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Tactile-based wearable system for improved hazard perception of worker and equipment collision

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ABSTRACT

Although past studies investigated automated hazard-identification methods, few explored workers' awareness capabilities for detected hazards. Recent research identified that workers have difficulty becoming aware of potential risks in harsh construction environments (limited vision and hearing). In response, this study investigated a new communication method with a wearable tactile-based system to improve worker's hazard perception. Built on past research, we identified key informational details to represent detected safety hazards, developed a tactile-based communication mechanism, and conducted a series of field trials. Results were assessed to determine the system's reliability with respect to several scenarios, conducted in a controlled environment for safety reasons. Test results demonstrated that the system is capable of alerting workers of pre-identified collision hazards without relying on their innate sensing (hearing and vision). Findings could help workers to become aware of detected hazards in harsh environments, where it is difficult to hear alerts or spot potential hazards.

1. Introduction

The construction industry accounts for a high proportion of worker fatalities among private industries in the United States, and the fatal four (i.e., falls, struck-by, caught-in/between, and electrocutions) are responsible for 60% of the total fatalities [1]. Among the fatal four, one of the most common causes of these fatalities is workers being struck by objects or vehicles [1]. At workplaces involving multiple workers on foot, along with equipment/vehicles, there is always the risk of collisions, causing injuries and fatalities, due to their working at close proximity. Statistics from 2011 to 2015 [2] show a total of 804 worker fatalities from being struck by accident. Out of those fatalities, 384 (48%) were the result of being struck by vehicles. A large proportion of those fatalities (220 of 384, or approx. 57%) were due to vehicle collisions occurring in construction sites, specifically resulting from forward-moving or backing-up vehicles [2]. Such fatalities highlight the need for preventive measures to save lives. Accordingly, the National Institute for Occupational Safety and Health (NIOSH) [3] has offered various preventive measures, such as: proper site layout; safe operation of equipment and vehicles around workers in construction sites by ensuring visual contact with workers on foot; implementation of a comprehensive safety program; and the use of sensing technology to detect workers on foot around equipment/vehicles. Despite such measures to prevent collision hazards, the statistics show that there has not been a significant improvement in construction safety.

For the prevention of collisions between workers and construction equipment, it is important that any potential collision be detected as early as possible, so that the possibility of an accident may be eliminated by taking proper measures. This means that collision prevention is a two-step process: 1) early detection of potentially risky proximity between workers and equipment; and 2) action taken to prevent a collision. Collision prevention is possible only if the two steps are taken in time. After the successful detection of a hazard in the first step, workers must become aware of the detected information to proceed with the second step. In other words, even though hazards are detected by sensing technologies, these detections are useless if the involved parties are not aware of the detected hazards, as they cannot take any preemptive actions. On this account, it is imperative to effectively warn the workers or equipment operators of potential hazards that are identified by in-place detection systems. A timely warning to workers of potential collisions can provide an additional safety buffer for workers. In the last decade, researchers have conducted several studies on both the detection and prevention of collision accidents.

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2. Studies related to proximity detection and warning

For proximity detection, researchers have demonstrated the capability of various sensing technologies, such as Bluetooth-low energy [4–8], radio frequency identification (RFID) [9], ultra-wideband [10–14], and global positioning systems [15]. Teizer and Cheng [16] proposed an automated approach to determine proximity hazards for the prevention of struck-by events at construction sites. Wang and Razavi [17] demonstrated the use of a global positioning system-aided inertial navigation system sensor for the detection of potential collision accidents with high accuracy. Park et al. [18] proposed the proximity detection of workers and equipment by using Bluetooth-based sensing technology to be used in roadway work zones. Their system was capable of detecting the proximity of workers at different pre-defined distances from equipment; however, the alert distances were not consistent in different directions. Later, the researchers [4] demonstrated an improvement in the performance of their proximity sensing system in dynamic conditions (i.e., moving vehicles and workers). Baek and Choi [7] demonstrated a similar application of a Bluetooth-based proximity system to detect collisions in underground work.

Similarly, Shen et al. [19] suggested a methodology to specify hazardous zones around different pieces of construction equipment. The allocation of such a hazard zone around construction equipment prevents workers from getting in close proximity to those pieces of equipment by improving their hazard awareness. In a recent study, Jo et al. [11] integrated a radio frequency, computer vision, ultra-wideband sensing system, and global positioning system to develop a collision prevention system, which is capable of automatically stopping the equipment on detection of a potential collision. A different study [20] used visuals from the cameras on heavy equipment to detect potential collisions between workers and the equipment, and devised an automated visual-based warning system. Similarly, Kim et al. [21] demonstrated the application of unmanned aerial vehicles for detecting possible collision accidents.

Beyond accident detection, recent studies explored methods of predicting accidents with real-time data from different technologies. One study [14] predicted possible accidents by using an ultra-wideband sensing technology and predicting the future location of the equipment. Further, other researchers [22,23] have proposed similar approaches, using site images and videos, for predicting the positions of workers and equipment to predict potential collision hazards. These studies about prediction techniques could contribute to providing additional time for preventive actions, compared with only detecting potential accidents.

Besides proximity detection and prediction, another important topic of study is to send warning signals to workers so that they are aware of the safety situations around them. On this account, researchers have implemented several approaches using mobile devices to generate warning signals in construction sites. Specifically to prevent collisions due to close proximity between workers and heavy construction equipment, researchers have used a radio frequency-based proximity sensing system to avoid potential worker-equipment collisions using audio and visual alerts [9,24,25]. The Bluetooth-based proximity sensing and warning system proposed by Park et al. [18] was capable of sending real-time warning signals to both workers and equipment operators through smartphones. Luo et al. [26] tested personalized auditory-verbal signals to warn workers of different hazard scenarios that are identified based on location tracking. Similarly, Kim et al. [27] proposed a wearable system based on augmented reality to alert workers of the orientation and distance of the potential hazards, as well as the level of safety.

Although these studies provided improvements in hazard awareness of workers, their applications suffer three drawbacks: 1) it requires workers to spend additional time looking around to analyze the situation before taking preventive actions. This can be a significant problem because a fraction of a second can spell the difference between life and death; 2) it requires additional devices to be carried, with some level of exposure from the body to hear sounds from the device or to see the visual warnings; and 3) it has not overcome the challenges resulting from harsh construction environments. Further, workers often fail to perceive alerts in the forms of beeping sounds and flashing lights. When alerts are generated, they have to reach individual workers by traveling through the air, but this is challenging at construction sites. In many cases, sound alerts suffer from noise interruption when traveling to workers, and visual alerts fail if workers' visual attentions are placed elsewhere because they are focused on their work or looking elsewhere. This is one of the core factors that comprise the underpinnings of this research, where we develop a technology to overcome this challenge.

Construction sites, especially roadway work zones, present considerably harsh working environments due to: 1) noise generated from traffic and construction activities; 2) workers' limited vision and hearing while on task; 3) night-time work; 4) workers' focus on construction tasks. These environments often cause challenges for workers to perceive warning signals. Concerning the ineffectiveness of warning signals, two studies [28,29] have tested various commercially available roadway safety systems and analyzed their warning capabilities. Unfortunately, it was identified that most of the audio and visual-based warning systems are inefficient; that is, they often fail to alert workers in harsh construction environments due to various reasons, such as: alarms not being loud enough compared to the noise level in the work zone; frequent false alarms; and insufficient reaction time for workers [28,29]. However, none of the studies have adequately focused on the effects of the adverse nature of construction sites, which are known to degrade/impair workers' senses.

In response to the problem of worker hazard perception, Cho and Park [30] developed a tactile-based communication system that used the sense of touch as the medium to communicate with humans. As such, this system is devised to eliminate the problems of hazard information traveling from the source point (i.e., hazard) to the destination (i.e., worker) by directly communicating the information to workers via tactile signals. This research conducted lab experimentations to identify basic tactile signal units to develop a tactile-based language for efficient communication [30,31] and demonstrated the potential application of their system for construction workers. Thus, the researchers identified eight distinct signal units, based on three signal parameters: signal duration, signal intensity, and signal delay. Those signal units were found to be easily distinguishable by the human sense of touch, and could be used as basic signal units to form a complete tactile-based language for communicating different information to workers, as deemed necessary. Further, the authors' team conducted an experimental study [32] to design the system configuration of a prototype tactile wearable system for effective signal communication to workers. This system configuration study focused on determining the number of motors, the optimum spacing between the motors, and their best configuration in order for this information to be used in a wearable system to ensure that signals from each motor are easily perceivable. Accordingly, the authors determined the number of motors based on potential essential information related to a general hazard situation, and conducted a series of experiments to test signal perception accuracy from individual motors at different motor spacings for different motor configurations. Finally, the study [32] identified a 4-2-4 arrangement of ten vibration motors at the spacing of 3 in. in a wearable system to be the most effective in terms of individual motor signal perception.

Taking advantage of such a tactile-based sensory system [32], the authors investigate a communication mechanism of this tactile system to alert workers of potential collision hazards in construction sites with informational signals. Note that this research focuses on the communication mechanism and workers' improved awareness, but it does not conduct a separate sensing research study to detect hazardous safety situations, which have been well covered by past research. In doing so, this research uses available data from past research to formulate messages to be delivered to test subjects. The capability to communicate such informational signals would enable workers to react promptly without requiring to spend time analyzing the situation or surrounding. Such performance of the tactile-based system has been demonstrated by Cho and Park [30] in an experimental study in which test participants were able to avoid potential hit by a ball thrown at them, entirely depending on the tactile signals. As such, this mode of communication overcomes most of the limitations of past studies and ultimately assists in enhancing the safety of workers from potential collisions with construction equipment. Therefore, in this study, the authors focused on developing a tactile-based communication method using the wearable system configuration developed from the past study [32], and demonstrating the feasibility and effectiveness of this system in communicating pre-identified collision-related hazard information to workers through a tactile-based language.

3. Research objective and scope

This research aims to develop a communication method of the tactile-based communication system that can help workers become aware of potential collision hazards, and to evaluate the system in terms of workers' abilities to understand its message in an environment where their vision and hearing are limited. Successful research can contribute to protecting the lives of construction workers on foot from collision accidents in construction sites by improving their hazard awareness/perception. For this purpose, the authors intend to inform the workers of any detected potential hazards promptly, so that they have sufficient time to take preventive measures and stay safe. As such, it is necessary to have a reliable means to communicate such information to workers. Thus, this study uses a tactile-based wearable system, previously developed by the authors' team [32], as the means of construction-hazard communication. This wearable system utilizes the human sensation of touch as a medium to communicate through vibration signals on the workers' backs. Using this system, this study devises a tactile-based language that is capable of transmitting collision-related hazard information to on-foot workers. To accomplish this, the authors have identified the need to proceed with the following specific tasks gradually:

1. To identify the crucial information to represent a potential collision hazard for effective communication with workers;
2. To determine an effective way to transmit vibration signals that include all identified information, using the tactile-based wearable system;
3. To determine the reliability of the hazard communication system through a series of field trials.

As discussed, this study focuses on a communication method for robust hazard awareness/perception, rather than developing hazard detection systems, which past research has predominantly explored. Therefore, this study assumes that the potential hazards are already detected by existing detection systems, and leverages the pre-identified information available from such detection systems for hazard communication to workers for improving their hazard perception capabilities. As such, the detection of collision hazards will not be discussed in this paper.

4. Research methodology

This section discusses the general framework of the tactile-based hazard communication system and the methodology adopted to accomplish the research objectives, followed by a detailed explanation of each step undertaken.

4.1. System overview

The tactile-based communication system in this study uses an optimized sensor configuration with ten vibration motors attached to a waist belt in a 4-2-4 configuration [32]. For reliable communication, motors should be placed at a location of the body where there are minimal physical interactions because physical interactions can cause difficulty for workers to sense tactile signals upon activation. To address this challenge, this system uses the workers' backs, as backs remain still even when workers are moving, and the effectiveness of using the back for perceiving tactile signals has been demonstrated by other studies [33,34] as well. To further improve workers' perceptions through their backs, the authors use a waist belt to firmly attach tactile sensors directly to test participants' backs, so that they can sense the tactile signals regardless of their movement and posture. Further, the vibration signal profiles are created using easily perceivable vibration signal strengths and durations, as identified by past research [30]. Workers are required to wear this system around their waist, on top of a thin layer of cloth, such that the vibration sensors are located on and firmly attached to their backs, symmetrically about the spinal line. Such use of the vibration sensors on the workers' backs has minimal signal perception interference due to their motion. Note that this prototype system uses a waist belt, as the system is still in development. After a full validation of system performance, it could be more effectively designed as a wearable vest.

Fig. 1 illustrates the framework of the tactile-based hazard communication system. The tactile system components, as well as a worker equipped with the system, are also shown in the figure. Upon the detection of a hazard by an in-place hazard detection system, information related to this hazard is available. To send this information, the developed tactile communication system consists of a server and wearable vibration motors. The server of the developed system (i.e., Communication Server in Fig. 1) can wirelessly receive information from detection systems employed in construction sites and relay it to individual workers by giving them hazard messages through vibrations. On perceiving the transmitted signals, the workers react to avoid potential risks. It should be noted that none of the components of this communication system needs to be installed on the equipment.

4.2. Development of system communication

In order to communicate hazard information using a tactile-based wearable system, it is a prerequisite to identify the essential information required to represent specific hazard scenarios. Such information, when transmitted to workers, should be able to describe the potential hazard scenario as precisely as possible, requiring minimum effort by the concerned workers. Thus, this method requires a careful selection of the vibration signal profiles for the communication purpose. Well-communicated information will enable the workers to become aware of the possibility of being caught in risks and take measures to avoid such risks. Thus, this research is designed as a three-step study, as shown in Fig. 2. The following sections explain these steps in detail:

4.2.1. Step 1: information to represent potential collision scenario

As the information transmitted to workers should be a good representation of the potential hazard scenario, this study determined the information to represent collision hazards based on past research and its findings regarding available information about construction collision accidents. Researchers identified that the distance between workers and construction equipment is a measure to determine whether the workers are safe or not [19,20,27]. Accordingly, researchers have attempted to keep workers at safe distances from equipment in various ways. Shen et al. [19] conducted a study to specify hazard zones around construction equipment and warn workers to avoid those zones. Other researchers [18,20] differentiated the distances between workers and equipment into different alert zones to indicate different levels of risk to workers.

To estimate a potential collision scenario, researchers have also accounted for the relative locations of construction equipment with

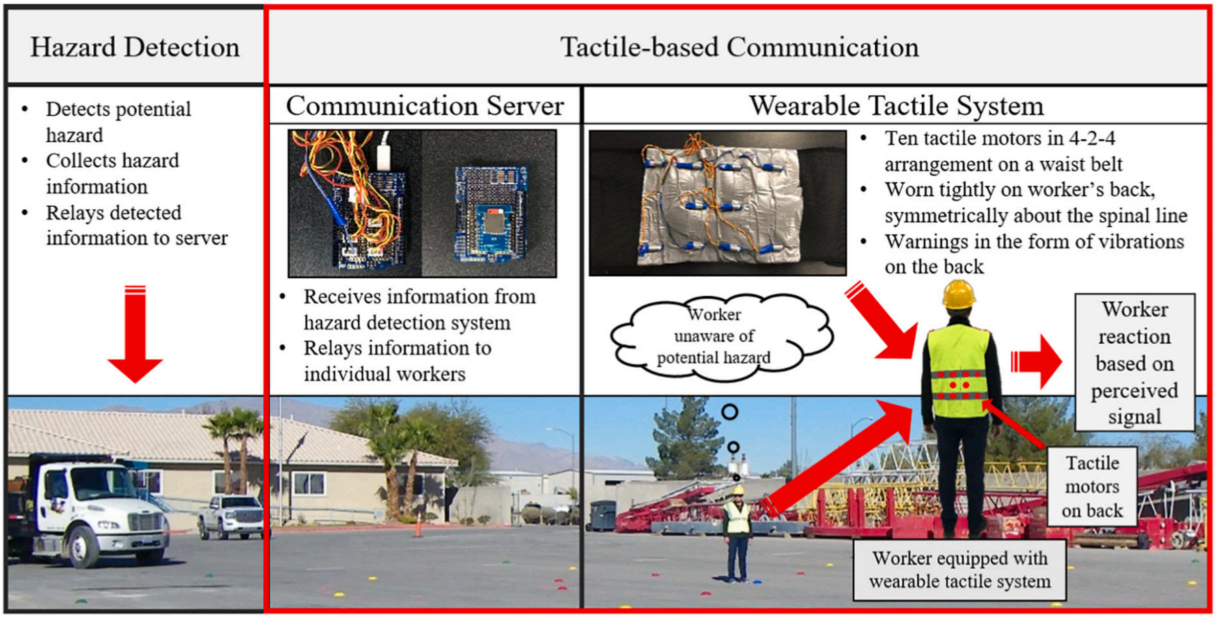


Fig. 1. Framework for tactile-based hazard communication system.

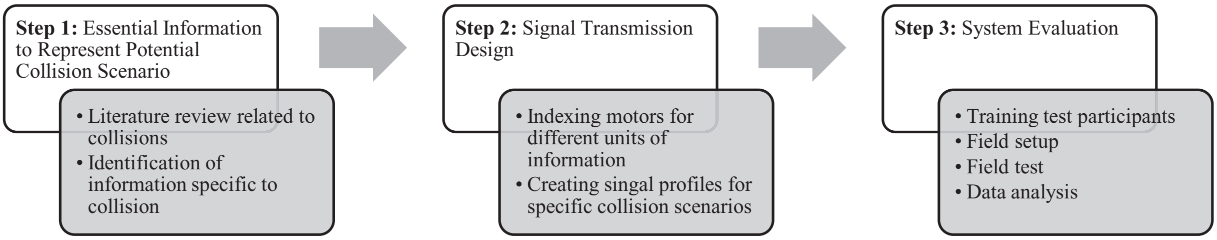


Fig. 2. Research methodology.

respect to workers' positions [18,27,35]. Knowing such relative locations enable workers to locate the approaching direction of construction equipment. In addition, the equipment velocity could be an important piece of information; however, exact and reliable information of equipment velocity is not available from existing research or currently available commercial collision prevention technologies. Further, the use of speed information as a communication parameter would require workers to spend time analyzing the risks before taking preventive actions. Such delayed response could result in insufficient reaction time. As such, speed information is not used in this research. However, the system can introduce additional tactile signals to include this information, if necessary. Besides, workers have to deal with specific construction equipment in construction sites. Such equipment could be a piece of fast-moving equipment on wheels such as a truck, or slower equipment. Statistics from 2011 to 2015 show that 29% of worker fatalities due to struck-by vehicles were due to trucks [2], and other pieces of equipment are responsible for a low proportion of fatalities. As such, knowing the type of construction equipment posing a risk will benefit workers, as it will allow them to intuitively have a good idea about the potential hazard.

Therefore, this study identified three essential pieces of information to represent a potential collision between workers and construction equipment: 1) the relative location of construction equipment (with respect to worker position); 2) the level of hazard (based on the distance between the worker and equipment); and 3) the type of equipment. Accordingly, these three pieces of information were used for the tactile-based communication of potential collisions in this study. With this information communicated, workers will be able to visualize the situation and take preventive actions as required. Details on this information, as adopted in this study, are explained in the following sub-sections:

i. Relative location of construction equipment

For the relative location of the construction equipment with respect to the worker's position, this study considered eight relative locations, each at 45° in the horizontal plane around the workers, as in the study by Park et al. [18]. For ease of communication, these relative locations are named Front (F), Back (B), Left (L), Right (R), Front Left (FL), Front Right (FR), Back Left (BL), and Back Right (BR), as shown in Fig. 3. This information would assist workers in locating approaching equipment around them.

ii. Level of hazard

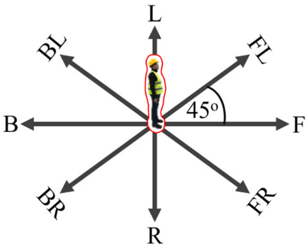


Fig. 3. Relative location.

The work zone around the worker is trisected with concentric circular boundaries of radii of four meters, eight meters, and 12 m to indicate a high hazard, moderate hazard, and low hazard zones, respectively, following similar test setups by other researchers [4,18,20]. These values are not fixed, as they are modifiable as needed per work characteristics, such as the types and speeds of vehicles/equipment operating in the work zone. With this zone information, as shown in Fig. 4, workers will know the approximate distance of the construction equipment from their positions.

iii. Type of construction equipment

Construction workers often work as a team, so they have specific construction equipment working in the team. As such, receiving information about specific equipment intuitively gives workers a considerable amount of information about the potential collision. Thus, the authors included a dump truck as one piece of equipment, considering the risk posed by trucks in the case of collision accidents [2]. Besides, the authors selected a wheel loader based on its confirmed availability for the field trials, in which potential hazard scenarios are simulated. Thus, expandable signal profiles were developed to include construction equipment information. These expandable signals can be used to indicate more than two pieces of equipment, if required.

4.2.2. *Step 2: signal transmission design*

In this step, the authors focused on devising the signal profiles for the effective communication of the hazard information, specified in *Step 1*, through the system with ten vibration motors (i.e., M1 to M10) arranged in a 4-2-4 layout, as shown in Fig. 5. For this purpose, the first step is to select the intensity and duration for unit signals that are combined to form a complete signal profile with desired hazard information. With trials from different participants, it was identified that the signal intensity of 2.5 V was easily perceivable while using the system on top of a thin inner cloth. Similarly, the minimum signal duration of 100 milliseconds and a delay of 50 milliseconds between consecutive signals were selected for the signal profiles.

After identifying unit signal properties, the next step is to define the signal profiles. Here it should be noted that these signals must be easily understandable with minimum effort to learn. One way to create such easily perceivable signal profiles with multiple information is to index different motors to indicate different information. This means that different motors vibrate to communicate different units of information, and this helps to create easily distinguishable signal profiles. In a previous study [36], it was determined that arranging the motors around the body of a person to indicate directions was effective in delivering directional information. However, in the case of this study, the vibration motors are arranged in a back-array method. Thus, for the ease of identifying relative location information, eight motors on the top and bottom rows (four on each row) were indexed in such a way that workers could easily detect the intended location of the construction equipment, based on the position of the vibrating motors on their backs. Similarly, two motors on the middle row were indexed to represent each piece of equipment, i.e., the wheel loader (E1) and dump truck (E2). However, it should be noted that these motors, E1 and E2, can be used to create distinct vibration patterns to indicate different types of equipment, allowing this system to incorporate more equipment, if necessary. Fig. 6 shows the motors indexed to represent different relative locations and equipment types. Motors M1, M4, M7, and M10 were indexed as Front Left, Front Right, Back Left, and Back Right locations, respectively. Similarly, motor pairs M2-M3, M8-M9, M1-M7, and M4-M10 were indexed as Front, Back, Left, and Right locations, respectively. Motors M5 and M6 were indexed to represent two pieces of equipment, E1 and E2.

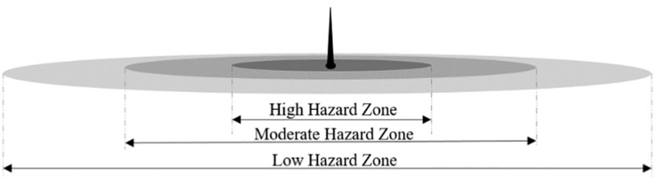


Fig. 4. Hazard level.

For communication of the hazard level, instead of indexing motors, the researchers used different vibration patterns for the motors that represent the relative locations. For the ease of distinction between different hazard levels, different vibration patterns were constructed with a different number of vibrations of respective motors. Accordingly, to indicate low, medium, and high hazard levels, the motors indexed to transmit relative-location information vibrated one time, two times, and three times, respectively. As an example, the vibration signals to represent a piece of equipment detected in a medium hazard zone behind a worker would have two vibrations of the two motors M8 and M9. Similarly, three vibrations of motor M1 would indicate a vehicle approaching from Front Left in a high hazard zone. Fig. 7 gives a pictorial representation of these vibration patterns for a vehicle approaching from relative location “Front Left.”

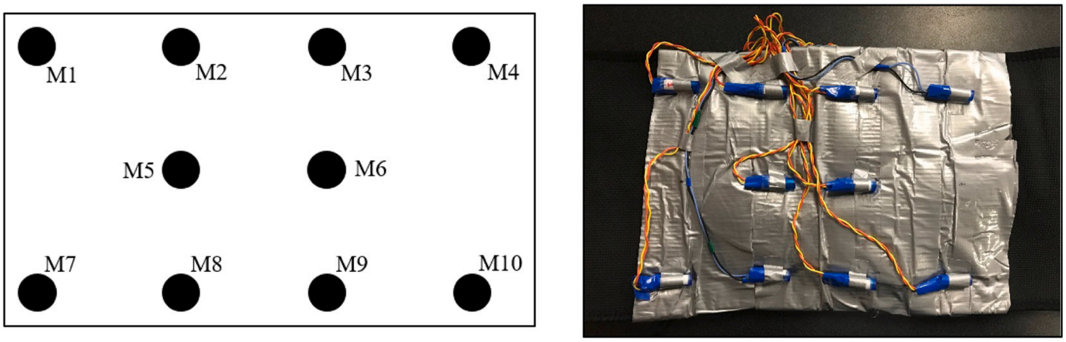
Accordingly, different signal profiles were created to represent different collision scenarios by combining unit signals from the indexed vibration motors. While communicating all three pieces of information at a time, the order of motor vibration in each signal profile followed: 1) the vibration of motors representing equipment type (i.e., motors in the 2nd row); and 2) the vibration of motors representing the relative location of the equipment; along with 3) the hazard level (i.e., motors in the 1st and/or 3rd rows). As such, the vibration occurs in two stages, i.e., the vibration of motors in the 2nd row (1st stage vibration) followed by vibration of motors in the 1st and (or) 3rd rows (2nd stage vibration), as shown in Fig. 6. Fig. 8 illustrates a pictorial view of sample signal profiles with different hazard levels.

4.2.3. *Step 3: system evaluation*

This step evaluated the wearable system in terms of its capability to transmit perceivable hazard information to workers. Thus, after finalizing the signal profiles for communicating potential collision hazards, a series of three field trials were conducted for the system evaluation. The following sections explain this step in detail:

i. Training test participants

As this is a safety application, becoming familiar with the system via training was necessary. Despite requiring different efforts to become familiar with the system, the experiments conducted in the past study [32] demonstrate that equally trained individuals do not present significant differences in perceiving signals from the tactile sensors. Accordingly, before the actual field trials, all participants were equally trained to recognize the information transmitted through different signal profiles, as designed for the field trials, in a laboratory setting. During the training, the participants were required to state the perceived hazard information for each transmitted tactile signal. They were further instructed to make specific move-away movements towards a safe zone to prevent potential collision with equipment, based on the perceived hazard signals during the field trials. The safe zones indicated by the shaded area in Fig. 9 lie on either side of the line along the direction of the approaching equipment, as indicated by the relative-location information of the equipment (shown in Fig. 3) on the transmitted signal. In addition to knowing the exact meaning of each vibration signal, such pre-instructions allow the participants to react as soon as they perceive the transmitted information without any delay. The training was conducted for five consecutive days, which helped the test participants to familiarize themselves with the vibration patterns corresponding to different hazard messages, and corresponding preventive actions



(a) Theoretical Arrangement

(a) Actual Arrangement

Fig. 5. 4-2-4 arrangement of vibration motors [32].

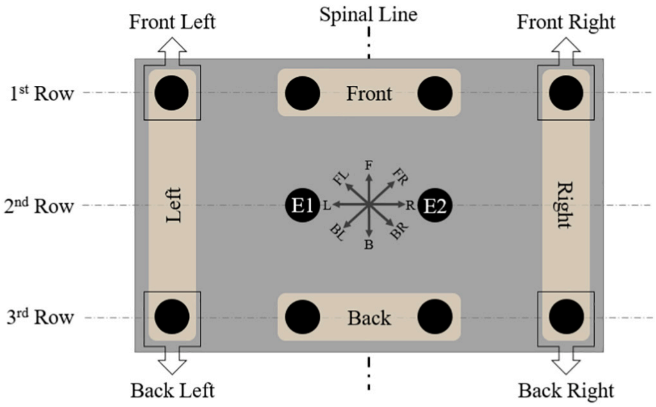


Fig. 6. Motor indexing for relative-location and equipment-type information.

following the perceived information. Thus, the training process accustomed the participants to the wearable system and the vibration signals.

ii. Field setup

The field trials were conducted in collaboration with a local contractor, Las Vegas Paving Corporation. Fig. 10 shows the site layout for the field trials. The field setup had the hazard zones marked by drawing concentric circles of radii of four meters, eight meters, and 12 m around the centrally located test participant, using markers of different colors. Red markers were used to indicate a high hazard zone; while yellow markers were used to indicate a medium hazard zone; and green markers were used to indicate a low hazard zone. The field trials involved five test participants (one female and four males), all of whom were familiar with the tactile-based communication system. The authors ensured that none of the participants had participated in earlier tactile-

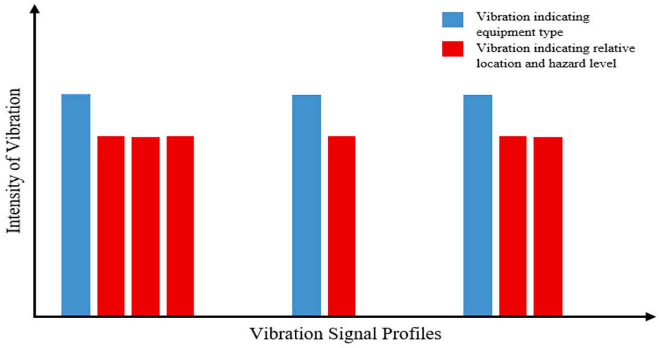


Fig. 8. Sample signal profiles.

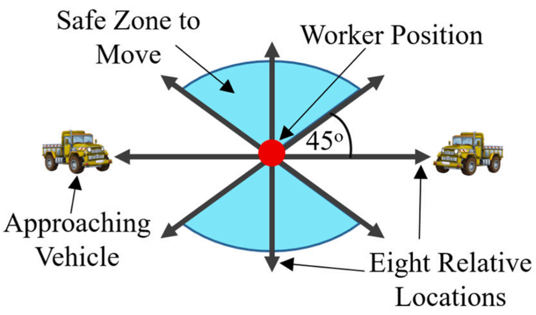
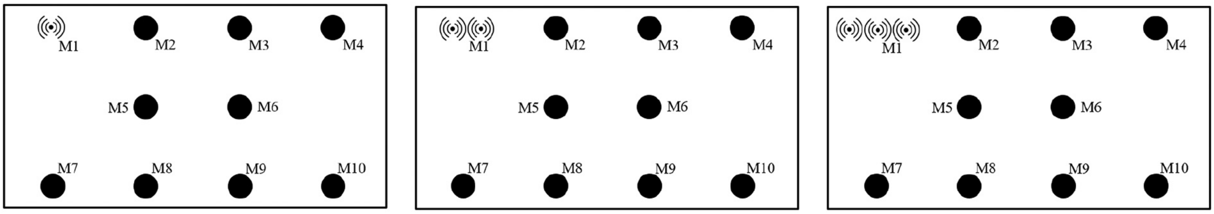


Fig. 9. Safe move-away zone.



(a) Low Hazard (M1 Vibrates Once)

(b) Medium Hazard (M1 Vibrates Twice)

(c) High Hazard (M1 Vibrates Thrice)

Fig. 7. Vibration patterns for a vehicle approaching from front left.

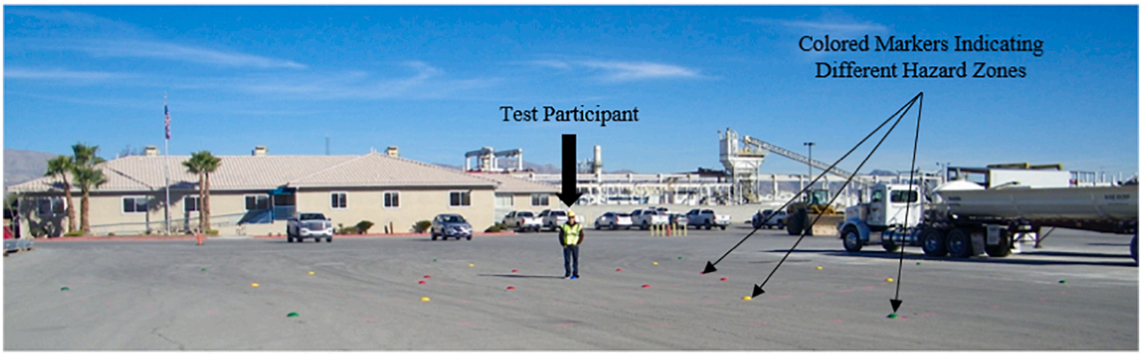


Fig. 10. Site layout for field trials.

related studies conducted by the research team.

iii. Field trials

During the field trials, the test participants were equipped with personal protective equipment (PPE) along with the communication system. To evaluate the system's communication capability in a condition where workers are unable to use their vision or hearing for potential hazard perception due to obstructed vision and loud noise, each participant's eyes and ears were covered. Such a field-testing scenario ensured that the participants could only rely on the tactile signals to perceive the situation, which enabled testing of the system for truly evaluating the test participants' perception in an environment where other senses are limited. Then each test participant was placed at the center of the marked zone, and a dump truck and a wheel loader approached towards the static test participant. It should be noted that the participants were static (i.e., not involved in any activities) and facing towards a fixed direction in a given test trial; however, their facing direction was varied to simulate different vehicle approaching directions corresponding to different warning signals. The researchers ensured that the approaching equipment and test participants were at safe distances at all times during the experiments to ensure a completely safe test environment. On receiving vibration signals, the test participants made specific move-away movements to a safe zone (Fig. 9), as pre-instructed during the training sessions.

The research team conducted three different tests, which were designed to explore the participant's perception ability as the amount of information communicated to the participant by the system increased. All of these field trials were conducted with the same site layout and the same testing procedure, i.e., a vehicle approaching the participant, as shown in Fig. 11. These tests are explained in the following sections:

Test 1: Relative location only

In this test, the participants were given signals with only the relative-location information of the approaching equipment, as shown in Fig. 12 (a). On receiving the signals, the participants moved away from their original location to avoid the potential collision accident, and then stated the information they received.

Test 2: Relative location and level of hazard

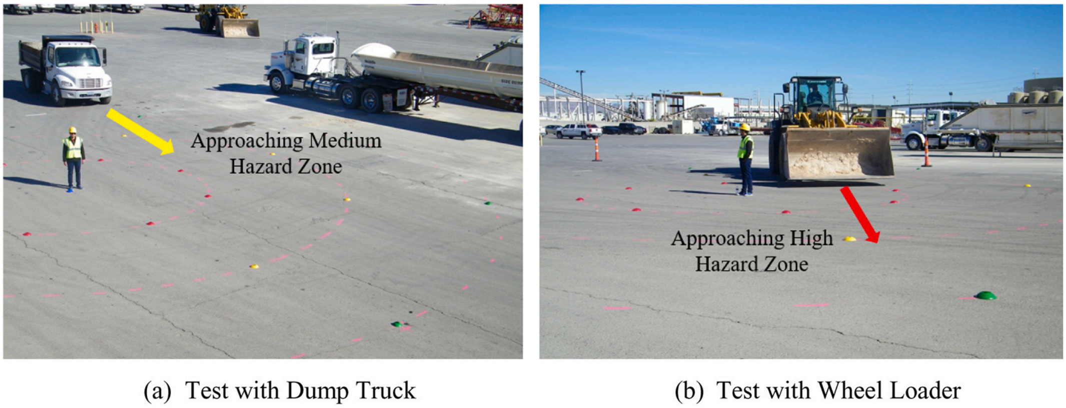
In this test, the participants received signals containing information related to the relative location of the equipment, as well as the level of hazard (indicating how close the equipment was to the participant, based on the markers). Fig. 12(b) gives a pictorial representation of the information communicated in this test. The reactions of the participants were the same as in the previous test.

Test 3: Relative location, level of hazard, and type of equipment

In this test, signals with information related to the relative location of the equipment, level of hazard, and type of approaching equipment (i.e., dump truck or wheel loader) were transmitted to participants, and they reacted similarly to the previous tests. Fig. 12(c) illustrates the information communicated in this test.

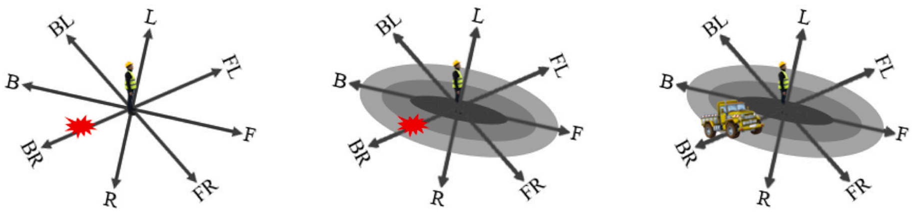
5. Results

During each field test, 250 vibration signal profiles were communicated to each participant (i.e., 250 signals × 5 participants × 3 tests = 3750 signals used in field tests). In Test 1, the participants were only sent the signals with the relative location of the approaching construction equipment, while in Test 2, the relative location of the approaching



(a) Test with Dump Truck
(b) Test with Wheel Loader

Fig. 11. Field trials.



(a) Test 1 (b) Test 2 (c) Test 3

Fig. 12. Pictorial representation of information communicated in field tests.

equipment, as well as the hazard level, were communicated. Thus, in these two tests, the vibration motors on the first and third rows, as seen in Fig. 6, were used for the communication. In the third test, the vibration signals included all three pieces of information representing a potential collision scenario. Thus, the participants received vibration signals from all motors in the third test. In order to minimize the learning effect due to similar signals during field trials, each field test was pre-planned in such a way that the consecutive sets of signals received by the participants did not resemble similar hazard situations, and each participant received the same set of 250 signals. In all test cases, signal transmissions were made to be received by the participants in less than one second, and the participants were quick enough to take move-away actions to avoid the approaching equipment in all test scenarios, which is similar to the findings of a past study [30]. After the move-away actions, each participant stated the signals that they perceived.

5.1. Overall field test results

Table 1 shows a summary of the results for the three field tests. For Test 1, the results show that the participants were able to correctly identify most of the vibration signals transmitted to communicate the relative location of the approaching construction equipment. Out of 1250 vibration signals transmitted in Test 1, the participants were able to correctly identify 1239 signals (i.e., 99.12% accuracy). For Test 2, the average accuracy for all participants was 98.64%, with 22 incorrect identifications out of 1250 signals. Similarly, the average accuracy for all participants was 94.64% for the third test. The decrease in perception accuracy from Test 1 to Test 3 was within our expectation as the tests became more complex by including more information from Test 1 to Test 3.

The test results presented in Table 1 are based on the correct identification of each piece of information transmitted through vibration signal profiles to the test participants. This means that the incorrect identification of any one of the information would categorize the result as incorrect. These results demonstrate that there was a decrease in signal perception accuracy with the increase in the amount of information transmitted to the test participants from Test 1 to Test 3 (i.e., one piece of information in Test 1 to three pieces of information in Test 3).

5.2. Perception accuracy of individual information

Among the pieces of information transmitted, there were eight different relative locations, three hazard levels, and two types of equipment. In order to determine the impact of such variation in the total amount of information transmitted to participants on correctly identifying said transmitted information, the authors determined participants' accuracy of identifying individual pieces of information transmitted through the vibration signals for Test 2 and Test 3. In Test 2, the vibration signals transmitted to each participant consisted of 250 pieces of relative-location information and 250 pieces of hazard-level information. Similarly, in Test 3, each participant received 250 signals for each of the three pieces of information. Thus, the researchers determined the amount of correctly identified information out of 250 signals for each piece of information transmitted (i.e., separately for 1) relative location, 2) hazard level, and 3) equipment type), and then calculated the perception accuracy for individual pieces of information, for each participant. The results for individual information perception accuracy for Test 2 and Test 3 are summarized in Table 2 and Table 3, respectively.

The results for Test 2 presented in Table 2 show a slight decrease in test participants' accuracy of identifying relative locations, in comparison to hazard level information. Similarly, in the case of Test 3 (Table 3), there was a gradual decline in perception accuracy between the equipment type, hazard level, and relative location of construction equipment (i.e., 99.04%, 98.08%, and 97.52%, respectively). These results indicate that the total amount of information is a factor responsible for determining the perception accuracy of the vibration signals.

Fig. 13 summarizes the incorrect identification of all three types of information transmitted in the three tests by all test participants. On close inspection of these incorrect perceptions, the results presented in Fig. 13(a) show that the majority of inaccuracies in the relative location of construction equipment were between BR and R, FL and L, FR and R, L and FL, and R and FR (see these locations in Fig. 3). As these locations are close to one another, such inaccuracies had less impact on undertaking move-away actions within the safe zone that is marked by the blue region in Fig. 9. Further, Fig. 13(b) shows the wrong identification of hazard levels between H1 and H2, and between H2 and H3. Similar to the impact due to incorrect identification of relative locations, such incorrect hazard level perception did not influence the move-away actions.

Table 1
Summary of field test results.

Test participants	Signals transmitted in each test	Accuracy of signal perception		
		Test 1	Test 2	Test 3
1	250	100.00%	98.80%	95.60%
2	250	98.00%	98.80%	95.20%
3	250	99.60%	98.80%	94.80%
4	250	98.40%	98.00%	90.80%
5	250	99.60%	98.80%	96.80%
Average accuracy		**99.12%**	**98.64%**	**94.64%**

Table 2
Communicated information perception accuracy for Test 2.

Test participants	Relative location	Hazard level
1	99.60%	99.20%
2	98.80%	100.00%
3	99.60%	99.20%
4	98.80%	99.20%
5	99.60%	99.20%
Average accuracy	**99.28%**	**99.36%**

Table 3
Communicated information perception accuracy for Test 3.

Test participants	Relative location	Hazard level	Equipment type
1	99.20%	98.40%	100.00%
2	97.60%	99.20%	99.60%
3	96.40%	98.40%	100.00%
4	96.80%	98.80%	97.20%
5	99.20%	97.60%	100.00%
Average accuracy	**97.52%**	**98.08%**	**99.04%**

5.3. *Statistical analysis*

For the statistical validation of these test results, which represent Bernoulli Trials [37], the researchers conducted the significance test by computing the 95% confidence interval for the probability of correct signal perception. Eqs. (1) and (2) were used to compute the probability and 95% confidence interval, respectively.

$$\text{Probability of correct signal perception (p)} = \frac{\text{Number of signals perceived correctly (C)}}{\text{Total number of signals (N)}} \tag{1}$$

$$95\% \text{ Confidence Interval} = p \pm 1.96 \times \sqrt{\frac{p(1-p)}{N}} \tag{2}$$

Table 4 summarizes the Bernoulli Trial results for the three field tests. The results show that all probability (p) values lie within the respective *95% Confidence Interval*. Thus, these results obtained from the field trials are valid, and it can be concluded that the system is capable of reliably communicating multiple pieces of information to represent a collision hazard, with an approximate accuracy of 95%.

6. Conclusion and discussion

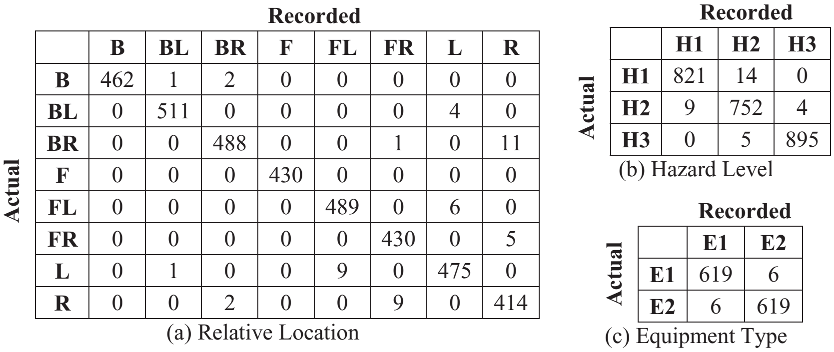
The timely communication of detected potential hazards to concerned workers at risk is an essential step to prevent injuries and fatalities on construction sites. However, there are challenges associated with hazard communication through existing methods, due to the lack of proper communication channels or external factors, such as the harsh construction environment. These challenges result in workers being unable to recognize potential risks, despite the warning signals being transmitted by existing systems, and thus, construction sites continue to have injuries and fatalities, which otherwise would be preventable with a better communication channel. To address such challenges, the authors focused on improving hazard communication to workers, by directly transmitting detected hazard information to them in order to make them aware of the hazards. The authors identified that a personalized wearable system, based on vibration signals, would serve the purpose through improved worker hazard perception capability. Despite the extensive use of artificial sensory systems in neurological studies to replace lost senses like sight or hearing [38–40], the applicability of such sensory systems to aid the sensing capability of construction workers has never been investigated by construction researchers. Thus, this study used a tactile-based artificial sensory system to communicate potential hazard information to workers through vibration signals, which activates an additional sense of touch on their backs besides vision and hearing for the hazard perception. In this study, the authors specifically focused on preventing collision accidents between on-foot workers and construction equipment.

For the accurate communication of hazard information, it is essential that the system swiftly deliver essential information representing the detected hazard scenarios to workers. Accordingly, the authors identified three essential pieces of information to represent a potential collision scenario: 1) eight relative locations (i.e., the approximate location of the hazard relative to the worker's position); 2) three hazard levels; and 3) two types of construction equipment. With these three pieces of information, distinct signal profiles were created to represent different hazard scenarios, and those signals were transmitted to workers using a tactile system with ten vibration motors on a waist belt. A series of three field trials were conducted with five test participants to determine the potential to communicate multiple types of information with different signal profiles. The field test results demonstrated that approximately 95% of the signals transmitted with the system were well-perceived by the test participants. The results demonstrated that the tactile-based system is reliable for communicating hazard information in the tested scenarios with a single worker and a piece of moving equipment. However, it is essential to train the workers to learn the tactile-based language, mainly the meanings of different vibration signal profiles, before this system can be used in construction sites. Such training will familiarize the workers with the tactile-based signal profiles, and hence, they can promptly react to the transmitted signals. Further, it is important to note that a future commercial system, or future research using such tactile sensors, must ensure that workers wear the system firmly attached to their backs.

During the field trials, the participants were static and not involved in any construction activities. However, it was observed among the test participants that they had difficulty in identifying signals due to loss of

Table 4
Summary of Bernoulli Trial results.

Description	Test 1	Test 2	Test 3
Total number of signals (N)	1250	1250	1250
Number of signals perceived correctly (C)	1239	1233	1183
Standard deviation (s)	0.0934	0.1159	0.2253
Probability of correct signal perception (p)	0.9912	0.9864	0.9464
95% confidence interval	(0.9860, 0.9964)	(0.9800, 0.9928)	(0.9339, 0.9589)



Recorded / **Actual**

	B	**BL**	**BR**	**F**	**FL**	**FR**	**L**	**R**
B	462	1	2	0	0	0	0	0
BL	0	511	0	0	0	0	4	0
BR	0	0	488	0	0	1	0	11
F	0	0	0	430	0	0	0	0
FL	0	0	0	0	489	0	6	0
FR	0	0	0	0	0	430	0	5
L	0	1	0	0	9	0	475	0
R	0	0	2	0	0	9	0	414

(a) Relative Location

Recorded / **Actual**

	H1	**H2**	**H3**
H1	821	14	0
H2	9	752	4
H3	0	5	895

(b) Hazard Level

Recorded / **Actual**

	E1	**E2**
E1	619	6
E2	6	619

(c) Equipment Type

Fig. 13. Incorrect perceptions.

attention during field trials, and they were unable to perceive parts of the transmitted information correctly. Considering this, it is obvious that workers focused on construction activities would have similar difficulty in perceiving complete hazard information from such signals. Thus, to overcome this challenge with signal perceptions (among workers either free or engaged in works), it is suggested to embed a mechanism within the vibration signal profiles (that might be an additional vibration signal) to alert participants of the incoming hazard-related vibration signals. On receiving such alert signals, the participants would know that they are going to get hazard-related signals. Thus, the participants would be alerted to pay attention to incoming hazard signals. Accordingly, the performance of the system in improving participants' hazard perceiving capability can be enhanced. Here it is noteworthy to mention that despite the cases with incorrect perception of some pieces of information, the participants were still able to identify a good amount of information correctly. Therefore, the system is capable of making people aware of the hazard to some degree.

Further, each of the signal units representing a piece of information can have a duration as low as 75 milliseconds [30], which means that the complete signal profile, with three pieces of information, can be communicated in less than 250 milliseconds. As such, the workers would be able to perceive the signals and react promptly to avoid the potential risk. In the scenarios with the possibility of multiple pieces of equipment threatening a worker, this system can communicate the information about the detected equipment in a sequence that expresses the order of equipment detected within the workers' risk zones. Signal perception test results from such scenarios would provide more insight on the effectiveness of the proposed hazard communication system in such work environments, along with any improvements required on the system. Besides, future investigations should focus on evaluating the system's performance, while alerting on-foot workers moving around construction sites to test their perception of the relative location information.

Furthermore, the hazard level indicated in this study is based on the distance between a worker and the equipment. However, the hazard level is affected by other factors as well, such as the speed of moving equipment and drivers' blind spots. Therefore, it is suggested to define the hazard level considering such factors, as well. Moreover, it should be noted that the current system is limited to communicating information obtained from available hazard detection systems. As such, this system would require potential modification to adapt with the continuous evolution in detection technologies to communicate complex worker-equipment hazard scenarios in the future. In addition, the feasibility of using this system to communicate other common types of construction hazards should be tested. Further research will develop this system as an alternative to communicating hazard information to workers in construction sites. The future research will also focus on developing a comprehensive safety system by integrating this communication system with different hazard detection systems. Such an integrated system at a full and working scale, being part of construction safety management, would significantly improve the safety of construction workers.

Data availability statement

Data collected during the study are available from the corresponding author by request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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