Immersive Virtual Reality for Evaluating Construction Worker Responses to Safety Hazards in Robotic Construction Workplaces

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Abstract— **This study presents an immersive virtual reality framework for evaluating construction worker responses to robot-related hazards in future construction workplaces. The virtual reality environment is used to simulate hazardous construction-site conditions involving drones, demolition robots, and autonomous mobile robots operating near human workers. By exposing participants to controlled hazard scenarios, the study enables observation of worker behavior, including distraction, hesitation, route deviation, proximity response, and preparedness for emerging hazards. The collected behavioral and self-reported responses can help identify unsafe operating conditions and support the development of future safety protocols. This approach provides a safe, repeatable, and ethically acceptable method for assessing worker-robot interaction risks before robotic systems are deployed on active construction sites.**

I. Introduction

The global construction industry is increasingly exploring autonomous and semi-autonomous robotic systems to improve productivity, precision, inspection capability, and worker safety [1,2]. Drones can support progress monitoring and inspection. Demolition robots can remove workers from selected heavy and hazardous tasks. Mobile robots can transport materials through dynamic work zones, and collaborative robots can assist with repetitive or physically demanding installation activities. These technologies also change how human workers move through the site, divide their attention, interpret machine intent, and maintain safe distances around equipment [3,4]. As a result, a safety challenge is not only whether the robot can operate correctly, but also whether workers can accurately anticipate and respond to robot behavior in complex construction environments.

These questions are especially important because construction sites differ significantly from controlled manufacturing settings. Construction environments are temporary, noisy, cluttered, spatially constrained, and constantly changing as trades, materials, equipment, and temporary barriers move across the site [5]. A robot that is safe in a structured laboratory or factory cell may create unexpected hazards when deployed around scaffolds, exposed edges, stacked materials, uneven walking surfaces, blind corners, dust, and multiple workers performing simultaneous tasks. Worker safety can be difficult to evaluate directly on physical construction sites without exposing participants to real struck-by hazards, fall hazards, pinch points, and equipment conflicts [6]. A central challenge, therefore, is the lack of safe, repeatable, and ethically acceptable methods for evaluating worker responses to robot-related hazards before deployment. Full-risk field experiments may be impractical or unsafe, while purely analytical assessments may fail to capture human behaviors such as hesitation, reliance, distraction, route deviation, startle response, or misinterpretation of robot intent. These behaviors are critical because robot-related construction hazards are not only physical; they also involve cognition, attention, trust, and communication. Workers must understand where a robot will move, whether it has detected them, when it intends to stop or yield, and how to interpret warnings or motion cues in a busy work environment.

This manuscript discusses how immersive virtual reality (VR) can help fill this gap by enabling controlled, simulated exposure to robot-related hazards while recording how workers respond. Rather than framing VR only as a training medium, the proposed work positions VR as a pre-deployment evaluation and design tool for future robotic construction workplaces. Through scenarios involving aerial robots, demolition robots, mobile material-transport robots, and collaborative installation robots, VR can be used to examine worker movement, proximity, hesitation, route choice, perceived risk, and response to warning cues. These observations can then inform safety protocols, spatial layout decisions, warning systems, robot navigation policies, and worker training before robotic systems are deployed on active construction sites.

II. VR-based Hazard Evaluation Framework

A. Setup of Immersive VR Environment

The Virtual Reality Laboratory at the National Institute for Occupational Safety and Health (NIOSH) facility in Morgantown, West Virginia houses a CAVE (Cave Automatic Virtual Environment)-type immersive display system used to present interactive virtual construction environments and task scenarios, as shown in Fig. 1. The system supports first-person visualization of simulated worksites in which participants can move through the environment, observe changing site conditions, and interact with virtual objects or equipment. This immersive display capability enables researchers to study

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worker behavior in realistic construction situations while avoiding direct exposure to physical hazards.

Virtual environments were developed to represent a range of robot-integrated work scenarios, including mobile robot operations, drone activity near workers, and demolition tasks involving remote robot operations. Each scenario can be configured with different visibility levels, lighting conditions, spatial layouts, robot positions, and control orientations to reflect varying on-site conditions. The simulated construction environment includes temporary and dynamic site elements such as scaffolding, material stacks, pallets, cords, unfinished rooms, debris, barriers, equipment, and partially completed structural components. Robot agents and construction equipment are modeled with consistent visual, audio, and functional attributes so that participants can interpret them as part of the surrounding worksite.

The virtual content was developed using 3D models of selected construction equipment, robots, and site objects, and was rendered in real time using getReal3D 4.1.0 for Unity3D 2019.3 rendering engine at 60 frames per second. Participants viewed the stereoscopic environment using Volfoni VR 3D glasses, shown in Fig. 2(a), which measure 175 × 55 mm and weigh 56 g. Depending on the task, participants interacted with the virtual environment using either a hand-held Logitech controller for object manipulation and placement or a dedicated controller for remote operation of the demolition robot. This setup allowed participants to perform task-specific actions while remaining visually and spatially immersed in the simulated environment.

Figure 1. CAVE-type immersive display system used to present virtual reality environments and tasks in the NIOSH Virtual Reality Laboratory.

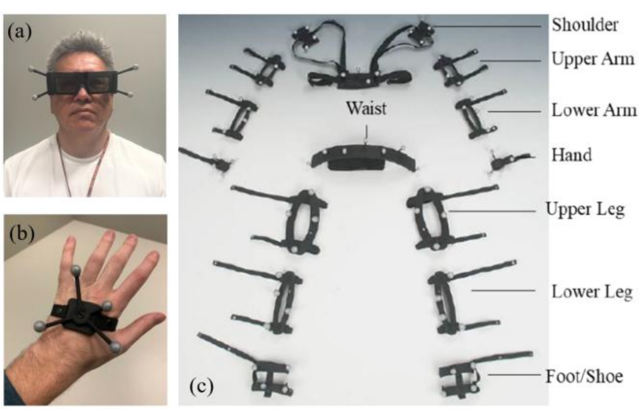

Figure 2. Motion tracking and visualization equipment: (a) Volfoni VR 3D glasses, (b) example marker cluster attachment on a participant, and (c) complete marker set diagram.

Participant movement was captured using an Advanced Realtime Tracking motion capture system installed in the VR Lab. Before each task, participants were fitted with marker clusters, as shown in Fig. 2(b), which were attached either over clothing or directly to relevant body locations depending on the tracking requirement. The marker configuration allowed multiple body regions to be monitored, including the shoulders or chest, upper arms, lower arms, hands, waist, upper legs, lower legs, and feet, as illustrated in Fig. 2(c). These motion data provide a basis for analyzing worker movement, posture, proximity to hazards, and behavioral responses.

B. Participant Task and Data Collection Flow

Participants first complete a study briefing, informed consent process, VR familiarization session, and system calibration. Each participant then enters an immersive construction scenario and receives a task instruction that reflects a realistic construction activity. During the task, a robot-related hazard event is introduced under controlled conditions. After the event, behavioral data are recorded and supplemented with post-scenario self-report measures. The participant is then debriefed before proceeding to the next scenario or experimental condition. This sequence can be repeated across multiple robot types, hazard conditions, or safety intervention designs. The structure allows each scenario to be evaluated in a consistent manner while still permitting variation in robot behavior, site layout, visibility, warning modality, and task demand. This repeatable structure is important because it allows researchers to compare worker responses across different hazard conditions and identify which design features may reduce unsafe behavior.

C. Worker Response Measures

The VR system captures both observable behavior and subjective perceptions. Behavioral measures in this study include reaction time, minimum distance to the robot, gaze direction, head orientation, path deviation, stopping behavior, hesitation, secondary hazard exposure, and task interruption. These measures can indicate whether the participant noticed the hazard, how quickly they responded, whether they maintained a safe distance, and whether their response created additional risk. Post-scenario questionnaires are used to collect self-reported measures such as perceived risk, trust in the robot, workload, comfort, warning clarity, and willingness to work in the same environment again. Combining behavioral and self-report data allows researchers to evaluate not only what participants did, but also how they interpreted the robot, the hazard, and the surrounding worksite conditions.

D. Safety Protocol Development

The main value of the framework is its ability to translate worker responses into actionable safety knowledge in a lower risk, simulated environment. For example, if participants consistently fail to notice a mobile robot approaching from a blind corner, the finding may support additional auditory cues, reduced robot speed, improved visual signaling, or changes to temporary site layout. If workers move backward when a drone approaches during work at height, the result may support minimum drone clearance distances near leading edges, scaffolds, or lifts. If participants reach across a collaborative robot's motion path, the observation may inform workspace boundaries, robot pause behaviors, or revised task sequencing. In this way, the VR framework can support the development of safety protocols before robots are deployed on active jobsites. Observed worker responses can also be used to refine exclusion zones, warning systems, robot navigation policies, speed limits, task procedures, and training materials. This makes the approach useful not only for identifying hazards, but also for evaluating whether proposed interventions are likely to improve worker safety.

III. ROBOTIC CONSTRUCTION HAZARD SCENARIOS

Each designed scenario includes a worker objective, a robot operation, a hazard trigger, and a response window. Once a hazard is triggered, the worker's response is recorded for later analysis.

A. *Scenario 1: Aerial Robot Proximity During Work*

This scenario, as shown in Fig. 3 (a), places a participant on an elevated work platform and asks them to perform a construction-related task while one or more drones circulate around the worksite. The drones may be used for inspection, mapping, or progress monitoring, but their movement occurs near the participant's work area. Over time, the working conditions can be slightly changed by adjusting drone proximity, flight path, speed, hover location, sound level, visibility, or warning cues. This allows the study to examine whether drone activity distracts the participant, interrupts task performance, or creates unsafe movement during work at height. The primary hazard in this scenario is not limited to direct drone collision. Instead, the focus is on how drone presence, sound, and unexpected movement may affect attention, balance, body movement, and situation awareness during an elevated task. Potential observations include whether the participant looks away from the work surface, pauses the task, steps backward or sideways, changes posture, loses awareness of platform boundaries, or reports discomfort at specific drone distances or motion patterns.

B. *Scenario 2: Demolition Robot Operation*

This scenario places a participant near a demolition robot performing tasks such as breaking up concrete, removing debris, or concrete chipping surfaces. The participant may be positioned as an inspector or nearby coordinator while the robot operates in the work area. The scenario, as shown in Fig. 3 (b), focuses on hazards that commonly occur during demolition activities, including robot arm swing, debris projection, dust, noise, blocked visibility, and restricted-zone violations. The VR environment can introduce different hazard events, such as roof collapse, floor collapse, debris movement, or the robot swinging toward the participant. These events allow researchers to observe whether participants maintain a safe distance, recognize the robot's operating boundary, react appropriately to sudden hazards, or unintentionally move into unsafe zones. This scenario is useful for evaluating whether workers understand demolition robot hazards and whether warning signs, exclusion zones, or verbal instructions are sufficient for safe coordination around heavy robotic equipment.

C. *Scenario 3: Autonomous Mobile Robot Navigation*

This scenario simulates the participant in a cluttered construction material logistics area with stacked drywall, pallets, conduit, rebar bundles, cords, hoses, tool carts, and unfinished corridors as shown in Fig. 3(c). The participant is asked to move between work zones while multiple autonomous material transport robots operate nearby. The robots may approach from behind, move toward the participant, cross the walking path, or emerge from blind corners. Their speed, approach direction, cargo size, and load visibility can be varied to create different levels of risk. This allows researchers to observe whether the participant stops, yields, changes route, accelerates, or enters a secondary hazard to avoid the robot. Findings can inform robot speed limits, right-of-way rules, path planning, cargo transport procedures, and warning-system placement.

(a)
(b)
(c)

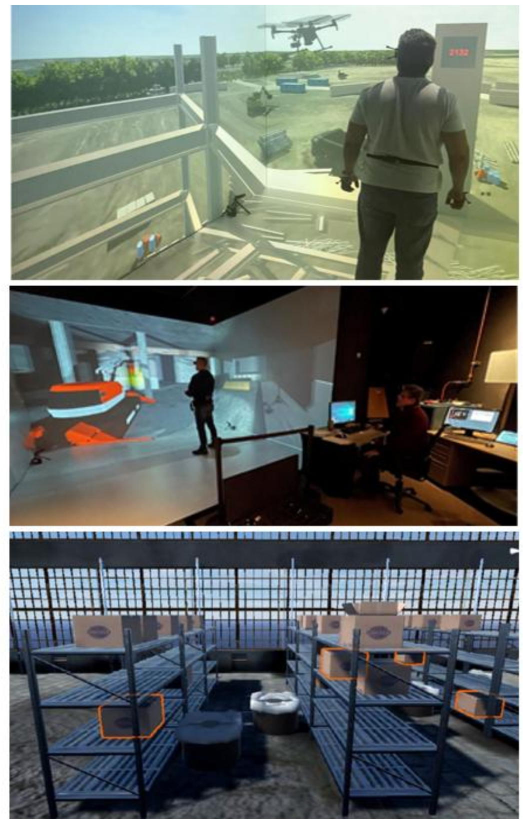

Figure 3. (a) Person working near drone in simulated environment. (b) Person interacting with demolition robot in the virtual construction environment. (c) Virtual environment with multiple material transporting robots moving around participant.

IV. CONSIDERATIONS AND EXPERIMENTAL OUTCOMES

Although the proposed scenarios represent different construction tasks and robotic systems, they provide a common basis for examining how workers perceive, interpret, and respond to robot-related hazards. The outcomes can support the development of safety protocols by identifying operating conditions that increase distraction, discomfort, delayed response, or unsafe movement. This section summarizes key study considerations and expected experimental outcomes across the drone, demolition robot, and mobile robot scenarios.

A. *Worker Distraction and Preparedness Around Drones*

The drone scenario examines how workers respond when aerial robots operate near an elevated work area. As drones approach the participant, workers may feel stressed, become distracted, or shift attention away from the assigned task. These responses are important because even brief distractions during work at height may increase the likelihood of unsafe movement, loss of balance, or reduced task accuracy. Experimental outcomes were evaluated by observing task correctness, task completion time, body movement, and self-reported discomfort under different drone operating conditions. Variables such as drone proximity, flight frequency, approach direction, hover duration, sound level, and participant familiarity with drones can be systematically adjusted. By comparing worker performance across these conditions, the study can help identify safe drone operating distances, appropriate inspection frequencies, and preparation or briefing requirements before drones are introduced near elevated workers.

B. *Hazard Preparedness During Demolition Robot Tasks*

The demolition robot scenario focuses on worker interaction with heavy robotic equipment during hazardous construction activities. Preliminary observations suggest that participants with prior experience playing similar computer games may operate the demolition robot more effectively, likely because they are more familiar with remote-control interfaces, spatial coordination, and camera-based navigation. This finding suggests that operator background and interface familiarity need to be considered when designing training protocols for remote robotic construction equipment. The scenario also allows participants to experience controlled demolition-related hazards, such as roof collapse, floor collapse, debris movement, or robot swing toward the worker. After repeated exposure to these controlled hazards, workers may show improved response rate, increased preparedness, and better anticipation of upcoming hazardous events. Experimental outcomes can include response time, correct avoidance behavior, control accuracy, collision frequency, and perceived readiness. These findings can inform training procedures, interface design, warning cues, and safe operating protocols for demolition robots.

C. *Safe Operating Conditions for Mobile Robots*

The mobile robot scenario evaluates how workers respond to autonomous material transport robots in cluttered construction environments. Participants may encounter robots approaching from behind, moving toward them, crossing their path, or carrying loads of different sizes at different speeds. Because workers may perceive risk differently, participants can show different psychometric responses to robot speed, cargo size, proximity, and approach direction.

In this study, 56 participants were recruited to evaluate these interactions. Despite individual differences, the experimental outcomes can help identify operating conditions that are more likely to reduce risk during worker-robot coexistence. For example, larger cargo sizes may require lower travel speeds or greater clearance distances, while faster robot movement may require earlier warning cues or more predictable paths. Fig. 4 illustrates the participant-robot separation distances recorded from two participants during the current study using the mobile-transport robots, which corresponds to the test conditions described in Fig. 3(c). In this scenario, each participant encountered two mobile robots while traveling between designated locations within the experimental environment. Measures such as yielding behavior, route deviation, stopping distance, minimum separation distance, near-miss events, and perceived risk can be used to relate safer operation to robot speed, cargo dimensions, and proximity. These results can inform practical guidelines for robot speed limits, cargo transport planning, right-of-way rules, and warning-system placement in construction sites.

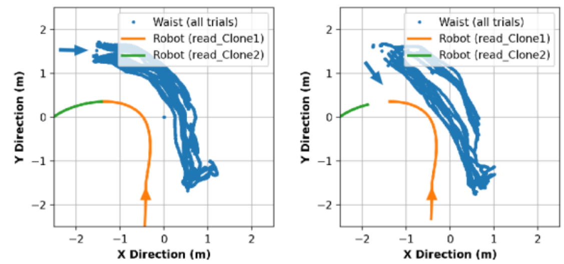

Figure 4. Relative positions of two participants and the moving mobile robots during the navigation scenario.

V. Conclusion

This paper presents immersive VR as an alternative, safe, and repeatable approach for evaluating construction worker responses to robot-related hazards. Three example simulations illustrate the ability to observe worker behavior under controlled hazardous conditions. The findings can inform future safety protocols, including clearance distances, speed limits, warning strategies, exclusion zones, and training requirements before robots are deployed on active construction sites.

Disclaimer

The findings and conclusions in this manuscript are those of the authors and do not necessarily represent the official position of NIOSH, CDC. Mention of any company or product does not constitute endorsement by NIOSH, CDC. Studies involving human participants were reviewed and approved by NIOSH's Institutional Review Board (protocol numbers 23-NIOSH-11 and 24-NIOSH-02).

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