielded average scores near the middle of the possible score range, suggesting a moderate contribution of auditory feedback to participants' overall sense of presence for both interfaces.

Participant feedback provided valuable insights that informed refinements to both the teleoperation interfaces and the experimental protocol. As documented in prior teleoperation research, depth perception has been recognized as a persistent challenge, underscoring the need for enhanced visual cues to support spatial awareness (Chen et al., 2007; Luo et al., 2021). The sensory-enhanced interface was generally perceived as more supportive of safety, but some participants also noted it might have induced higher cognitive load, particularly due to the greater number of screens and data streams compared to the standard interface.

Participants also provided valuable suggestions for improving the interface layouts. To better align with participants' needs, we moved the end-effector and exocentric views, which participants identified as more critical for task performance, from the side screen to the top screen for improved visibility. Consequently, the side screen in the sensory-enhanced interface displayed the point cloud and outrigger views. Additionally, the initial laptop screen showing robot status information (temperature, fuel levels, hydraulic pressures, maintenance indicators) and proximity warnings was eliminated, and this information was integrated into the center screen alongside the egocentric and bird's-eye views. These adjustments directly addressed participants' concerns about information overload and interface complexity while preserving situational awareness.

Along with these visual interface changes, we also modified the audio feedback system to improve safety. Originally, both interfaces provided sound feedback through spatial audio headphones. However, the headphones were later replaced with TV speakers because participants struggled to hear the researchers' instructions and safety alerts, which could lead to accidents.

This pilot study had several limitations. First, the sample size was small (N = 10), limiting statistical power to detect differences between interface types and increasing the risk of Type II errors. Second, although all participants were construction workers, their experience with construction machine operations varied widely, potentially influencing their perceptions of usability, trust, and presence, and their task performance. Third, participants used the interfaces for a limited time during the pilot test, and longer-term use may change their perceptions of usability, trust, and presence. Additionally, while eye-tracking data were collected during the study, intermittent internet connection issues caused communication failures between the cellphone app and the eye-tracker, leading to calibration and tracking losses and video corruption. These issues made eye-tracking data unreliable during analysis. However, the issue was resolved by stabilizing the data acquisition setup for subsequent studies. Finally, while this analysis focused on subjective self-reported measures of trust, usability, and presence, further analyses of objective task performance and gaze behavior are necessary to provide a more comprehensive evaluation of interface effectiveness.

To address these limitations, in subsequent full-scale studies, we will recruit more construction workers to robustly analyze how different interface designs affect operators' performance and safety, using both objective and subjective measures. We will also conduct moderation and mediation analyses of the data to examine how demographic characteristics (e.g., age, machine operating experience) and operator responses (e.g., workload) explain observed performance and safety outcomes.

Conclusions

This pilot study provided valuable preliminary insights into usability, trust development, and presence afforded by two teleoperation interfaces for compact demolition robots. Both the standard and sensory-enhanced interfaces supported increasing trust over time, and presence scores were consistent with established reference values in the teleoperation and VR literature. Similarly, SUS scores for the initial designs of both interfaces were rated similarly to those of interfaces in industry and academia.

Next, participants' feedback highlighted specific areas for interface refinement, including improved depth cues and interface layouts. Importantly, iterative adjustments to the interface configuration and experimental protocol were made based on this feedback, highlighting the value of the selected user-centered approach in designing teleoperation systems that better support operator needs.

While results should be interpreted with caution due to sample size and other limitations, this work represents an important first step toward developing teleoperation systems that enhance operator safety, usability, and situation awareness in demolition. Moving forward, integrating objective performance data and involving a broader range of experienced operators will be key to validating and extending these initial findings.

Acknowledgments

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