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Embedded Safety Communication System for Robust Hazard Perception of Individuals in Work Zones

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1. ABSTRACT

Although safety is given the topmost priority in the construction industry, reported severe injuries and fatalities indicate insufficient attention to worker safety. Past studies have demonstrated significant progress in identifying potential hazards (i.e., hazard detection); however, such detected hazards are not well communicated to workers. Past research demonstrated that workers often fail to perceive, be aware of, or sense warnings generated by hazard detection systems. Thus, this study explored a method to improve workers' hazard perception, with a focus on a tactile-based, wearable system to effectively alert workers to previously identified potential hazards. The main objective of this study was to develop a prototype Embedded Safety Communication System (ESCS) and determine its capability to improve workers' perceptions of hazards that are communicated to them. In this project, the research team developed the ESCS prototype, investigated the system configuration, created tactile messages to send hazard-related messages, and conducted field tests to validate system effectiveness. The test results indicate that the tactile signals transmitted with the ESCS prototype are capable of communicating potential hazards to workers, especially in harsh environments where workers' innate sensing is limited.

2. KEY FINDINGS

- The tactile-based communication system (ESCS) demonstrated its ability to communicate hazard information to workers.
- The distinct tactile signal units, based on three signal parameters (signal intensity, signal duration, and signal delay), could be used to construct communicable tactile signals to deliver information.
- Past literature studies, followed by the layout tests, identified an effective layout of vibration motors based on motor sensitivity, spacing, and layout test results.
- The 4-2-4 configuration of ten vibrating motors could effectively communicate key hazard information with higher accuracy, when compared to a 1-3-3-3 configuration.
- The signal perception capability of individuals could be significantly improved with continuous training.
- Based on current work zone safety technology and past research, the key information units required for communication were the relative location of hazard, hazard level, and the type of hazard (e.g., equipment type). This information could be effectively communicated with the help of ten vibrating motors, indexed to represent various units of information.
- The field trials validated the effectiveness of using the prototype ESCS as a hazard communication system in construction work zones.

3. INTRODUCTION

The safety of construction workers is given the highest priority in the construction industry (Wu et al. 2015). As such, workers are equipped with required personal protective equipment (PPE) for their safety, and there are qualified safety inspectors to ensure safety on construction sites. Despite such efforts, fatal accidents are common, and there has been an increasing trend of worker fatalities in the US (Bureau of Labor Statistics 2018). The construction industry alone accounts for approximately 20% of such fatalities (OSHA 2018). These reports show that efforts to ensure safe work zones are not sufficient. A few studies have reported that the conventional method of visual safety inspection is not capable of identifying all potential hazards on construction sites (Carter and Smith 2006; Park et al. 2018; Perlman et al. 2014;

Sacks et al. 2009; Sakhakarmi et al. 2019). Accordingly, researchers are continuously working to support safety managers in maintaining site safety by devising innovative technologies to detect and communicate potential work-zone hazards.

Past studies have explored various methods of automated hazard detection using sensing technologies, such as radio frequency identification (Marks and Teizer 2012; Teizer et al. 2010), ultra-wideband (Carbonari et al. 2011; Jo et al. 2019), Bluetooth (Park et al. 2017; Yang et al. 2018), vision (Kim et al. 2017), and inertial measurement unit sensors (Jebelli et al. 2016). Although such studies achieved success in utilizing technology to detect the proximity of hazardous situations in real time, their methods of communicating such information to individual workers were impeded in several ways. The prevalently used alarm sound technologies **often fail to warn workers,** especially in noisy work zones (Fyhrie 2016; Wang et al. 2011). The adverse nature of construction sites often impairs workers' audio and visual sensing abilities, and results in their failure to perceive these types of warnings, despite such risks being identified/located using various technologies. As such, the existing hazard detection systems are not fully capable of communicating warning signals to workers, due to their impaired sensing in such an environment. Therefore, there is a need to find effective ways to communicate hazard information in such a way that the communication is not adversely influenced by external factors.

In response to the challenge associated with hazard communication, this project was initiated to develop a prototype ESCS. It is a tactile-based, wearable communication system that uses vibrating motors. It is worn on the backs of workers to communicate previously detected hazard information to them in the form of vibration signals. Such signals, in the form of the sensation of touch, can provide an additional sensing ability, beyond their innate-sensing abilities (e.g., vision and audio), which previous research has found to be inadequate in certain construction environments. Thus, the proposed research may offer a transformative approach to workers' hazard awareness in the adverse nature of the construction site. The system development process included a series of laboratory experiments. Further, several field trials were conducted to determine the effectiveness of the hazard communication system in delivering key hazard information to workers. The field trial results demonstrated the capability of the prototype ESCS to communicate distinct signal profiles, and the test participants were able to perceive the specific hazard information contained within the signal profiles.

4. OBJECTIVES

The main goal of this research was to develop a prototype ESCS, which is a tactile-based hazard communication system to warn workers of detected potential hazards on a construction site. This system uses vibration signals to communicate the hazard information and enables workers to sense hazards, without using their senses of vision and hearing. The research team used tactile sensors attached to the backs of workers to stimulate their sensory nervous systems, in order to communicate safety messages directly to them. To accomplish this goal, the research objectives were designed as follows:

1) Create the real-time ESCS and identify the key information to represent construction hazards resulting from proximity breaches by construction equipment and intruding vehicles in work zones.
2) Identify the best configuration of the vibratory sensors. This task investigates the potential sensor configuration for optimal perception by individuals.
3) Establish an effective way to construct the tactile messages with key elements. As tactile messages have different signal intensities, signal peaks, valley durations, and pulse delays, this task investigates methods for codifying and testing various signal profiles.

4) Assess system performance by conducting tests in various scenarios through field trials.

5. METHODS

System Development

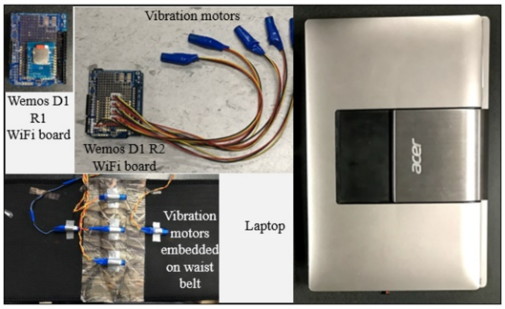

Figure 1. Prototype ESCS system

The first part of this research was to develop a prototype ESCS. The researchers used vibration motors and Arduino boards for the prototype development, as shown in Figure 1. The prototype system consists of two sub-systems, i.e., a personal tactile-signal component and a server component. The personal tactile-signal system consists of vibration motors embedded on a waist belt, and the vibration motors are controlled by Arduino boards, in order to generate tactile signals for hazard communication. This wearable system is securely attached to the tactile sensors at the back of a test participant. The server system uses an additional Arduino board to receive hazard information from a hazard detection system, and then relay it to the personal tactile-signal system in order to alert workers. For this study, the research team developed software that can be used with laptops and mobile devices. Figure 2 shows the layout of a mobile application used for testing the transmission of the vibration signals.

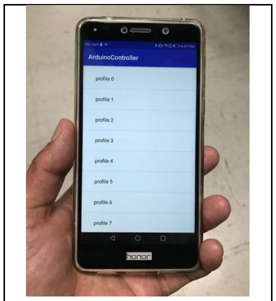

Figure 2. Mobile application

Key Hazard Information and Number of Vibration Motors

Along with the prototype development, the researchers identified key information, based on past studies, to represent a potential collision accident. The distance between workers and vehicles/equipment has been identified as a measure to determine worker safety in previous studies related to collision (Kim et al. 2017; Son et al. 2019). In other studies (Park et al. 2016b; Son et al. 2019), distance has been categorized into different hazard zones to indicate different levels of risk to workers. To determine a potential collision hazard, researchers (Kim et al. 2017; Park et al. 2016b; a) also accounted for the relative locations of vehicles/equipment. The type of construction equipment is another piece of information that needs to be communicated in the case of a potential collision between workers and construction equipment, as knowing the type of equipment allows the workers to intuitively have a good idea about the nature of the situation. As such, this study considered the relative location of vehicle/equipment, level of hazard, and the type of equipment as the key information to communicate a potential collision between workers and construction equipment. However, in the case of a collision due to an intruding vehicle, the type of vehicle is not a key parameter to communicate, as far as the information on the detected intrusion point is transmitted. Thus, this study considered the relative location of intrusion point and the hazard level as the key information to communicate to workers in intrusion cases.

These key types of information were used as the basis for determining the number of vibration motors required to effectively deliver warnings to workers. Figure 3 shows a typical hazard scenario in a work zone due to a collision between a worker and construction equipment, as well as the hazard communication process using the prototype ESCS. The relative hazard location information is represented by two components, such as direction and distance with respect to an individual worker's position. For the relative directional information, this study considered eight directions, each at 45°, with respect to a worker's position in the horizontal plane. The distance information was categorized into different regions based on the proximity level, as represented by the circular boundaries around the worker in Figure 3; the researchers included the information related to the hazard zone (instead of exact distance information) in the hazard notification information. Accordingly, the researchers used 10 vibration motors to communicate information related to a detected hazard: eight motors were indexed to indicate eight directions (relative locations), together with hazard level, while two other motors were used to represent equipment type. This means that different motors vibrate to communicate different units of information, and this helps to create easily distinguishable signal profiles.

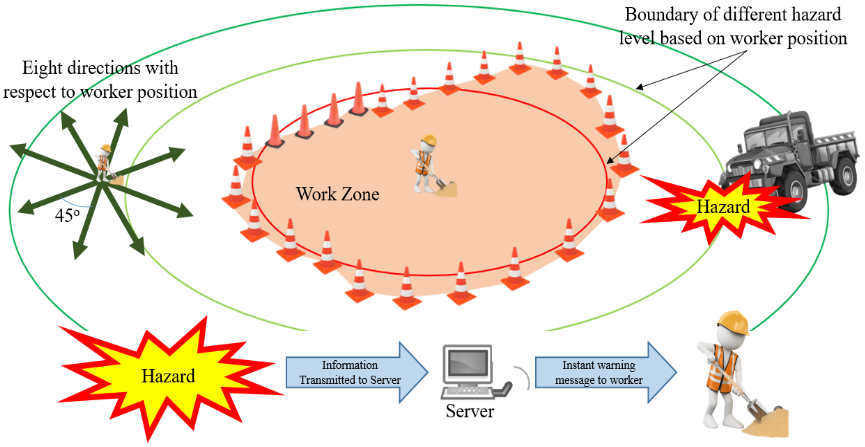

Figure 3. Tactile-based hazard communication system

Experimental Studies

The researchers conducted three experimental studies progressively, as the ESCS was developed and the communication protocols were refined. The three experimental studies are subsequently discussed in the following sections. For these studies, the test participants were selected based on their capabilities to sense vibration signals on their backs. Further, different participants were employed for different tests, mainly to make the study results more reliable. Thus, this resulted in different numbers of test participants in the three experimental studies: six individuals in the first experimental study, and five in the other two studies.

Sensory System Configuration Study

This experimental study aims to determine the best configuration of the ten tactile sensors for a worker's effective perception of the key communicated hazard information. For this purpose, the researchers conducted two separate studies (i.e., spacing and configuration) in sequence. These studies involved six test participants who were capable of identifying vibration signals on their backs. All experimental tests were conducted in a controlled laboratory setting. The participants were initially trained to identify different signals before testing, in order to determine their capabilities to recognize the transmitted signals accurately. The following sections explain these studies in detail:

a. Spacing Study

For the spacing study, the researchers used five vibration motors embedded on a waist belt, as shown in Figure 4. This study tested different spacings between adjacent motors, in order to determine an optimum spacing between vibration motors, so that there was minimum confusion between the signals received from adjacent motors. This was to enable participants' identification of individual motors, and assist in determining the sensory configuration that could be used to create easily distinguishable signal profiles using a combination of different motors. Figure 5 shows a test participant equipped with PPE and the prototype ESCS on his back for the study.

This study tested six different spacings between adjacent vibration motors, as shown in Table 1. For each of the spacings, the test participants were asked to identify 300 signals from different motors. The study results, summarized in Table 1, show that the vibration signals are better perceived with greater spacing between vibration motors. The perception accuracy decreases with less spacing. Further, the participants found it difficult to identify signals from motors arranged on the vertical axis (i.e., motors 1, 2 and 3), compared to the motors arranged on the horizontal axis (i.e., motors 4, 2 and 5). At the spacing of 2.5 inches between adjacent motors, the participants had approximately 95% accuracy of correctly identifying signals from individual motors. Thus, a minimum spacing of 2.5 inches was adopted in further studies, for a better perception of signals. The optimum range for the spacing of motors is 2.5 inches to 3.25 inches.

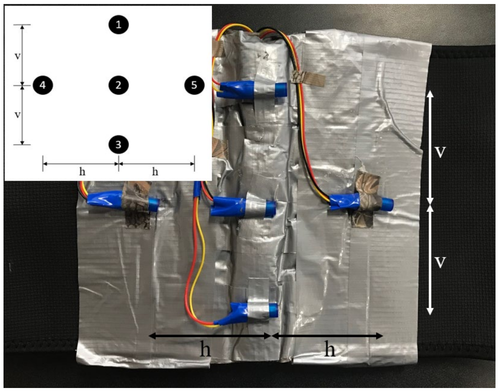

Figure 4. Arrangement of vibration motors for spacing study on the waist belt

Figure 5. Test participant

Table 1. Summary of spacing study results

S.N.	Vert. Spacing (v inches)	Hor. Spacing (h inches)	Individual motor perception accuracy (%)				
			1	2	3	4	5
1	3.25	3.25	99.44	100	100	100	100
2	3.00	3.00	99.72	100	99.72	100	100
3	2.75	2.75	94.17	99.17	100	100	100
4	2.50	2.50	94.72	98.61	96.67	99.72	100
5	2.25	2.50	90.28	98.06	95.83	100	100
6	2.00	2.50	86.67	97.50	93.33	100	100

b. Configuration Study

The purpose of the configuration study was to determine a suitable layout for ten vibration motors that would result in better signal transmission. Therefore, this study tested the capability of individuals to accurately identify signals from different motors. From the literature review, it was determined that the navigation assistance devices developed by other researchers used two configurations of vibration motors: (a) around the waist of the user (Durá-Gil et al. 2017; Elliott et al. 2010; Van Erp 2005; Faugloire and Lejeune 2014; Grierson et al. 2009, 2011) and (b) a back-array arrangement on the user's back (Ross and Blasch 2000; Tan et al. 2003). This study adopted the back-array configuration because the system should be attached to body parts that are relatively free; the backs of workers generally remain free during construction activities, compared with other body parts. Thus, using motors on the back would be the most appropriate for workers' effective signal perception.

Preliminarily, two back-array configurations of the 10 vibration motors were identified for this study. The first was a 1-3-3-3 motor configuration, which had one motor on the first row and three motors on the second, third, and last rows, as shown in Figure 6. The next configuration was a 4-2-4 motor configuration, with four motors on the first and last rows, and two motors on the second row, as shown in Figure 7.

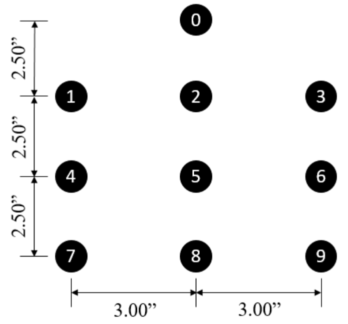

Figure 6. 1-3-3-3 motor configuration

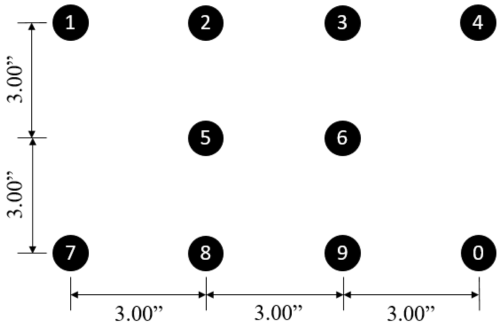

Figure 7. 4-2-4 motor configuration

In the preliminary study, each of the test participants was asked to identify 600 signals from different motors for each motor configuration. Table 2 summarizes the comparative results of the test participants.

Table 2. Configuration study preliminary test results

Test Participant	Average Accuracy	
	1-3-3-3 Configuration	4-2-4 Configuration
1	87.17%	94.33%
2	87.17%	95.83%
3	81.17%	90.67%
4	84.33%	95.50%
5	85.33%	93.50%
6	89.33%	96.67%

Table 2 shows that each participant had better accuracy in recognizing signals from the 4-2-4 motor configuration compared to the 1-3-3-3 motor configuration. Accordingly, the 4-2-4 motor configuration was identified to be best suited for the intended purpose of this study, as demonstrated by its better performance compared to the 1-3-3-3 configuration. For validation of these results, follow-up tests were performed with new test participants, who had not been involved in the previous tests. Each participant was asked to identify 120 signals at a time, and the tests were repeated 10 times. Figure 8 shows the signal perception accuracy of each participant plotted for the 10 trials. The plot shows that there was continuous improvement in the signal perception capability of all test participants over the 10 trials, finally resulting in above 97% accuracy, despite lower accuracies in initial tests. These results show the impact of training over time; i.e., the perception capability of individuals improves with continuous training.

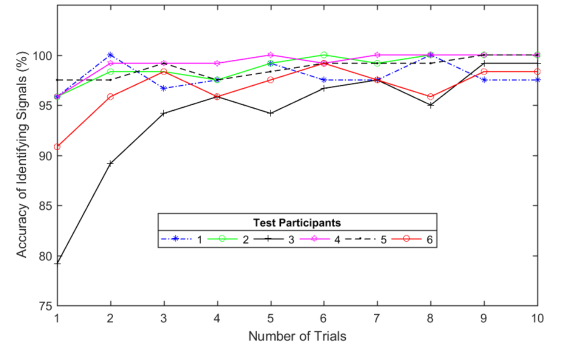

Figure 8. Performance of test participants

Signal Parameter Study

This study focused on identifying basic signal units that could be used to develop a completely tactile-based communicable language. For this purpose, the researchers conducted an experimental study to identify distinguishable signal units based on three signal parameters: signal intensity, signal duration, and signal delay, as shown in Figure 9. By varying any of these parameters, different signal profiles could be constructed to represent different information.

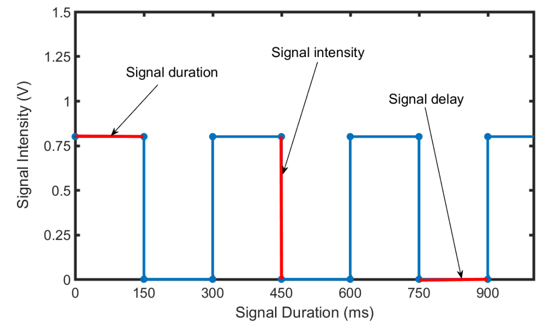

Figure 9. Signal parameters

For signal intensity, ten different signal units, between the intensities of 1.3 volts to 3.1 volts, were selected. Similarly, ten different signal units, with durations between 75 milliseconds and 500 milliseconds, were selected for both signal duration and signal delay. All of these signal units were indexed from one to 10. Table 3 shows the 30 indexed signal parameter values used in this study.

Table 3. Signal unit indices for the signal parameter study

Parameters	**Signal Index**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Signal Intensity (V)	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1
Signal Duration (ms)	75	100	150	200	250	300	350	400	450	500
Signal Delay (ms)	75	100	150	200	250	300	350	400	450	500

For each signal parameter, five test participants were asked to identify 40 signal units for each of the indexed signals. The transmitted signals and the signals perceived by test participants were recorded and analyzed using probability density plots to identify distinct signal units. Figure 10 shows the probability density plots of the three signal parameters. In the plots, the overlapping area between the signal indices indicates whether the signals were distinct or not. The smallest overlapping area between two signal indices means that those signals were distinct. Thus, the overlapping areas between the signal indices were calculated for each signal parameter.

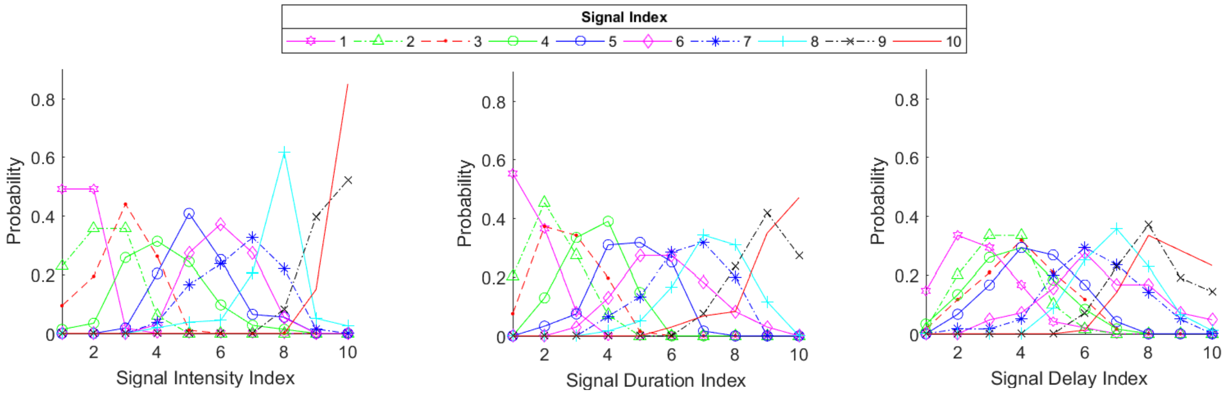

Figure 10. Probability density plots for each signal parameter

Based on the minimum overlapping area between signal indices, eight signal units were identified to be easily distinguishable, out of the 30 indexed signal units. Figure 11 shows the distinct signal units for each signal parameter. In the case of signal intensity, indexed signal units one, five, and 10 were found to be easily distinguishable. Similarly, indexed signal units one, five, and nine of signal duration, and indexed signal units one and 10 of signal delay were found to be distinguishable signals, respectively.

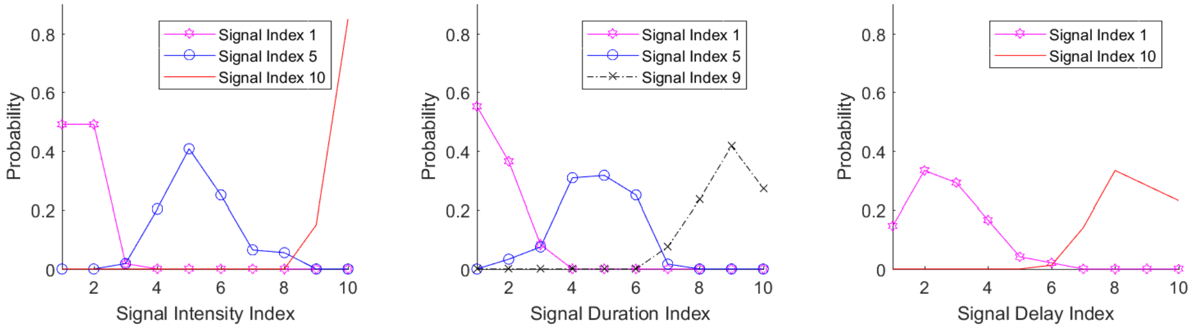

Figure 11. Distinct signal units for each signal parameter

Field Trials

The research team collaborated with a local contractor, Las Vegas Paving Corporation, to conduct field trials to determine the potential of the 4-2-4 sensory configuration for the optimal perception of communicated information by individuals. The field trials were conducted for the following two cases of collision:

- Collision between workers and construction equipment;
- Collision due to intruding vehicles.

Different signal profiles were created using the distinct signal units identified from the signal parameter study, and the combination of signals from an indexed vibration motor arranged in a 4-2-4 layout. In the field trials, specific information was communicated to test participants with distinct signal profiles. Five test participants were involved in the field experiments; all of them were familiar with the ESCS and had been trained to identify the information communicated through different signal profiles in a laboratory setting before the actual field trials.

Collision between workers and equipment (Case 1): Figure 12 shows the site layout for the field trials related to construction site hazards due to a collision between workers and on-site equipment. For this study, the hazard zones were marked by drawing concentric circular boundaries of radii at four meters, eight meters, and 12 meters. The markers of different colors were used to indicate different levels of hazard zones around the test participants. The red markers were used to indicate a highly hazardous zone, while the yellow markers were used to indicate a medium hazard zone, and the green markers were used to indicate a lower hazard zone. The test participants were equipped with PPEs along with the prototype ESCSs. Further, participants' eyes and ears were covered, to ensure that they could only rely on the communicated tactile signals to sense the hazard situations.

Figure 12. Site layout for field trials – Case 1 (Collision between workers and on-site equipment)

During the field trials, each test participant was located at the center of the marked zone and different types of equipment approached towards the participant. A dump truck and a wheel loader were used in the trials, and it was ensured that the approaching equipment and test participants were at safe distances at all times during the experiments. The research team used a proximity detection system, a Bluetooth-based system, that was found in a past CPWR's small study, 16-1-PS (Cho et al. 2017) to detect the proximity of the equipment. Then the research team conducted three different tests with the same site layout and the same testing procedure; i.e., a vehicle approaching the participant, as shown in Figure 13. The three tests were designed to explore the participant's perception ability as the amount of information communicated to the participant by the ESCS increased. The purpose of this research was to promptly communicate detected hazard messages to workers by using tactile signals, given that early and prompt hazard awareness would give them enough time to take preemptive actions. Therefore, it is reasonable to assume that workers would be able to check the detected hazard sources upon receiving the communicated tactile warnings in order to determine what action(s) to take. However, in the current studies, the researchers covered the eyes and ears of the test subjects, so the test subjects were pre-instructed to make specific move-away movements based on the signals they received. These tests are explained in the following sections:

i. Test 1: Relative location only
In this test, the participants were given signals with only the relative location information of the approaching equipment. 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.

ii. 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). The reactions of the participants were the same as in the previous test.

iii. 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.

(a) (b)

Figure 13. Field trials for Case 1 (Tests 1, 2, and 3)

Collision due to intruding vehicles (Case 2): Figure 14 shows the field setup for this test (Test 4) related to collision accidents in roadwork zones due to the intrusion of outside vehicles. The roadwork zone is marked with the traffic cones, and a pickup truck is used to represent the intruding vehicle. For this test, the detection of intrusion was manually measured under significant margins of safety (i.e., safe condition), due to potential safety issues. Based on the detected intrusion point, the five test participants (with eyes and ears covered) were transmitted vibration signals containing information related to the intruding vehicle (i.e., the relative location of intrusion and hazard zone). After receiving tactile signals, the participants were pre-instructed to make specific move-away movements, as was done with the previous tests. Then their responses were recorded.

(a) (b)

Figure 14. Field test to transmit intrusion hazard information – Case 2 (Test 4)

Table 4 shows a summary of the test results for all field trials performed with five test participants. The results show that the accuracy of participants' perceptions of the communicated signals gradually decreased, with an increase in the amount of information communicated through the tactile signals (i.e., from Test 1 to Test 3). However, the overall minimum accuracy was observed to be approximately 95% for the four field tests.

Table 4. Field Test Summary

Test Participants	Signal Perception Accuracy (%)			
	Test 1	Test 2	Test 3	Test 4
P1	100.00	98.80	95.60	95.00
P2	98.00	98.80	95.20	97.00
P3	99.60	98.80	94.80	100.00
P4	98.40	98.00	90.80	95.00
P5	99.60	98.80	96.80	100.00
Overall Accuracy	**99.12**	**98.64**	**94.64**	**97.40**

6. ACCOMPLISHMENTS AND RESULTS

This study developed a prototype ESCS using tactile sensors for the communication of detected hazard information on construction sites. The sensory system configuration was determined through experimental laboratory tests. The tests demonstrated that larger spacing between vibration motors results in better signal communication. Based on these findings, as well as a comparative study between a 1-3-3-3 configuration and a 4-2-4 configuration of 10 vibration motors, the 4-2-4 configuration has been identified as the best configuration of motors, resulting in minimal signal miscommunication. This configuration allowed for the creation of signal profiles using multiple indexed-vibration-motors to communicate hazard information to workers. The follow-up tests using the 4-2-4 configuration for 10 trials demonstrated that the signal perception capability of individuals notably increased with training (i.e., better performance of the prototype ESCS with continuous training of workers).

The study of signal parameters demonstrated the capability of the system to communicate distinguishable tactile signals to workers in a discrete manner. For the correct communication of hazard information, it is important that the system swiftly deliver key detected hazard information to workers. For this purpose, the types of information included in the tactile signals were the relative location (i.e., the approximate location of hazard relative to worker position), level of hazard, and vehicle/equipment type entering the work zone. The distinct signal units, identified from the signal parameter study, were used to form a complete tactile-based language, using multiple indexed-vibration-motors to communicate the key information to individuals. Field trials conducted to test such signals, using multiple pieces of information, found that the test participants efficiently perceived the communicated signals with good accuracy. These field trial results validate the effectiveness of using this system to communicate detected hazard information to workers in work zones.

Therefore, this study successfully developed a prototype ESCS through laboratory tests. Further, its feasibility to communicate signals to workers containing information to prevent work-zone collisions, either with on-site vehicles/equipment or outside vehicles, was determined through controlled field trials. Further study to communicate tactile signals based on other possible hazards, detected by hazard detection systems, would give more validation for the application of this system in work zones. Such validation would require the integration of the prototype ESCS with available hazard detection systems, and the conversion of the detected hazard information into corresponding tactile signal profiles. These communicated signals would enable workers to take actions to prevent potential fatalities in construction work zones.

7. CHANGES/PROBLEMS

There were no changes in key staff, plans, or methods.

8. FUTURE FUNDING PLANS

For future research to enhance the current prototype system, the research team plans to seek additional funding from the National Science Foundation and local construction companies.

9. LIST OF PUBLICATIONS/PRESENTATIONS

Journal Publications:

1) Sakhakarmi, S. and Park, J. "Investigation of Tactile Sensory System Configuration for Construction Hazard Perception." Sensors 2019, 19 (11), 2527.

Conference Presentations:

1) Sakhakarmi, S. and Park, J. "Wearable Tactile System for Improved Hazard Perception in Construction Sites." 2020 ASCE Construction Research Congress, Arizona State University, Tempe, Arizona, USA. (Full paper submitted)
2) Sakhakarmi, S., Park, J., and Cho, C. "Prototype Development of a Tactile Sensing for Improved Worker Safety Perception." 2019 ASCE International Conference on Computing in Civil Engineering, Atlanta, Georgia, USA.

10. DISSEMINATION PLAN

The researchers will disseminate the findings of this study and follow-up future research through various channels:

- Journal publications in top journals such as Sensors, ASCE Journal of Construction Engineering and Management, and Automation in Construction
- Conference papers or posters in 2019 ASCE International Conference on Computing in Civil Engineering and Construction Research Congress 2020

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