Feedback System for Enhancing Human-Robot Interaction Performance in Construction Robots

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ABSTRACT

Many fatal incidents in the construction project occur during the earthmoving phase. Teleoperation has been a promising solution for such dangerous tasks since this method can remove humans from hazardous workplaces. Although humans are not on the jobsite for safety reasons, teleoperation requires human-in-the-loop automation, so humans need to robustly operate the construction robot at a distance. Operating equipment from a distance often reduces task performance and safety performance since spatial awareness of human operators is restricted compared to onboarding control. It is an important issue since the decisions and actions taken by operators directly affect the performance of construction robots. This study proposes the use of a feedback system for the teleoperation of construction robots to improve proximity sensing of risks and improve the human operator's understanding of obstacles in the workplace where robots are used. The proposed teleoperation feedback system is validated with a human subject experiment in the virtual environment. This research will contribute to the body of knowledge on improving teleoperation, human operators' spatial awareness, and human-robot interaction task performance.

INTRODUCTION

Teleoperation is one type of human-in-the-loop automation that requires human operators to understand the workplace and control the robot end-effector at a distance via information feedback interfaces and control interfaces (Lee et al. 2022). Human operators are the final decision makers who gather information, process information, generate plans, and execute the robot's end effectors' movement via interfaces in teleoperation. In this way, humans are able to operate in complex situations without being physically exposed to dangerous workplaces and avoid fatal injuries to human workers. However, conducting tasks with the teleoperation of excavators is not always simple. Sometimes delicate control is required when excavating the soil around obstacles. Avoiding these obstacles is crucial in construction in terms of safety, time, and cost. An excavator hitting underground utilities, for example, would result in fatal injuries to the workers around the site, delays in the schedule due to time lost on repairs and halted operations, and increased costs due to repairs and indirect costs (Liu et al. 2022). Since the excavator is a heavy machine, even a single hit can result in fatalities or damage to properties and their associated infrastructure system network. Prior studies point out that limited awareness of the surrounding environment of the distanced excavator in teleoperation could make operators, especially novices, find it challenging to control the end effector delicately in the difficult task. Consequently, it is imperative to enhance the situational awareness of the operator of the teleoperation excavator, in particular with regard to proximity sensing to avoid obstacles.

In the case of on-boarding excavator control, operators utilize their senses including hearing, vision, vibration, and touch for understanding the environment and control the excavator. However, teleoperators generally perceive the environment primarily using visual cues, which differs significantly from what they might experience during onboarding. It is known that the lack of telepresence or situational awareness leads to inaccurate control and poor excavation performance. Thus, enhancing telepresence or situational awareness is crucial in the teleoperation of excavators. The term “telepresence” is defined as the experience of being present at a distant location (Hosseini and Lienkamp 2016; Sheridan 1992).

The purpose of the study is to propose a system that provides distance information on obstacles that should not be hit by excavators during teleoperation tasks to operators. The system provides real-time proximity sensing with electro-tactile feedback to enhance the operator's awareness of their proximity, telepresence, and situational awareness in teleoperation. The pilot test result shows that this system helps to enhance situational awareness and human-robot interaction safety performance, even in the high stressed situation. The paper is organized as follows. The background section provides an overview of related works and gaps in knowledge. In the methodology section, a detailed description of the proposed method is provided. In the result section, the results of the experiments are discussed. Finally, the conclusion section outlines the findings of this study along with the discussion.

BACKGROUND

Teleoperation in construction. There has been extensive interest in the automation of construction robots recently to avoid fatal accidents to human workers on hazardous construction sites. Fully automated construction robots have been studied with simple or repetitive construction tasks, however, there is still long way to go to solely rely on fully autonomous robots for unrepetitive, unique, difficult tasks considering the current technology limitations. The automated task should be done in the order of understanding the working environment in real-time with sensors, understanding the planned task, considering options, and executing the best options possible. However, there are still technical challenges in gathering and processing such information and producing the optimal decision in terms of data transmission from one to another in dynamic and challenging construction tasks in real-time. For example, the excavator's task and working environment are dynamic in comparison to that of robotic bricklayers and factors to be taken into account are changing, which causes the computation cost to be much higher than that of bricklayer robots. In addition, more reliable excavator movement algorithms for the task are required in dynamic situations in terms of accuracy and safety. Thus, still, humans need to be in the loop of the construction automation system.

Proximity sensing and information feedback. Prior studies have been conducted regarding how to support humans by providing additional information that assists in preventing collisions. For proximity sensing, the radio frequency identification (RFID) sensor (Jo et al. 2017), wireless magnetic sensors (Kim et al. 2022; Teizer 2015), pose estimation with 2D cameras (Wen et al. 2023), and the Unmanned Aerial Vehicle (UAV) assisted method (Kim et al. 2019) were employed in order to detect hazards surrounding the excavator and prevent the collisions or accidents. For visual information feedback for excavator operators, a visual assistant with geospatial augmented reality with the approximate location of buried utilities (Su et al. 2013), 3D excavation model guidance based on Ground Penetrating Radar (GPR) data to prevent utility strike (Tanoli et al. 2019), and visual annotation by highlighting obstacles in adverse weather condition during teleoperation of excavator (Hong et al. 2020), and vibrotactile force feedback system (Nagano et al. 2020) have been conducted. In short, existing studies have obtained distance information to obstacles, especially invisible underground utilities, and excavators in the field and virtual environments in various ways, and other parts of studies have developed systems that provide the information that can help such operators on interfaces.

Gaps in knowledge. In spite of the fact that previous research has developed applications regarding obstacle avoidance, it would be beneficial to go a little further than simply verifying that the information provided is of sufficient quality or that it is delivered effectively to users in non-stressed conditions. The excavation working environment is dynamic and challenging since there are obstacles around the excavator and these might in real-time or require a high cognitive load for some tasks. Therefore, it is necessary to confirm that the information can be properly accepted by human operators and check whether operators are in good hands even in a high-stress environment (Lee and Ham 2022a).

Goal of this study. Visual assistance could lead operator's visual cognitive overload during dexterous excavation tasks, audio cues can be diminished because of the noisy surroundings, and the vibrotactile interface could lead to micro mis-control which could lead to an accident. To develop an interface that minimizes the limitation, this study proposes an electro-tactile feedback system for proximity sensing, while validating the effectiveness of this system in highly stressful situations for the operators, which is known to be high time pressure.

METHODOLOGY

Proximity sensation feedback system. In this study, we employed transcutaneous electrical stimulation to provide sensory feedback to the operator. The ulnar nerve was stimulated with a frequency inversely proportional to the distance between the excavator bucket and underground utilities. This means that the frequency increases as the bucket approaches the buried utility line and decreases as the bucket moves away from it. Therefore, it was designed to allow the participant to feel more frequent pulsing prior to the collision and within a certain distance, as well as buzzing when the bucket and utility collided. The stimulation was conducted based on the real-time distance data from the virtual excavation environment and determined amplitude and frequency range for each participant (Figure 1). Virtual excavation model has been used to see excavator operator's performance in various studies (Lee and Ham 2022b, Liu and Ham 2022) To determine the range of the amplitude (V) and frequency (Hz) for each participant, the amplitude (V) and frequency (Hz) values were tested before the experiment.

Range of amplitude and frequency. Since each individual has a different resistance value, the amplitude and frequency must be adjusted accordingly. Amplitude (V) determines the intensity of stimulation, and frequency (Hz) determines the period of stimulation for each participant. In this experiment, the current was controlled by the DC Power Supply at a constant of 0.06A to ensure the participants' safety. Initially, the amplitude range was adjusted with the frequency set to 10 Hz. A starting point of 5V was used as the basis for the range of amplitude, and the intensity of stimulation was gradually increased by 0.5V. The range of amplitude for each participant was determined by two points. The first point is the amplitude point at which a participant's first experience of a stimulus occurs at a certain amplitude, the second point is the point at which the participant feels uncomfortable about proceeding with the experiment because of the strong intensity of the stimulus. The mean of the two amplitude points was used both in finding the frequency range and in the experiment. For example, if a participant first felt stimulation at 10V and discomfort at 20V while checking by raising 0.5V, 15V was applied to experimental conditions. Then, based on the amplitude for each participant, the frequency range was found for each participant. The reason for determining the frequency range is due to the fact that there is no pulsing when the frequency exceeds a certain level, but only buzzing when it exceeds that level. The aim is to determine the frequency of the buzzing and make this frequency when there is a collision. The lowest frequency value was given equally to all participants as 10Hz. The frequency was increased from 10 Hz by + 5 Hz in order to achieve the maximum buzzing sensation for each participant, where they felt more buzzing than pulsing for the first time. If a participant felt buzzing at 50 Hz for the first time, in that person's experiment, a stimulation frequency of 50 Hz was given when a collision occurred.

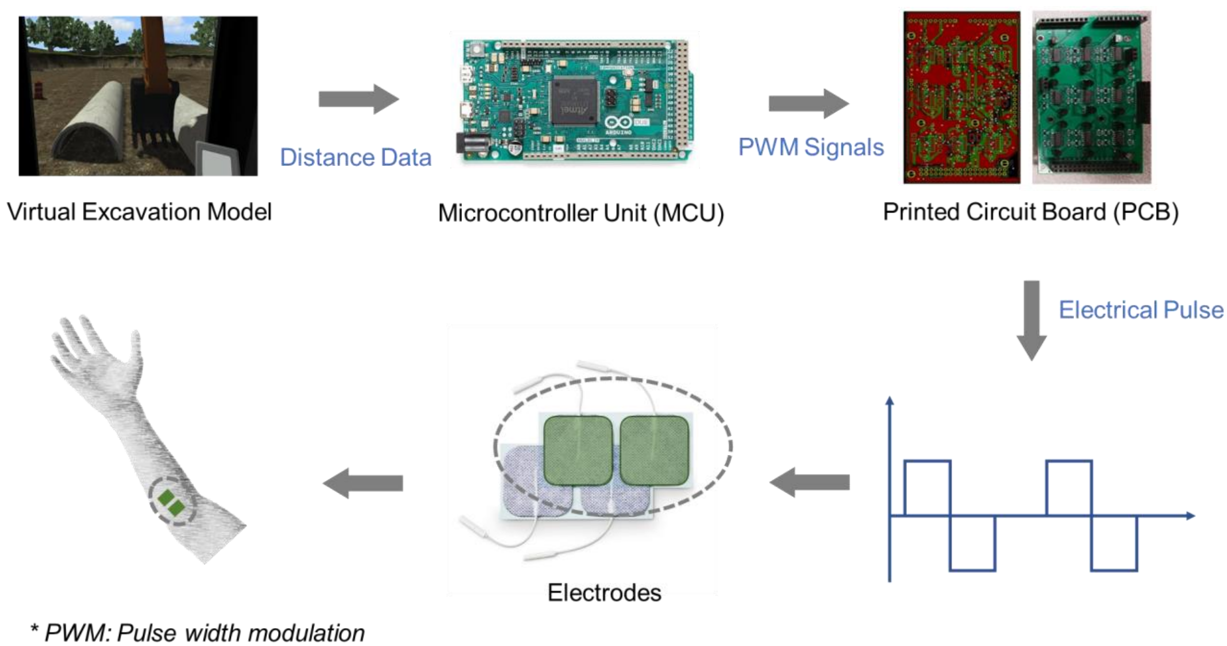

Figure 1. Configuration of the electro-tactile feedback system.

Location for proximity sensation feedback. The stimulation was applied to the ulnar nerve near the right elbow of the participants. Our team conducted a pilot experiment to test stimulating nerves located near the fingers or hands as well. Some participants have noted, however, that these stimuli interfere with and affect the control of the joysticks, which are the control interface for excavator teleoperation. As a result, the elbow was determined to be the location for stimulation (Figure 1).

Participants. This study focuses on novice operators who are known to have more safety accidents as compared to the experts. Thus, we collected the data from 19 healthy students at

Texas A&M University majoring in construction-related fields (e.g., Construction Science, Civil Engineering, Architecture) and who passed the qualification test. All of the participants had less than two years of work experience in the construction industry and no experience operating any kind of construction equipment, including excavators.

Qualification test. Before the experiment, there was a qualification test to ensure they were eligible for the main experiment. Through pilot tests, we confirmed that if the participant fails the test, their data shows that they make too many errors during the experiment, which cannot be used for analysis. All of the participants in this experiment passed the qualification test and conducted the main experiment. There are eight directions for controlling the two joysticks. Participants were asked to control the joystick based on the manager's direction in the qualification test. If a participant could control the joystick without making any single mistake 15 times in a row, they were considered "qualified." It was considered a failure when they make a single mistake on one test. They had ten chances to take the qualification test. When the participant failed ten times, they were considered not eligible for the experiment.

Experimental procedure. After passing the qualification test, participants were asked to answer their backgrounds (e.g., age, major, experience) in the pre-test survey session. As part of the guidance and training sessions, safety guidelines were provided during excavations, and the participants had the opportunity to practice operating excavators with two joysticks on their own. There were two groups in this study, the non-electro-tactile group and the electro-tactile group. Each group consisted of three participants. The non-electro-tactile group did not use an electro-tactile proximity sensing system when the task was performed. For the electro-tactile group, they used an electro-tactile proximity sensing system during their task. After the task, there was a post-test survey and interviews to see how the participants actually thought about the experiment and the proposed system.

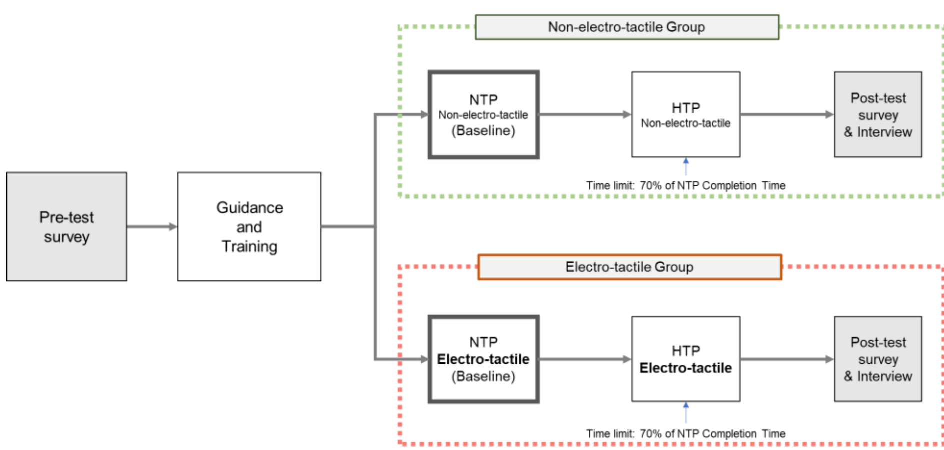

Figure 2. Experimental procedure.

Task design. Each participant was assigned the excavation task. They were asked to 1) dig soil between the two concrete pipes and not hit them, 2) dump soil on the left side of the excavator, 3) do this a total of 5 times, 4) dump a minimum of 8 tons of soil in the dumping area at the end (Figure 3), and if there is a time pressure, 5) finish the task within the time limit. Based on the completion time of the No Time Pressure (NTP) session, the time limit for the High Time Pressure (HTP) session was determined. For the HTP session, 70% of the completion time of NTP was assigned for the time goal (Lee and Ham 2022b). For example, if a participant completed the NTP task within 300 seconds, they were instructed to complete the HTP task within 210 seconds. In time pressure sessions, the time pressure was given verbally if the participant was behind schedule, for example, "Hurry up!", "You are late!", and "You are behind schedule". There are ways to give time pressure by showing the remaining time on the screen, verbal expression, or sound alert. Pilot test results, however, indicate that verbal expression is the most effective method for expressing time pressure in this experimental setting.

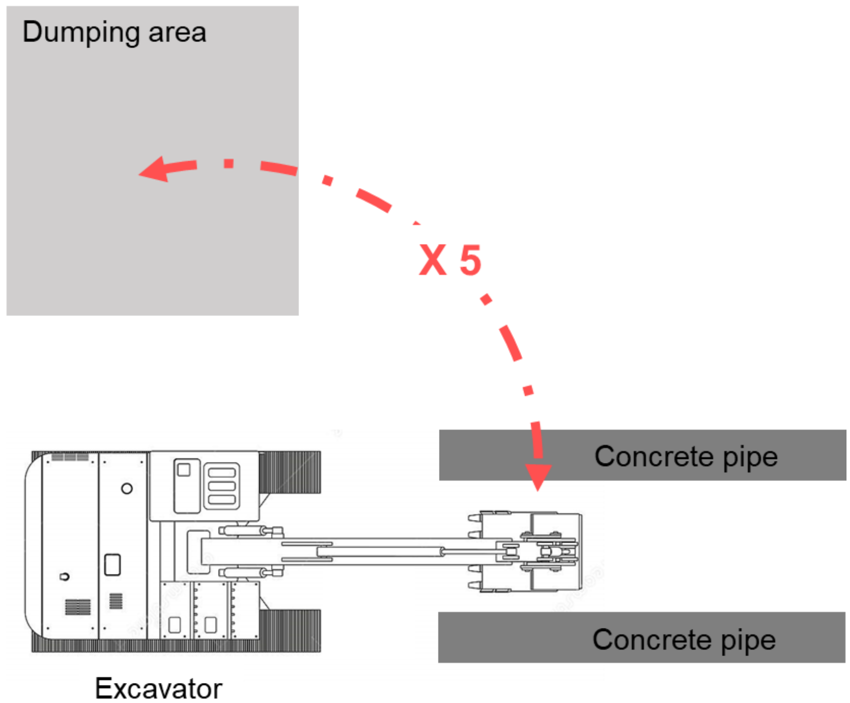

Figure 3. Excavation Task during the Experiment.

Performance metrics. Our study focuses on the performance of avoiding collisions since the proposed feedback system enhances spatial awareness and proximity sensing. Thus, there were four main performance metrics used in this experiment: the number of collisions, the total duration of the collisions, the average duration of the collisions, and the collision time per minute. In addition, the proximity sensing ability has been rated in both non-electro-tactile and electro-tactile groups.

Statistical analysis. The effectiveness of the feedback system was evaluated by comparing the means of the performance metrics for each group, as there were a limited number of participants for this experiment.

EXPERIMENTAL RESULTS

Number of Collisions. Once the task (5 times of digging and dumping) is done, the total number of collisions was measured. The decreased number of collisions means that smaller areas of utility line were damaged during the task, resulting in improved safety for human-robot interaction performance during teleoperation. Non-electro-tactile participants ($M_{NET\_NTP\_CN}$ = 10.00) exhibited around three times more collisions than the electro-tactile participants ($M_{ET\_NTP\_CN}$ = 3.50) during NTP sessions. Furthermore, non-electro-tactile participants

($M_{NET\_HTP\_CN}$ = 19.33) exhibited around three times more collisions than the electro-tactile participants ($M_{ET\_HTP\_CN}$ = 6.50) during HTP sessions (Table 1).

Table 1. Collision numbers.

Time Pressure	Device	N	*Mean (N)*	*SD*
No	Non-ET	9	10.00	10.28
	Electro-tactile	10	3.50	4.84
High	Non-ET	9	19.33	20.99
	Electro-tactile	10	6.50	7.93

Total duration of the collisions. In view of the weight of excavator buckets, continuous hitting or collision for a prolonged period of time can result in significant damage to underground utilities. Thus, after each task, the duration of the total collision was recorded. The result shows that there was a drastically decreased in overall collision duration with the existence of the proposed feedback system. During NTP sessions, electro-tactile participants ($M_{ET\_NTP\_CT}$ = 2.19) exhibited more than three times less duration than non-electro-tactile participants ($M_{NET\_NTP\_CT}$ = 7.27). It was found that electro-tactile participants ($M_{ET\_HTP\_CT}$ = 3.50) displayed nearly three times less duration than non-electro-tactile participants ($M_{NET\_HTP\_CT}$ = 11.54) during HTP sessions (Table 2).

Table 2. Duration of collisions.

Time Pressure	Device	N	*Mean (N)*	*SD*
No	Non-ET	9	7.27	11.72
	Electro-tactile	10	2.19	2.83
High	Non-ET	9	11.54	13.51
	Electro-tactile	10	3.50	4.31

Average duration per collision. This measure shows the recovery ability during the collision. The less average duration of collisions indicates that the participant tried to retract the excavator bucket from the underground utilities as quickly as possible in case of collision. Electro-tactile participants ($M_{ET\_NTP\_TC}$ = 0.44) exhibited nearly 20% shorter average collision durations than non-electro-tactile participants ($M_{NET\_NTP\_TC}$ = 0.61) during NTP sessions. As compared to non-electro-tactile participants ($M_{NET\_HTP\_TC}$ = 0.60), electro-tactile participants ($M_{ET\_HTP\_TC}$ = 0.58) demonstrated that there was no big difference between the two conditions in the HTP. Based on this result, we can conclude that our system assists participants to get out of collisions as quickly as possible when they occur in the NTP (Table 3).

Table 3. Average duration per collision.

Time Pressure	Device	N	*Mean (N)*	*SD*
No	Non-ET	9	0.61	0.36
	Electro-tactile	10	0.44	0.50
High	Non-ET	9	0.60	0.36
	Electro-tactile	10	0.58	0.49

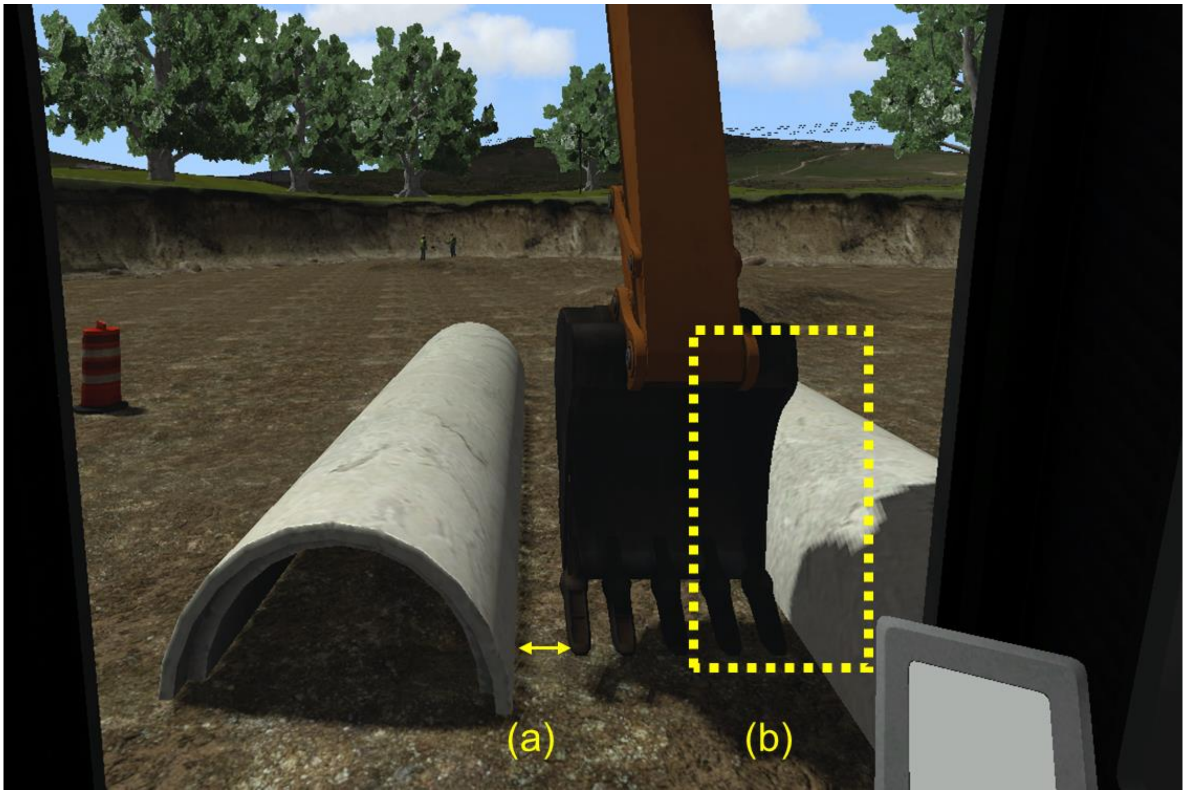

Figure 4. Distance in (a) visible area (b) blind area.

DISCUSSION AND CONCLUSION

In this paper, we developed an intuitive interface while increasing the situational awareness of human operators. We found that the proposed electro-tactile interface is superior to the non-electro-tactile environment based on collision-related performance metrics. Also, the electro-tactile feedback system lowered not only the number of collisions but also the collision duration even in the presence of high time pressure where human operators were highly stressed. According to the interviews of the participants, it was said that the proximity sensing ability was improved compared to the environment without the feedback system. In particular, as shown in Figure 5, it is said to be more effective because proximity sensing can be performed not only to the visible area but also to the blinded area. Overall, this system provided intuitive distance information feedback to human operators without increasing their cognitive load. In future studies, it will be necessary to conduct experiments with an increased number of participants and to conduct verification in a variety of aspects.

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