Human Factors in the Demolition Robot Hazard Zone: A Multi-Factor Virtual Reality Investigation

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Abstract— **Demolition robots are increasingly adopted in the construction industry to remove operators from hazardous locations; however, the flexibility to operate these machines remotely may introduce a new hazard if operators position themselves within the robot's hazard zone. This paper presents the experimental setup and preliminary results of a National Institute for Occupational Safety and Health (NIOSH) project investigating the factors that may influence demolition robot operators in the selection of their working location, as well as human behavior and trust perception when unexpected robot motions occur. Data were collected in a Cave Automatic Virtual Environment (CAVE) immersive Virtual Reality Lab using N = 33 participants (approximately one third of the target sample). Study 1 examines operator separation distance from the robot across four demolition scenarios and three lighting conditions. Study 2 examines cognitive workload (NASA-TLX) and human-robot trust across three scenarios with varying exposure to unexpected robot motions. Preliminary results indicate that robot configuration height may influence operator positioning, with ground-level demolition producing the smallest separation distances. Trust declined significantly after operators experienced unexpected motions, regardless of their sequential order. This finding preliminarily supports the hypothesis that operators may incorrectly assume the robot moves only when commanded, contributing to misjudged hazard zone assessment. These findings have implications for the design of safer demolition robot interfaces and operator training protocols.**

I. Introduction

Demolition is an important part of construction; it involves dismantling, razing, wrecking, and removal of any building or structure, and thus it has hazards associated with it [1]. Traditionally, excavating machines have been used for demolition work. Among the most common hazards identified in demolition procedures are collapse of buildings, falling from heights, or being struck by falling objects or flying debris. Similarly, among the most common hazards posed by excavating machines include striking others, overturning and striking operator, or being struck by falling objects or flying debris [2]. Under the North American Industry Classification System, demolition contractors are included within NAICS 238910, Site Preparation Contractors. Among construction subsectors, Site Preparation Contractors had the highest number of caught-in/between fatalities during 2011–2015. Of those fatalities, 91.5 percent involved workers caught in or crushed by collapsing structures, equipment, or material [3]. Further, data from the Bureau of Labor Statistics (BLS) for excavating/loading machine operators reveal that between 2009 and 2018, there were 124 fatalities and 3,520 injuries involving days away from work for this occupation [4, 5]. More than a third (35.2% of fatalities and 37.9% of injuries) were caused by contact with objects or equipment.

To address these hazards, equipment manufacturers developed special types of machines known as demolition robots. A demolition robot resembles an excavating machine without a cab, is more compact—since it can fit through doorways and stairs—and provides more power. Importantly, demolition robots are operated through a cabled or wireless remote control, removing the operator from a hazardous location inside the machine. Paradoxically, the flexibility to operate the demolition robot from any external location could result in a new hazard if the operator locates him/herself within the demolition robot's hazard zone; that is, within a distance close enough to the machine where the operator could be struck, pinched, pinned or crushed by any part of the demolition robot. Market data from the Association for Advancing Automation (A3) indicate that demolition robots account for approximately 90% of all construction robots sold [6].

While current national surveillance databases do not specifically identify demolition robot-related incidents due to the lack of a classification code, in 2019 the Washington State Fatality Assessment and Control Evaluation (FACE) program issued a Hazard Alert when two workers in two separate accidents were severely injured while using demolition robots [7]. One operator was pinned between the outrigger and a wall after accidentally activating the remote control; the other operator had his foot crushed by the outrigger when it temporarily lost contact with the floor while the operator applied more pressure on the tip of the breaker. In both cases, the operators placed themselves in the hazard zone of the demolition robots. These two examples, along with the rapid incursion of demolition robots in the construction market, show the need for a systematic analysis of risk exposure among demolition robot operators and control measures to improve worker safety. Furthermore, despite the growth of demolition robot adoption, there is a lack of systematic studies of operator's location selection as well as perceived safety and trust in the robot.

This manuscript presents the experimental setup as well as preliminary results of a project being conducted by the National Institute for Occupational Safety and Health (NIOSH) to understand factors that may influence demolition robot operators in the selection of their working location.

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II. OJECTIVES

The project is comprised of two studies. The objectives of Study 1 are to explore human-related, environment-related, and control-pad interface related factors and how they may influence the selection of the demolition robot operator's working location. The objective of Study 2 is to investigate human behavior and perceptions of safety and trust of the operator when working with a demolition robot in the presence of unexpected events. The premise of Study 2 is that operators may assume the demolition robot will only move when commanded by the remote control. The main area of focus in this paper is discussing the experimental setup for the study and although early, preliminary data are shared.

III. METHODOLOGY

Data collection for both Study 1 and Study 2 is currently being conducted in NIOSH's Virtual Reality Lab in Morgantown, West Virginia. At the time of this paper, a third of the study population, i.e., 96 participants, has been completed. Therefore, the data presented in this paper consist of preliminary results to provide initial insight for consideration. Participants have included both males and females. Eligibility criteria include being greater than 18 years old and having some experience in the construction sector. Participants are being recruited from Morgantown, WV and the surrounding area. This study was reviewed and approved by the CDC NIOSH Institutional Review Board (IRB).[§]

A. VR Environment and Robot

The Virtual Reality Laboratory consists of a Cave Automatic Virtual Environment (CAVE) immersive display system used to present interactive virtual construction and/or demolition environments and task scenarios. 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 worker behavior in controlled realistic construction situations while avoiding direct interaction with actual demolition robots, and thus exposure to physical hazards.

The virtual environment developed for this study consists of an indoor demolition site and a virtual demolition robot, as shown in Figure 1. Participants control the virtual demolition robot with a wireless remote control.

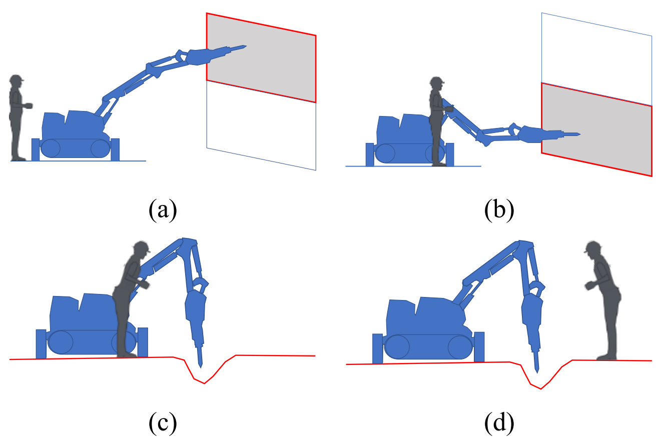
There are two main control modes: Player mode and Robot mode. In Player mode, participants can use the remote control to move around the virtual demolition robot and select their working location based on comfort level and the visibility conditions. In Robot mode, participants can use the remote control to operate the virtual demolition robot to complete the assigned demolition tasks. Participants also wear markers on each wrist and on their back to track their location in the virtual environment using a human motion capture system. The goggles and the remote control are also provided with markers to track their position inside the virtual environment at all times.

[§] See 45 C.F.R. part 46; 21 C.F.R. part 56.

Figure 1. View of the virtual indoor demolition site with the virtual demolition robot and a real human operator.

B. Conditions and Scenarios

In Study 1, participants are tasked with operating the demolition robot to conduct demolition work in four different scenarios and under three different lighting conditions. The four scenarios are shown in Figure 2 and consist of demolishing the upper half of a vertical wall, the lower half of a vertical wall, the ground in front of the robot, and the ground with the operator and the demolition robot facing each other. The three lighting conditions are good, medium, and poor lighting, as defined by OSHA recommendations [8].



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

Figure 2. Demolition scenarios for Study 1: a) Upper vertical, b) lower vertical, c) ground level, and d) ground level facing robot.

In Study 2, participants are tasked with demolishing a wall by removing specific blocks highlighted by the system. Specifically, they operate the various parts of the robot to place the end effector tool, i.e. a chipping hammer, against the highlighted block. Then, they activate the chipping hammer and in approximately 3 seconds, the block is removed. Right before the block disappears, a number is displayed for a fraction of a second. If the number is even, the participant has to acknowledge it by pressing a button on the right side of the remote control; conversely, if the number is odd, the participant should acknowledge it by pressing a button on the left side of the remote control. This odd/even number acknowledgement task serves as a distraction, adding a mental load to the participant.

There are three main scenarios. First, there is a baseline scenario in which participants conduct the demolition tasks and no unexpected motions occur. Upon completing the baseline scenario, participants are asked to complete two questionnaires: 1) A National Aeronautics and Space Administration (NASA) Task Load Index questionnaire [9], and 2) a Robot Trust questionnaire, to assess their workload level and their level of trust on the robot, respectively.

The second scenario presents the participants with four unexpected motions while conducting the demolition task, in the following order: First, when the participant is engaging the tool against a block, the outriggers of the robot lift momentarily and fall swiftly back to the floor. This condition happens when the robot is exerting excessive force against the wall and could crush the feet of the operator if they happen to be near one of these outriggers. The second unexpected motion consists of the robot's arm swinging rapidly towards the operator. This condition could happen if the operator accidentally pushes the joystick of the remote control, or if a hydraulic hose fails, and could strike the operator if positioned inside the hazard zone of the robot. The third unexpected motion represents the roof fall after being hit by the robot's arm. In this condition, the environment simulates various roof blocks falling on top of the virtual demolition robot which could crush the operator if he/she is located inside the robot's hazard zone. Finally, the fourth unexpected motion represents a partial floor collapse. This event causes the demolition robot to tilt towards the operator which could potentially injure the operator if he/she is located inside the robot's hazard zone. Upon completing the second scenario, participants are asked to fill in the NASA Task Load Index, and the Robot Trust questionnaires.

The third scenario presents the participants with the four types of unexpected motions in random order while conducting the demolition task. Upon completing the third scenario, participants are asked to fill in the NASA Task Load Index, and the Robot Trust questionnaires.

C. Participant Response Measures

Dependent variables measured in this project can be grouped into three categories: 1) Human motion behaviors, 2) performance, and 3) self-reported measures. Under human motion behaviors are the instantaneous position of participants in the virtual environment, and thus their separation distance from the virtual demolition robot. Performance is measured by counting the number of blocks removed per minute during the different scenarios and lighting conditions. Self-reported measures include the NASA Task Load Index and the Robot Trust questionnaire.

IV. PRELIMINARY RESULTS

The preliminary results presented in this section use 33 participants who completed both Study 1 and Study 2 (i.e., approximately a third of the intended study sample). The most important variable measured in Study 1 is the separation distance between the participants and the virtual demolition robot under each visibility scenario and lighting condition. Figure 3 shows four plots that represent the top view of the virtual environment with the virtual demolition robot. The red fan-shaped shaded area is the robot hazard zone; an area where the operator can get struck, hit, pinched, or crushed by any moving part of the demolition robot. The blue line represents the path that participants took to position themselves relative to the virtual demolition robot. The green triangle indicates the starting position for each scenario.

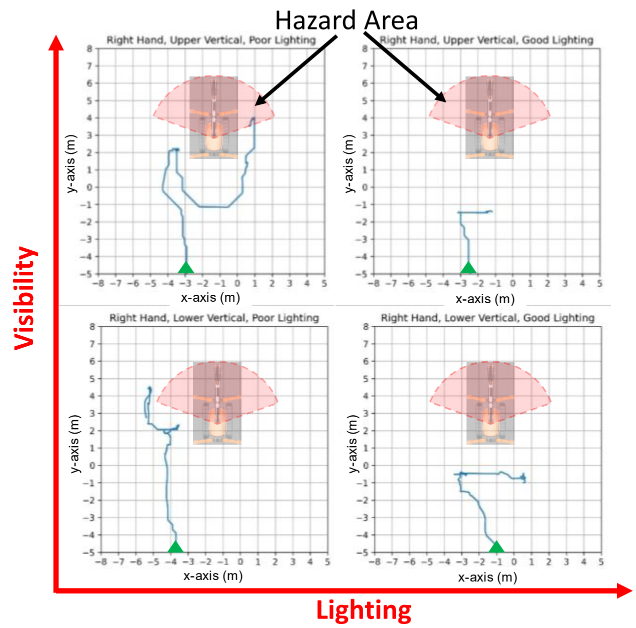


Figure 3. Typical top view maps showing the path of the human participants and their location relative to the virtual demolition robot.

Table I presents the descriptive statistics, i.e. mean ± standard deviation, for the mean separation distance in meters between the participant and the virtual demolition robot for the left-hand marker only.

Table I. Descriptive statistics for the mean separation distance in meters between the participants and the virtual demolition robot for the left-hand.

		Lighting Condition		
		Good	**Medium**	**Poor**
Visibility Scenario	**High Vertical**	4.021 ± 2.243	3.594 ± 1.863	3.193 ± 1.580
	Low Vertical	3.737 ± 2.215	3.291 ± 1.544	3.295 ± 1.797
	Ground Level	3.288 ± 1.528	2.965 ± 1.310	2.671 ± 1.266
	Facing Robot	3.512 ± 1.702	3.457 ± 2.099	3.575 ± 2.248

In terms of task performance, participants were grouped by age: < 24 years, 24-55 years, and >55 years of age. Figure 4 shows the performance results for these three groups.

Regarding self-reported measures, Table II presents descriptive statistics for the NASA-TLX weighted overall score and all six subscale ratings across the three scenarios. NASA-TLX scores range from 0 to 100, with 100 indicating higher perceived workload levels. Finally, regarding the Robot Trust questionnaire, Table III presents descriptive statistics for overall trust and the five hypothesis-relevant trust items.

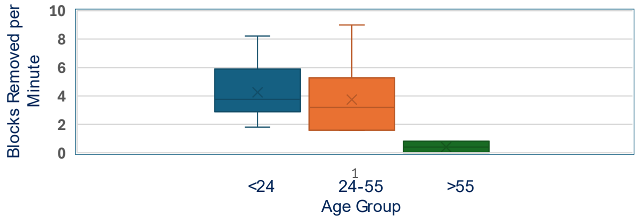


Figure 4. Performance results grouped by participant age.

Table II. NASA-TLX Descriptive Statistics (M ±SD).

Subscale	**S1: Baseline**	**S2: Ordered**	**S3: Random**
Overall (weighted)	53.74 ± 14.15	58.81 ± 17.32	56.92 ± 17.40
Mental Demand	49.24 ± 23.49	59.06 ± 23.57	55.15 ± 21.38
Physical Demand	15.76 ± 10.24	21.72 ± 19.45	22.58 ± 20.51
Temporal Demand	48.18 ± 22.07	49.38 ± 23.99	45.30 ± 25.18
Performance	54.70 ± 17.76	57.50 ± 21.18	53.48 ± 24.70
Effort	54.24 ± 18.92	65.47 ± 19.28	59.09 ± 23.63
Frustration	53.91 ± 25.77	61.88 ± 25.07	61.67 ± 26.97

Table III. Descriptive statistics (M ±SD) for the five most relevant factors of the Human-Robot Trust questionnaire.

Item	**S1: Baseline**	**S2: Ordered**	**S3: Random**
Trust Mean (all items)	56.47 ± 12.29	48.27 ± 15.46	47.17 ± 16.25
T02: Act consistently?	66.67 ± 19.15	49.39 ± 23.71	52.42 ± 23.85
T03: Reliable?	67.58 ± 22.22	48.48 ± 25.87	50.00 ± 25.12
T04: Predictable?	68.79 ± 20.27	43.03 ± 27.10	45.15 ± 23.86
T09: Have errors?	43.94 ± 23.97	54.24 ± 28.07	49.39 ± 27.72
T12: Malfunction?	31.82 ± 18.95	48.48 ± 26.12	44.55 ± 25.38

V. DISCUSSION

Across all conditions, preliminary results indicate that the Ground Level scenario consistently produced the smallest separation distances (range: 2.671–3.288 m), while the High Vertical scenario consistently produced the largest (range: 3.193–4.021 m), suggesting robot configuration height may influence how close operators position themselves regardless of lighting.

Although not initially anticipated, it is observed in the initial sample that older participants required more time to familiarize themselves with the various remote-control functions, and in general, remove fewer blocks than younger participants on average. This preliminary trend can be seen in Figure 4, which shows that the block removal rate decreases as the age of the participant increases. Participants were also asked if they have experience playing video games and if so, when was the last time they played a video game; the majority of the young participants reported playing a video game recently; thus, the effect of video game experience on performance will be further explored in the final study sample.

Table III shows that Trust declined following exposure to unexpected robot and structure motions. Importantly, trust did not differ significantly between Scenarios 2 and 3, indicating that a single exposure to unexpected robot motions — regardless of their sequential order — may reduce operator trust. This will also be further explored in the final study sample.

VI. CONCLUSION

This paper presents a brief overview of the experimental setup and some preliminary data of a project being conducted by NIOSH to understand factors that may influence operators of demolition robots in the selection of their working location, as well as human behaviors and perceptions of trust on the demolition robot when unexpected events occur.

It was observed from the preliminary data that when conducting demolition work at ground level, operators tend to locate closer to the demolition robot than when conducting upper vertical wall demolition. Regarding the trust of the operator towards the demolition robot, it was observed that trust declined substantially when unexpected events occurred.

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DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the U.S. Centers of Disease Control and Prevention or the National Institute for Occupational Safety and Health.

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