Design and Evaluation of a Connected Work Zone Hazard Detection and Communication System for Connected and Automated Vehicles (CAVs)

AUGUST 2019 | Final Report

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. 03-050	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Design and Evaluation of a Connected Work Zone Hazard Detection and Communication System for Connected and Automated Vehicles (CAVs)		5. Report Date August 2019 6. Performing Organization Code:
7. Author(s) Michael Mollenhauer Elizabeth White Nazila Roofigari-Esfahan		8. Performing Organization Report No. Report 03-050
9. Performing Organization Name and Address: Safe-D National UTC Virginia Tech Transportation Institute		10. Work Unit No. 11. Contract or Grant No. 69A3551747115/Project 03-050
12. Sponsoring Agency Name and Address Office of the Secretary of Transportation (OST) U.S. Department of Transportation (US DOT)		13. Type of Report and Period Final Research Report 14. Sponsoring Agency Code

15. Supplementary Notes

This project was funded by the Safety through Disruption (Safe-D) National University Transportation Center, a grant from the U.S. Department of Transportation – Office of the Assistant Secretary for Research and Technology, University Transportation Centers Program.

16. Abstract

Roadside work zones (WZs) present imminent safety hazards for roadway workers as well as passing motorists. In 2016, 764 fatalities occurred in WZs in the United States due to motor vehicle traffic crashes, which are the second most common cause of worker fatalities. The advent of connected and connected automated vehicles (CVs/CAVs) is driving WZ safety practitioners and vehicle designers towards implementing solutions that will more accurately describe activity in WZs to help identify and communicate imminent safety hazards that elevate crash risks. A viable solution to this problem is to accurately localize, monitor, and predict WZ actors' collision threats based on their movements and activities. This information along with CV/CAVs' trajectories can be used to detect potential proximity conflicts and provide advanced warnings to workers, passing drivers, and CAV control systems. This project aims to address WZ safety by delivering a real-time threat detection and warning algorithm that can be used in wearable WZ communication solutions in conjunction with CVs/CAVs. As a result, this research provides a key element required to significantly improve the safety conditions of roadside WZs through prompt detection and communication of hazardous situations to workers and CVs/CAVs alike.

17. Key Words Connected Vehicles; Roadway Projects; Connected Work zone, Sensing, work zone safety, ultra-wide band, connected vehicle-to-infrastructure, V2I	18. Distribution Statement No restrictions. This document is available to the public through the Safe-D National UTC website, as well as the following repositories: VTechWorks, The National Transportation Library, The Transportation Library, Volpe National Transportation Systems Center, Federal Highway Administration Research Library, and the National Technical Reports Library.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	28	$0

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Abstract

Roadside work zones (WZs) present imminent safety hazards for roadway workers as well as passing motorists. In 2016, 764 fatalities occurred in WZs in the United States due to motor vehicle traffic crashes, which are the second most common cause of worker fatalities. The advent of connected and connected automated vehicles (CVs/CAVs) is driving WZ safety practitioners and vehicle designers towards implementing solutions that will more accurately describe activity in WZs to help identify and communicate imminent safety hazards that elevate crash risks. A viable solution to this problem is to accurately localize, monitor, and predict WZ actors' collision threats based on their movements and activities. This information along with CV/CAVs' trajectories can be used to detect potential proximity conflicts and provide advanced warnings to workers, passing drivers, and CAV control systems. This project aims to address WZ safety by delivering a real-time threat detection and warning algorithm that can be used in wearable WZ communication solutions in conjunction with CVs/CAVs. As a result, this research provides a key element required to significantly improve the safety conditions of roadside WZs through prompt detection and communication of hazardous situations to workers and CVs/CAVs alike.

Acknowledgements

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The project team would also like to acknowledge the support of the Virginia Transportation Research Council (VTRC), a division of the Virginia Department of Transportation, and specifically Cathy McGhee and Mike Fontaine, who served as a subject matter expert and reviewer of this final report.

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Introduction

Roadside work zones (WZs) present safety hazards for roadway workers as well as passing motorists. In 2017, 710 fatalities occurred in WZs in the U.S. due to motor vehicle traffic crashes (1). In 2015, a WZ crash occurred once every 5.4 minutes in the U.S., for a total of approximately 96,626 crashes in WZs, marking a 7.8% increase in crashes from 2014 and a 42% increase from 2013 (2). This increase can be attributed to a number of factors, including an aging national highway infrastructure, resulting in the need for rebuilding and improving existing roadways. Increased road work activity often takes place on roadways experiencing higher levels of traffic, especially in urban areas, often requiring the creation of night time WZs to avoid peak travel times (2). These factors result in more dangerous situations for workers as well as passing vehicles.

Accidents involving motor vehicle collisions are a leading cause of roadside WZ fatalities as well. Between 2005 and 2010, vehicle collisions were the second most common cause of worker fatalities in roadside WZs, after runovers/backovers by construction equipment (2). An average of 121 workers per year lost their lives at roadway WZs between 2003 and 2015 (3). Transportation events accounted for 73% of these fatalities, 61% of which were due to a worker being struck by a vehicle in the WZ (3).

WZ fatalities have been largely attributed to unsafe roadway proximity and lack of workers' and/or passing motorists' situational awareness. WZs and the presence of WZ workers often violate driver expectations and, as a result, workers and passing traffic are placed in unsafe proximity to each other. Successful WZ safety management hinges on detailed and early detection of threats and sending providing workers timely information to workers. Furthermore, advanced warning of worker presence can help both human drivers and connected and connected automated vehicles (CVs/CAVs) prepare for and avoid collisions with WZ actors.

Previous research conducted by team members has focused on improving roadway workers' safety through both worker trajectory planning (4; 5) and the design of a wearable GPS-based communication system (6). However, performance issues with localization accuracy and warning strategies were identified as issues in the wearable communication (6).

As such, this research seeks to improve upon previous results by developing reliable real-time threat detection as well as localization and communication strategies. This research's overarching goal is to increase roadway workers' situational awareness and to inform drivers of CVs/CAVs of detected hazardous situations to avoid imminent safety hazards. To this end, this research utilizes current and emerging transformative technologies that will work in conjunction with CVs/CAVs to minimize the increased safety risks associated with roadside WZs. Equipping roadway WZ actors with the technology to ultimately communicate with approaching CVs/CAVs can help eliminate imminent safety hazards associated with passing motorists before they occur and reduce the occurrence of accidents by alerting workers to unsafe exposures.

Background

Construction safety has always been a great concern in the industry. It is even more of a concern for highway construction workers, since they have to work in close proximity to high-speed traffic. From 2003 to 2015, 1,571 deaths related to highway construction work were reported according to the Center for Disease Control and Prevention (7). The Federal Highway Administration

(FHWA) reported that a highway WZ fatality occurs every 8.7 minutes, and an injury associated with highway construction WZs occurs every 9 minutes (8). As a result, organizations and researchers have provided methods to improve safety conditions of highway construction workers, many of which focused on integrating innovative technologies to reduce safety risks at highway WZs. These studies have focused on reducing vehicle speeds through WZs as well as developing guidance for WZ designs using various approaches (9), including mobile safety barrel robots to eliminate barrel-placement tasks for construction workers in busy highway traffic (10), and applying decision support systems to assess safety risks associated with highway activities (11).

One of the most important issues that needs to be addressed to improve highway construction safety is warning workers of dangerous situations to allow them enough time to react before an accident occurs. Previous studies have indicated that even though essential safety training has been put in place to improve construction workers' safety awareness, the unsafe behaviors of construction workers in addition to their lack of situational awareness remained a major cause of many accidents in highway WZs (12).

Work Zone Intrusion Alarm Technology (WZIAT) was developed in an effort to address this problem. The technology integrates proximity detection and an alarm system to send audible alerts to workers, taking into account the reaction time needed for workers to act on the received warning (13). However, these methods only considered intrusion into the WZ from outside, without due consideration to WZ actors and work conditions. To address this gap, this project aimed at developing a holistic prototype system that integrates highway WZs with passing traffic (CVs/CAVs) to prevent imminent threats to either or both. To this end, the objectives of this project were to create a specification for a worker localization and communication system prototype and to utilize ultra-wide band (UWB) technologies for real-time threat detection and warnings, taking into account all actors. The following research questions were addressed:

1. What is the current status of WZ safety as related to CV/CAV advisories and warnings?
2. Can ultra-wide band (UWB) technology be used for reliable localization and mapping of roadside WZ actors in real world environments? Are there any off-the-shelf systems currently available that will work for the WZ safety–CV/CAV application?
3. Can threat detection algorithms be developed that accurately portray the location and movement patterns of WZ actors while minimizing false alarms?
4. Can a WZ hazard detection system improve the situational awareness of both WZ actors and approaching CVs/CAVs to significantly reduce collisions?

Method

The following tasks outline the approach used for addressing the research questions stated above.

Task 1: Project Management

Throughout the project, the team held project management meetings on a regular basis as required by the needs of the project. The team held a project kick-off meeting at the Virginia Tech Transportation Institute (VTTI) in March 2018. Subsequently, the team began holding bi-weekly meetings via Skype to discuss the project's progress. Budget tracking was completed on a monthly basis as well to ensure that the project stayed on budget.

Task 2: Literature Review

Task 2 included a brief review of the current state of WZ safety practices as related to CV/CAV advisories and warnings. The review also included an exploration of currently available localization technologies. Based on this review, the team believed that UWB was a good fit for this application in that it was capable of providing support for both the localization and communication functions in a single package. The review then focused on identifying existing or emerging UWB off-the-shelf component options to be used in this project for localization. The team also researched and evaluated available human-machine interface (HMI) communication technologies suitable for informing WZ personnel of potential hazards. The full literature review can be found in the Appendix.

Task 3: Build the UWB System

In this task, the team at VTTI built the localization and communication system using the DecaWave UWB technology selected in Task 2. The system utilized three static UWB sensors (referred to as anchors) in a constellation to provide localization for five additional mobile sensors (referred to as tags). WZ actors could then be localized while in range of the anchor constellation when equipped with a mobile tag.

VTTI's Center for Technology Development created a light-weight plastic enclosure (about 6" x 4" x 4") to house the tag and the battery together and protect the components from outside elements (Figure 1). These plastic enclosures served to protect the hardware components for the prototype build, but the team envisions a more streamlined and integrated component assembly incorporated into a wearable device for actual deployment. A battery charger, which included five ports and a USB to microUSB adaptor, was also built.

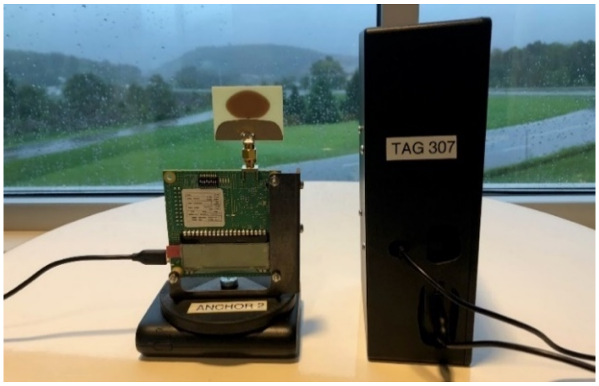

Figure 1. A picture of the DecaWave anchor tag setup (left) and mobile tag setup in the plastic enclosure (right).

During the build process, a number of issues were overcome. The development team spent a great deal of time completing range testing and experimenting with different system settings in order to maximize range and explore ways to test without line of sight. Based on preliminary testing, the transceiver was found to have a range of 80 m while maintaining desired accuracy.

The team also developed a calibration process to rotate the X/Y plane from the DecaWave sensor into the WGS84 GPS North/East plane. The WGS84 Cartesian Plane uses North (y) and East (x) axes. As shown in Figure 2, a rotation process was required to change a tag/anchor location from the DecaWave plane (Dy/Dx) to North/East (y/x).

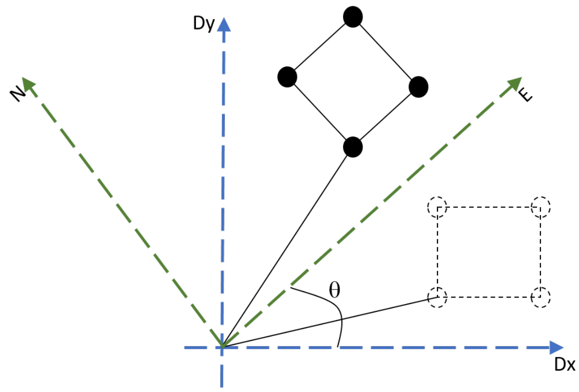

Figure 2. Graphical representation of the rotation process utilized to convert from X/Y plane from the DecaWave sensor into the WGS84 GPS north/east plane.

Upon completion of testing and calibration, the team finalized the build of the UWB system. The final system consists of three anchor tags that are used in a triangle configuration to communicate with five mobile rover tags that can be placed on workers who are on foot or operating construction equipment. One of the anchor tags is connected to an experimenter laptop with internet access to transmit the localization data of the tags to the VCC Cloud, which feeds VTTI's web-based situational awareness tool, VCC Monitor. With this tool, the location of the tags can be tracked in real-time on the map display.

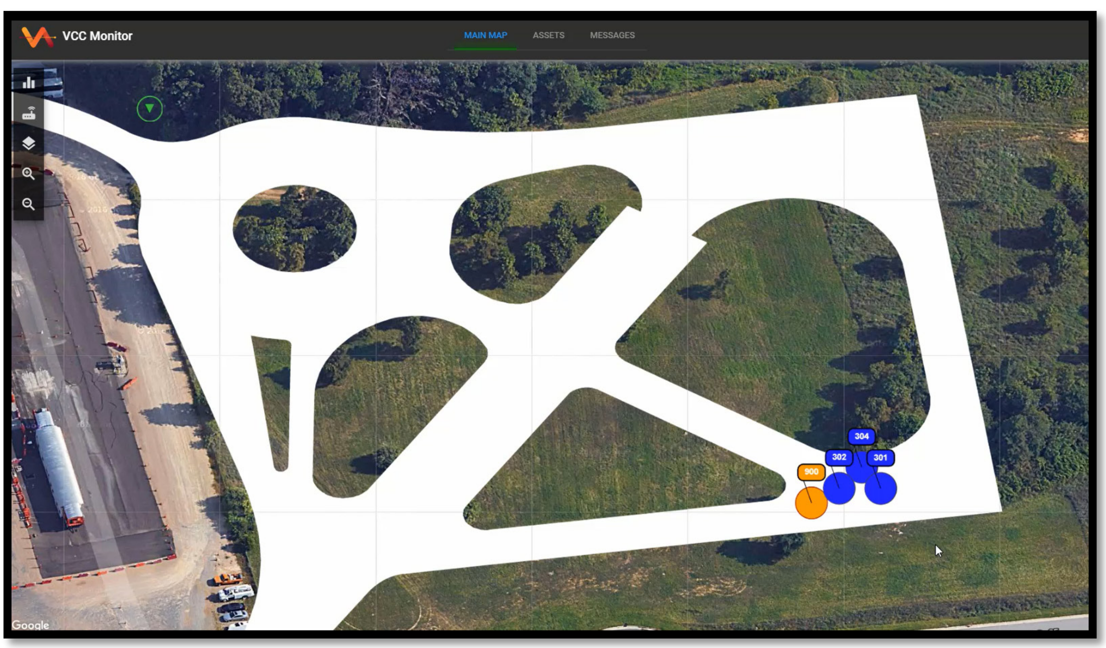

Figure 3. A picture of VCC Monitor, VTTI's web-based situational awareness tool that displays the real-time locations of UWB anchors and mobile tags (blue circles) and CAVs (orange circle).

Each of these components communicates with the VCC Cloud, which is part of VTTI's existing data management infrastructure. The VCC Cloud hosts the threat detection algorithm (created in Task 4) which is responsible for processing incoming worker position and movement data to determine any threat and then transmitting the warning and localization information to nearby CVs/CAVs. The VCC Cloud is used as the data and communications hub for both system development on the Virginia Smart Road and the demonstration in Task 5. The VCC Cloud provides a centralized system that supports the management of CV/CAV message traffic between entities interacting in the connected environment. CVs/CAVs support connection to the VCC Cloud computing environment via cellular or dedicated short-range communications (DSRC) communications. All message traffic is received by the Cloud and posted to a series of message queues, providing a convenient access point and application programming interface (API) through which other applications may access the system. All message traffic is archived to a persistent data storage and management system.

A VTTI-owned CV was also utilized as part of this system for data collection and demonstration purposes. The CV was equipped with a DSRC radio and an on-board unit (OBU) to send basic safety messages, which include the vehicle's location (using DPGS) in real-time. The vehicle's location was also tracked in real-time in the VCC Monitor map display.

Task 4: Data Collection and Algorithm Development

Detecting all potentially hazardous situations, prioritizing imminent threats, and minimizing false positive threat warnings within a WZ environment are key goals of this research. The aim of this task was to provide solutions for minimizing workers' exposure to hazardous proximity situations to avoid struck-by accidents between WZ actors and passing motorists. In this research, a "struck-by" safety accident occurs when a worker's uncertain movements create a risk, or when the worker's exposure to that risk leads to loss of control for both the worker and/or passing CVs/CAVs. Therefore, the team developed a threat detection algorithm that recognizes and predicts workers' movements relative to their activities within an active WZ so that warnings will only be provided when real worker-CV/CAV conflicts exist, thereby reducing false positive alerts.

Work Zone Database

A database of roadway WZ equipment, worker activities, and their relevant movements and characteristics was developed. Based on the constraints associated with the various WZ activities, the database includes safety requirements for various WZ actors dictating how each actor can move. The database was created in Microsoft Access and is actively connected to the threat detection algorithm. The database stores detailed information regarding roadway equipment (including their attachments), various work trades, and WZ activities and their relevant movements. The database also includes safety requirements for various WZ actors dictating how each actor can move relative to their activities and the distance required for each actor to safely carry out their assigned activities. The data regarding activities and their respective movement profiles was collected during the data collection subtask (see the following section for more information). The stored information is utilized in the threat detection algorithm to create a warning area and an alert area for WZ actors. The average length and width of equipment under each category is calculated as input designed to be "one size fits most" when generating alert and warning areas for equipment.

ID	Brand	Vehicle	Model	Overall_Length(m)	Overall_Width(m)	Weight(kg)	Click to Add
1	Caterpillar	Vibratory Asphalt Compactor	CB54-XW	4.93	2.2	11898	
2	Caterpillar	Vibratory Soil Compactor	CS-423E	4.96	1.8	6515	
3	Caterpillar	Vibratory Soil Compactor	CS-433E	4.96	1.8	6515	
4	Caterpillar	Vibratory Soil Compactor	CP-433E	4.96	1.8	6915	
5	Caterpillar	Utility Compactor	CB22B	2.58	1.11	2553	
6	Caterpillar	Utility Compactor	CB24B	2.58	1.31	2723	
7	Caterpillar	Utility Compactor	CB24B-XT	2.58	1.31	3123	
8	Caterpillar	Utility Compactor	CB32B	2.58	1.41	2808	
9	Caterpillar	Utility Compactor	CC24B	2.58	1.31	2441	
10	Caterpillar	Asphalt Compactor	CB14	2.05	0.88	1620	
11	Caterpillar	Asphalt Compactor	CB14-XW	2.05	1.08	1840	
12	Caterpillar	Asphalt Compactor	CB14-Full-Flush	2.05	0.96	1600	
14	Caterpillar	Utility Compactor	CB34	3.12	1.39	3940	
15	Caterpillar	Utility Compactor	CB34-XW	3.12	1.4	4200	
16	Caterpillar	Utility Compactor	CC34	3.12	1.39	3670	
17	Caterpillar	Vibratory Asphalt Compactor	CB434D	4.2	1.67	7380	

Figure 4. Equipment database.

Work Zone Map

This step entailed creating a map that localizes WZ actors based on how they can move as dictated by their planned activities. This map identifies the general WZ layout, barrier types, and other areas that affect the threat identification algorithms. The real-time WZ map was also developed to demonstrate movement patterns and proximity of various WZ actors. Trajectory information and proximity representations of workers-on-foot, equipment and vehicle are overlaid on Google maps. The Proximity Map illustrates safety areas of each actor and displays warnings (presented in red when unsafe proximity is detected) when different actors' warning areas overlap. Safety areas introduced in this research consist of two zones: alert areas and warning areas. The alert area is an inherently unsafe area around the actor. It is a fixed area in which, if invaded, the actor can be harmed due to unsafe proximity. Warning areas represent a lower level of risk than alert areas but are still considered hazardous. The development and details of safety areas is presented in the Algorithm Development section. The trajectory map is used to illustrate the real-time location of each actor. To create a trajectory for actors, the system recognizes each actor's category then displays the location on the map in each second.

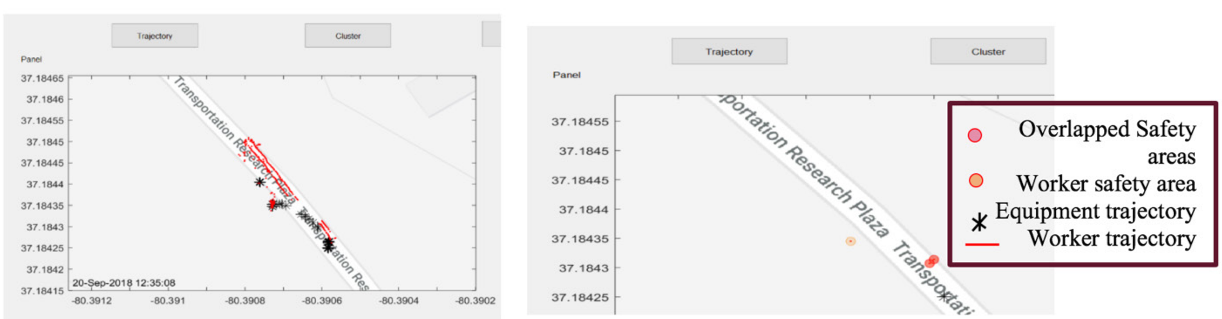

Figure 4: An example of a real-time WZ map representing a) trajectory of actors (left) and b) proximity of actors (right).

Data Collection

The purpose of this step was to provide a set of WZ configurations to train a simulation model of the threat detection algorithm to ensure all possible unsafe situations are taken into account. Initial data were collected on the Smart Road utilizing the UWB system to provide baseline WZ actor movement data during a variety of activities to better understand how volumes and movement status may be defined. Additional data were collected to simulate plausible worker-CV/CAV and worker-equipment conflicts and hazardous proximities. This data collection included various live roadway WZ scenarios staged along the Smart Road (described in detail below), providing individual workers and equipment positioning and passing vehicle trajectories to support the development and validation of the algorithms developed during this task. The collected data include typical naturalistic data variables plus video from the vehicles.

Three types of scenarios were developed for data collection: workers-on-foot, equipment, and CV/CAV scenarios. The team ran multiple iterations of each type of scenario on the highway section of the Smart Road using three different locations—a curved section; a straight, flat section; and a straight, sloped section—in order to collect data encompassing multiple real-world roadway configurations. Data collection scenarios were presented to VTTI's safety committee in order to gain approval to collect data on the Smart Road. The UWB-Alpha system developed in the third task was used for data collection. Figure 5 below shows an example of the UWB system setup used to collect data on a straight section of the Smart Road. Two cones (Cone 1 and Cone 2 in the figure) were equipped with sensors and represented the start and end boundaries of the WZ. Workers-on-foot and work equipment were tagged with UWB tags. In the case of workers-on-foot, the tag was considered the central point to develop the safety areas. For the equipment, two to four tags were mounted, depending on the size of the equipment, and were used to calculate the central point and develop safety areas. For data collection on curved roadway segments, an extra equipped cone was used to define the middle point for the curve configuration.

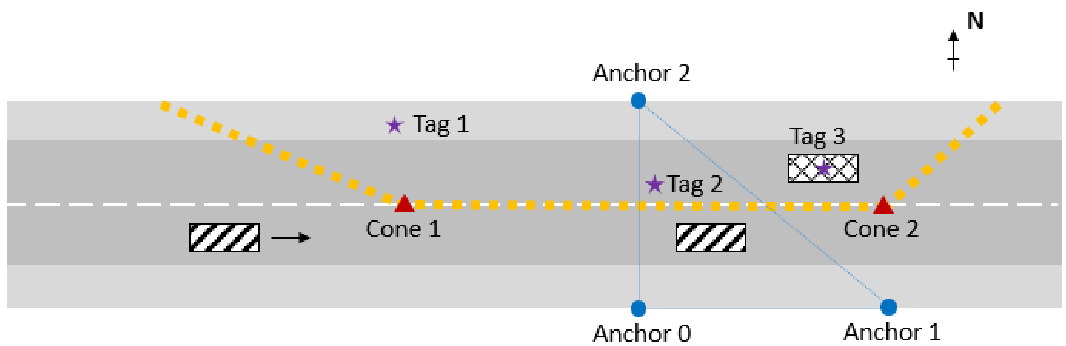

Figure 5. An example of the UWB system setup on the straight roadway section.

Equipment used in the experiments included a zero-turn lawnmower, a compact 4x4 utility vehicle, and a dump truck (indicated by "Tag 3" in the above figure). A CV (hashed rectangle in the figure) was also used in the experiments, and real-time locational data from the vehicle's OBU was sent through the VCC Cloud to VCC Monitor. In addition to the CV, each UWB tag (including anchor tags situated on cones and mobile tags on equipment or held by workers-on-foot) could be tracked in real time on VCC Monitor.

The research team conducted a literature and industry review to identify major activities involved in highway construction. The results of the review were used to create a list of activities to classify the movement patterns of WZ actors in order to predict their near-future movements. A total of 49 movement patterns were identified and categorized using the data collected, including three jackhammering samples, 16 walking samples, 10 rolling samples (hand-held equipment which required regular moving), 14 moving backward samples and six random movement samples (Table 1). During data collection, the workers-on-foot were instructed to mimic the movement patterns of each activity category and multiple passes were completed for each movement category.

Table 1. Description of Activity Categories Used for Activity Recognition

Category	Description
Jackhammering	Utilizing hand-held equipment which required a consistent or inconsistent static position, such as jackhammering, drilling, etc.
Walking	Normal walking or running.
Rolling	Utilizing hand-held equipment which required regular moving, such as a small compactor, etc.
Guiding	Workers may walk backward to guide dump truck or other heavy equipment to adjust equipment location(s).
Random	Random movement of workers, may include change of directions and other unpredictable activities.

Algorithm Development

In this step, the data collected in the previous task were used to develop the threat detection algorithm. The primary goal of the algorithm is to detect all potentially unsafe proximities between WZ actors and prioritize real imminent threats, taking into account all contributing factors. These factors include real-time location, movement and potential reactions of WZ actors, trajectory of passing CVs/CAVs, activity-related movement pattern history, WZ barrier type, real-time WZ configuration, and the space required for each WZ actor to accomplish their activities safely (called safety area herein). The algorithm utilizes location and WZ actors' movement and activity-related movement history, accordingly, to develop average work volumes and recognize worker activities. The recognized activities are then used to predict short-term movement probabilities and the required safety area for each actor. In this way, the developed algorithm minimizes the number of false positive alarms that can be generated and sent to the WZ actors and passing CVs/CAVs. Figure 6 shows the flow of data in the algorithm.

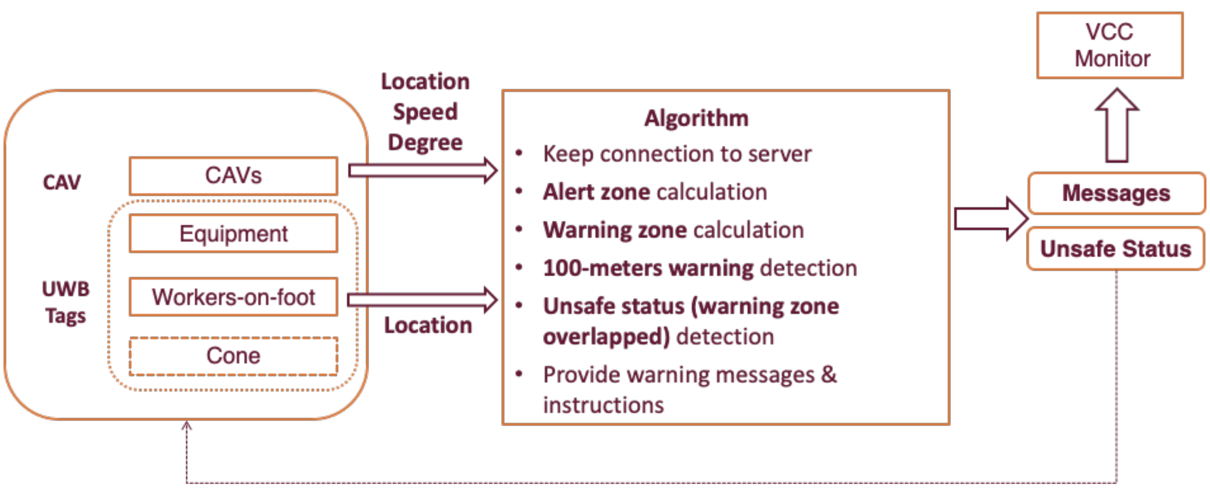

Figure 6. A diagram showing the flow of data in the algorithm.

Proximity Hazards Identification

The first step in the algorithm development was to identify potential hazardous proximities using the data stored in the database and gathered during the data collection. As such, safety areas were designed for each WZ actor (i.e., workers-on-foot, construction equipment, and CVs/CAVs) that considered the difference in movement patterns and type of vehicles/equipment as shown in Figure 7.

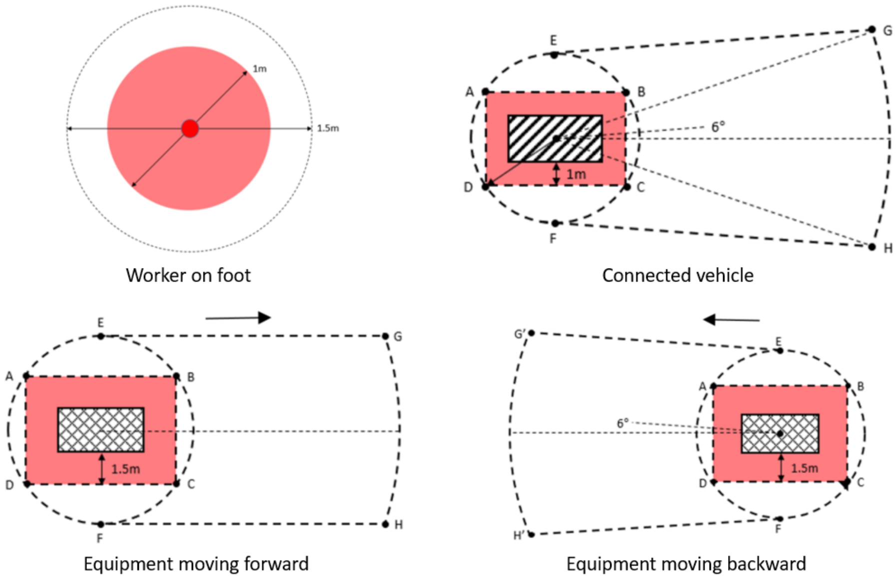

Figure 7. Representation of the safety areas designed for each WZ actor.

Safety areas introduced in this paper consist of two zones: alert areas (shaded in red in Figure 7) and warning areas (the remaining area within the dotted lines). The alert area is an inherently unsafe area around the actor. It is a fixed area in which, if invaded, the actor can be harmed due to unsafe proximity. Warning areas represent a lower level of risk than alert areas but are still considered hazardous. The warning area is defined by predicting the actor's location in the near future depending on their speed and current movement pattern/direction. The warning area helps in predicting potential hazards and reducing false positive alarms. If the warning area is larger or smaller than a reasonable scale, a false alarm will be sent, or no alarm will be sent even when an actor would be in imminent threat in the next few seconds. As such, the warning area helps predict potential hazards, preventing them before they reach the alert area (where a crash is definite).

For workers-on-foot, 1 m and 1.5 m are used as the radius of the primary alert area and the warning area, respectively, as shown in Figure 7. They are adopted based on the average minimum required distance between workers with different work operations and the vehicle's expected stopping distance (10). The size of workers' safety areas varies by different factors, including the activity (as explained in activity recognition), distance to the WZ border, and the shape of the road (described herein). A larger safety area is considered when a higher degree of danger is expected in order to be able to detect potential hazards earlier.

When it comes to equipment and vehicles, dynamic alert areas are designed based on the movement patterns and direction of travel. Key parameters for safety areas include velocity, direction, dimensions of the equipment or vehicle (length and width), and the friction coefficient of the road surface (0.8 is used as a typical value of friction coefficient in this research). Construction equipment and vehicles share roughly the same alert and warning area configuration with a few differences. Analysis of the CV movement resulted in a fan-shaped safety area with additional degrees of freedom considering the lane change. The safety distance is determined by computing vehicle/equipment stopping distance, considering the driver's reaction time as well as the deceleration time once the driver reacts. Equipment in WZs usually move in one direction with no additional degrees of freedom (no merging between lanes while carrying out an activity). As a result, the safety area for equipment moving forward is the same as for vehicles, without consideration of the steering angle. When the equipment moves backward, the safety area must also include the back of the equipment. Because the equipment operator has a limited field of view while reversing, a longer safety distance and larger turning angle are considered for backward-moving equipment to account for equipment blind spots. Considering a single lane change, a 6-degree steering angle is adopted to calculate the expanded warning area.

In addition to the type of actors and activity related movement, other factors related to workers' movements were also considered in the algorithm to detect potential threats. Workers' distance from border, road type (straight or curved), WZ barrier type, and undergoing activity were considered in determining safety areas and the relative data was gathered during the data collection, as shown in Figure 8.

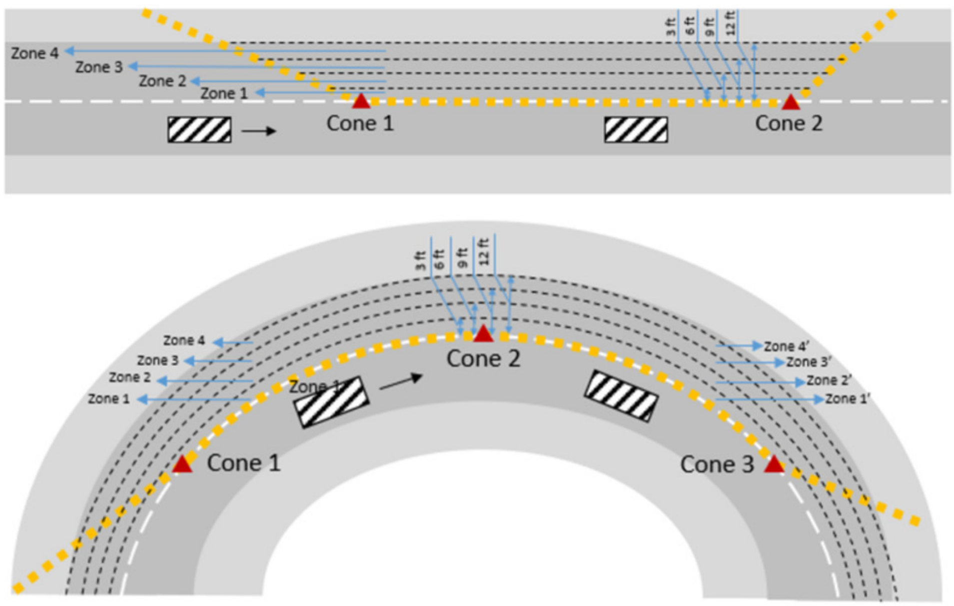

Figure 8. Representations of the data collection variations for straight and curved roadway segments.

The distance to the WZ border is also taken into account when determining the warning area. The closer workers stand to the WZ border, the higher the risks of being exposed to potential collisions. The U.S. Interstate Highway System generally employs a 12-foot standard lane width. In this research, a 3-foot width is used as a unit for partitioning. Hence, four separate zones are created in a single lane, as seen in Figure 8. Zones closer to the WZ border require larger warning areas with an assumed increase of 0.5 m of diameter between two adjacent zones. As such, warning areas with a diameter of 1.5 m were determined for workers positioned at the farthest zone (zone 4).

Vehicles are subject to centrifugal movement when traveling on a curve at a high speed, potentially leading to serious rollover accidents. Thus, curved sections of roads are more dangerous than straight sections. As a result, curved sections require larger warning areas for workers-on-foot to ensure their safety. As a worker approaches the border, the warning area diameter linearly increases by 0.5 m as the worker moves into each subsequent subzone (Figure 8). For curved sections, due to the higher risk caused by centrifugal movement of vehicles, the area to the right of Cone 2 (as shown in Figure 8 where the vehicle is departing the curve) could be more dangerous. As such, an 0.5 m increment is added to the diameter of warning areas after workers pass Cone 2 to compensate for the higher risk. Before passing Cone 2, the profile of the warning area in the curved section is the same as that in straight sections. This results in earlier detection of imminent threats and ensures additional safety for workers where they are more exposed to passing traffic, i.e., near the border.

Activity Recognition

The research team conducted a literature and industry review to identify major activities involved in highway construction. The aim of this step was to provide a list of activities based on what WZ actors' movements can be classified and what working activity can be detected and used to predict near-future movement. Data relative to each activity was collected and was then used to train the machine learning model. The second step in algorithm development was to utilize the data collected for each movement category (from Table 1) to train the machine learning model. The machine learning model was then utilized to classify workers' behavior in real-time based on the training data and to recognize activity categories of workers-on-foot. The safety areas were then developed based on the activity, as different levels of exposure to potential hazards are considered for each activity. Supervised learning was performed using MATLAB. Four feature selections for classification were speed, static time, movement direction as parallel/perpendicular to traffic, and going with/against traffic direction. All models in the Classification Learner toolbox were tested and compared, and the trained model with the highest accuracy was selected for activity classification and prediction. Initially, 65.3% accuracy was the highest achieved from Ensemble Bagged Trees, a combined machine learning method that groups weaker learners and outputs a stronger result. In order to improve the accuracy, the training process was split into two steps. The first step was to define the direction of movement in terms of parallel/perpendicular and moving with/against traffic parameters as shown in Table 2. Subsequently, using the detected movement directions, undergoing activities are recognized in the second step. This way, direction information was double verified, and the model accuracy was significantly improved. As a result, the accuracy was enhanced through further verification to 75.5% from Ensemble Bagged Trees.

Table 2. Influencing Factors in Activity Prediction

Prediction	Category
Direction	Parallel, Perpendicular, None
Traffic	Facing, In, None

Escape Direction Detection

The last step of developing the threat detection algorithm involved delivering instructions to workers about detected hazards, taking into account their activity classification and movement. Potential unsafe proximities are presented in red on the map when there is an interaction between safety areas of various actors suggesting an imminent threat. Eight points are considered around workers (north, northeast, east, southeast, south, southwest, west, and northwest) with each one a direction of potential escape. When a potential conflict/imminent threat is detected based on the predicted movement of actors and CV/CAV trajectories, the algorithm identifies the points that are located within the conflicting actors' safety areas. As such, each of the points outside of the conflict area(s) can be considered as a viable escape direction, taking into account all involved actors in the detected hazardous situation and the prediction of future trajectories and proximities of the actor with other actors. The current implementation solves for the escape direction on the server only, but in future iterations, an appropriate HMI will be developed to induce movement of the actor towards a safety escape direction. The actor could be directed to any of the viable escape directions that do not conflict with the other actor via a warning system, as shown in Figure 9. The team is currently working on integrating the algorithm into the VCC Mobile Application, so the warnings can also be sent to passing CVs/CAVs. It should be noted that escape directions are only considered for workers-on-foot. In the case of CVs/CAVs, they will receive notification regarding a potential threat to workers and will be instructed to brake.

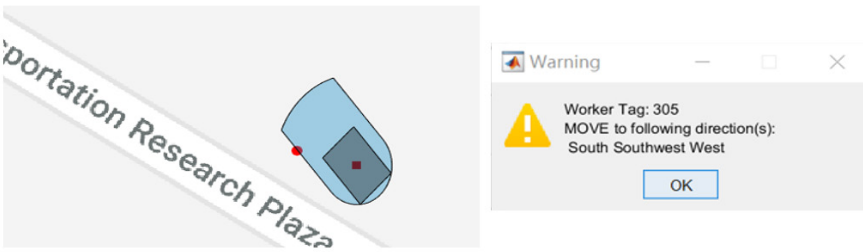

Figure 9. Visualization of a detected threat and generation of escape direction for a WZ actor in danger.

Task 5: Prototype Demonstration

Finally, a demonstration was conducted in May 2019 for Virginia Department of Transportation (VDOT)/Virginia Transportation Research Council stakeholders on the Smart Road to show proof of concept for the UWB system built in Tasks 3 and 4. In this demonstration, two to three example WZs were setup near staged lanes of traffic, each featuring different WZ tasks.

During the demonstration, mobile rover tags were carried by "workers" on foot, mounted on WZ equipment, and placed on cones to signify the WZ borders and to support their instantiation into the VCC Cloud system. Lastly, a CV, driven by a trained VTTI experimenter, drove predetermined routes alongside the roadway WZs demonstrating the proximity and threat message delivery to drivers when various threat levels existed. VTTI's existing VCC Mobile Application was utilized to demonstrate user interface concepts for the passing CV drivers. This prototype Android application demonstrated how real-time threats, determined by the threat detection algorithm, could be communicated to passing motorists or CVs/CAVs.

This demonstration showed the effectiveness of the threat detection algorithms developed in Task 4 and the capabilities of the UWB system and served as a platform to discuss potential follow-on development activities (Safe-D project: 04-104) relating to the localization of WZ entities and associated warning strategies with project stakeholders.

Results and Discussion

UWB System Results

The DecaWave system provided a range of only about 80 m in the outdoor environments used for testing and data collection, as opposed to the range of 290 m advertised in DecaWave's product materials. The system did provide a relative position accuracy of the tags of approximately 10 cm when within that 80 m range of the sensor constellation.

Despite the troubleshooting steps taken during the system build, the team was not able to improve the system's range. Upon further research, the team determined that UWB sensors work most favorably in indoor environments with walls and other solid objects that provide reflection to propagate/replicate the UWB signal. Thus, an open outdoor environment such as the Smart Road (and most other roadside construction environments) is not very conducive to UWB sensors.

Results may vary in other environments, such as urban canyons or more densely structured environments.

Algorithm Results

Four sets of experiments were carried out to collect data needed to develop the threat detection algorithm. The experiments were done on different parts of the highway section of the Smart Road: a half-mile straight section and curve section located at the highway section exit. During the experiments, various construction activity data was simulated and collected. The activities performed included jackhammering/drilling and similar activities consisting of workers being stationary for a period of time, walking parallel to traffic or perpendicular to traffic, approaching the WZ border, rolling/compacting consisting of slow parallel movements, guiding consisting of walking backward to guide trucks and heavy equipment, and random movements. Various scenarios for movement relative to heavy equipment were also carried out in different WZ locations, and at areas entering and exiting the WZ. Three workers, three piece of construction equipment (mule, mower, and truck) and one CV were involved in each set of experiments. The location data collected was used as training data in the algorithm to train the activity recognition part to recognize and categorize activities with similar movement patterns to those training data. Two sets of data were collected on each section, where one set of data was used to train the model and the other was used to test the accuracy of activity recognition. The developed two step activity recognition was able to reach 76% accuracy as shown in the matrix in Figure 10.

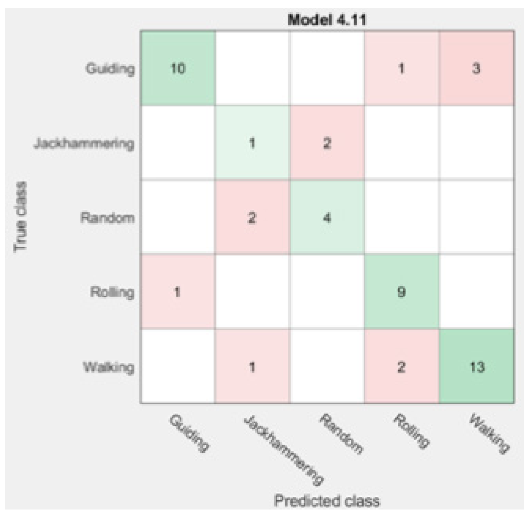

Figure 10. Confusion matrix of ensemble bagged trees.

The data collected during the experiments was also used for initial testing and visualization of the threat detection algorithm. Three other sets of tests were carried out to evaluate the implementation of the algorithm in the VCC Cloud and to ensure real-time flow of data to/from the server and prompt detection of the threats resulting in change of status. Based on the detected status and the message sent to the VCC Cloud server from the algorithm, the color of the dot representing the vehicle (or the tag) on VCC Monitor is changed. When the vehicle approaches an active WZ and is 100 m from the closest worker, the status is changed to proximity and a message is sent to the VCC Cloud server, which then changes the color of the vehicle dot to orange on the VCC Monitor display and also sends a proximity message to the respective driver. The proximity warning helps raise drivers' awareness of the existence of an active WZ ahead. Similarly, when an imminent threat is detected between any two or more actors, a threat message is sent to the VCC Cloud server to signal the entity is in a collision imminent situation. As a result, the color of the representative dots for the in-danger actors (i.e., worker, vehicle or equipment) is changed to red, and a message is shown on VCC Monitor and on the VCC Mobile app for drivers. It should be noted that the algorithm minimizes false alarms by considering the safety area and trajectory prediction combined. In other words, a proximity will only trigger an alarm when an imminent threat is detected based on the current and predicted trajectory of the actors. As an example, if a worker is working parallel to traffic near the WZ border while a vehicle is passing, an alarm will not be triggered, as the two near future trajectories do not collide. The experiments successfully verified the real-time acquisition of data from actors and communication of various safety statuses between the VCC Cloud, MATLAB algorithm, VCC Monitor and VCC Mobile app.

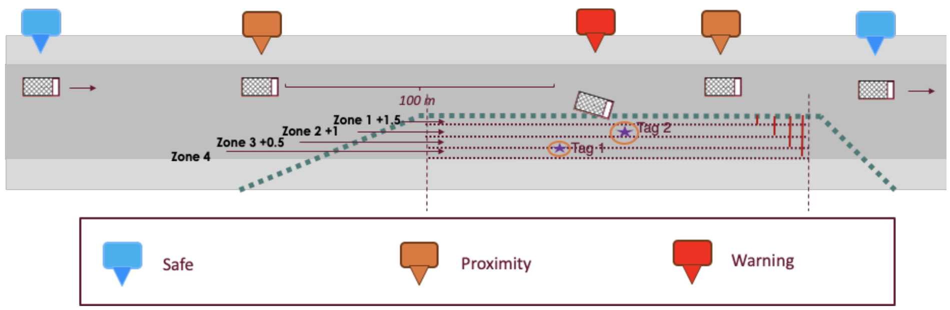

Figure 11. Visualization of change of status for vehicles passing WZ.

Conclusions and Recommendations

There is significant demand for products that can elevate safety in WZ environments. The advent of CVs/CAVs is driving WZ safety practitioners towards implementing solutions that will accurately and easily communicate the location of roadside workers to passing vehicles. At the onset of this project, and based on an initial technology review, the team believed that UWB sensors would be an optimal solution for accurately localizing WZ actors since it didn't have a line of sight requirement. However, upon further review and testing, the UWB technology proved to be less than ideal in an open outdoor environment, and therefore would not work well in the roadside WZ use case due to the general lack of reflective surfaces outside.

As such, the team will take the lessons learned regarding UWB technology and move forward with building a deployable, wearable WZ technology that uses an alternative localization technology.

Additional Products

The education and workforce development products as well as the technology transfer products that resulted from this project can be found on the project page of the Safe-D website. The final project data set is located on the Safe-D Collection of the VTTI Dataverse, as described below.

Education and Workforce Development Products

VTTI participated in an event held by VDOT on April 9, 2018 in Richmond, Virginia to bring awareness to WZ safety during the National Work Zone Awareness Week. VTTI shared various VCC applications relating to WZ safety, including the WZ Mapping Application, with hundreds of VDOT employees during this event. VTTI held a CV/CAV training with about 50 VDOT employees on May 31, 2018, in Fairfax, Virginia. This training included the presentation of information on the WZ builder application and other WZ safety elements.

The database was presented in the existing undergraduate level course (BC 2114: IT in Construction) taught by Dr. Roofigari-Esfahan in the Department of Building Construction at VT, focusing on the safety constraints for highway activities and movement of workers. The algorithm was also presented in the existing undergraduate level course (BC 2114: IT in Construction) taught by Dr. Roofigari-Esfahan in the Department of Building Construction at VT, focusing on the hazard detection strategies.

In November 2018, a poster was prepared and presented to industry experts at VTTI's ribbon cutting event for their new Automation Hub building. This event included many industry experts, including representatives from top automotive manufacturers and regional/state road operators. The graduate student assisting on this project presented this poster, summarizing the project, the methods used, the experiments/data collection activities, the results, and planned future work.

A conference paper was developed and was submitted and accepted for oral presentation at the International Workshop on Computing in Civil Engineering (1C3E). A journal paper expanding on the conference paper is also under development. The advising committee for this project's graduate student's thesis was also formed and the student finished writing her master's thesis and will graduate in Spring 2019. Another PhD student (cost shared) was involved in carrying out the literature review relative to experiment plans as well as data collection experiments.

Technology Transfer Products

This project evaluated the use of UWB technologies for outdoor WZ worker localization. Ultimately, the project team has concluded that while UWB can be used to accurately localize a worker in a WZ, the practical range and line of sight limitations observed during implementation limit its effectiveness as a WZ solution. The actual range of the UWB system was found to be about 80 m, which is far less than the advertised range of 290 m. UWB does provide 10 cm accuracy when deployed with the shorter range constellation, but practically speaking, it may not be feasible to deploy enough of the base stations to cover large WZ areas and to avoid line of sight limitations between the base stations and tags. Therefore, the project team does not recommend the use of UWB technologies in outdoor WZ environments as a result of this project's findings.

The project did result in the development of some important products that can be used in the development of solutions that employ alternative localization technologies. For example, the algorithms for classifying worker activity, detecting conflict potential, and providing warnings to drivers and workers were developed and deployed within the VCC Cloud computing environment. These algorithms will be used during the implementation of a connected Smart Vest that will be built during the team's follow-on Safe-D project 04-104. This vest will use Real-Time Kinematic -corrected GPS instead of UWB but will use the algorithms and communications channels established during this project to assess and act on the threats.

Throughout the course of this project, the team engaged with multiple WZ safety stakeholders, including subject-matter experts from VDOT as well as private industry representatives from companies such as Flagger Force and iCone. VTTI also met with Transurban and DBi Services to discuss WZ safety. DBi volunteered to be an "early implementer" of a worker localization and communication system similar to that which we attempted to develop in this project, and which we will continue to develop in the 04-104 project.

The team also documented the final demonstration of this UWB system to showcase the communications and proximity and threat message delivery resulting from the algorithm developed in Task 4. This documentation included a video that can be shared with industry partners and other stakeholders engaged throughout this project, and will also support the follow on project 04-104.

Two scientific papers will be generated as a result of this project as noted above.

Data Products

Location data was collected from the highway actors during data collection (Task 3). The data include GPS coordinates collected and sent to the server through UWB tags held by workers and mounted on equipment, and CAV data collected through an OBU. The data was received in CSV format and was used to train the algorithm developed in Task 4. The data collected from the tags consists of the following information: tag ID, timestamp, and latitude and longitude for tags and anchors. The data collected from CV OBUs include RSEID, RSE group, timestamp, latitude, longitude, elevation, heading, acceleration, and vehicle dimensions. This data can be accessed at the following link:

https://dataverse.vtti.vt.edu/dataset.xhtml?persistentId=doi%3A10.15787%2FVTT1%2FXUJAWN

References

1. American Road & Transportation Builders Association. Work zone fatal crashes and fatalities. *The National Work Zone Safety Information Clearinghouse.* [Online] 2019. https://www.workzonesafety.org/crash-information/work-zone-fatal-crashes-fatalities/#national.
2. FHWA. Facts and Statistics - Work Zone Activity. *Work Zone Management Program.* [Online] February 5, 2017. [Cited: March 11, 2019.] https://ops.fhwa.dot.gov/wz/resources/facts_stats/activity.htm.
3. Centers for Disease Control and Prevention. Highway work zone safety. [Online] June 19, 2017. https://www.cdc.gov/niosh/topics/highwayworkzones/default.html.
4. *Proceedings of Canadian Society for Civil Engineering.* Roofigari-Esfahan, N., Wang, J & Razavi, S. Vancouver, UBC, Canada : s.n., 2015.
5. *Smart Tracking of Highway Construction Projects, International Workshop on Computing in Civil Engineering.* Roofigari-Esfahan, N., Du, S., Razavi, S. & Anumba, C. Seattle, WA : s.n., 2017.
6. Bowman, D. S. & Martin, T. L. An innovative intelligent awareness system for roadway workers using dedicated short-range communications . *Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC).* [Online] 2015. https://cvi-utc.org/wp-content/uploads/2015/10/Bowman_Final.pdf.
7. *Work Zone Intrusion: Technology to Reduce Injuries and Fatalities.* Nnaji, C., J. Gambatese, and H.W. Lee. 4, 2018, Professional Safety, Vol. 63, pp. 36-41.
8. *Evaluation of SHRB work zone safety devices.* Agent, K.R. and J.O. Hibbs. 1996.
9. SonoBlaster Work Zone Intrusion Alarm. *Transpo Industries.* [Online] 2017. https://www.transpo.com/roads-highways/safety-products/wz-intrusion-alarm.
10. *What drives consturction workers' acceptance of wearable technologies in the workplace? Indoor localization and wearable health devices for occupational safety and health.* Choi, B., S. Hwang, and S. Lee. 2017, Automation in Construction, Vol. 84, pp. 31-41.
11. *Feasibility analysis of heart rate monitoring of consturction workers usin ga photoplethysmography (PPG) sensor embedded in a wristband-type activity tracker.* Hwang, S., et al. 2016, Automation in Construction, Vol. 71, pp. 372-381.
12. *Action recognition using a wristband-type activity tracker: Case study of masonry work.* Ryu, J., et al. 2016, Construction Research Congress.
13. *Maytag-A wearable wrist device for localization applications.* Silva, S., P.M. Mendes, and L. Domingues. 2010, Pervasive Computing Technologies for Healthcare.
14. [Online] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4883398/ .
15. *DecaWave.* [Online] https://www.decawave.com/products/trek1000.
16. Lombardo, J. How connected vehicles make work zones safer. *For Construction Pros.com.* [Online] August 17, 2017.

https://www.forconstructionpros.com/asphalt/article/20867242/how-connected-vehicles-make-work-zones-safer.

17. *Developing a decision-making framework to select safety technologies for highway construction.* Nnaji, C., et al. 4, 2018, Journal of Construction engineering and management, Vol. 144.

Appendix

Literature Review

Technology Review

At the onset of the project, the team believed that UWB's capabilities were a good fit for this application in that it could provide support for both the localization and communication functions in a single package. For this use case, the chosen localization technology must meet certain accuracy standards (must be reliably less than or equal to one m in order to provide at least lane-level accuracy). In addition to being accurate, the chosen technology components must be durable, compact, and require relatively low power consumption allowing all WZ personnel to wear or carry the "tag" or tracked component at all times while at the WZ. The technology must also be easily deployed on the side of the road. UWB technology, unlike other localization technologies (e.g., infrared, ultrasound) "does not require a line-of-sight and is not affected by the existence of other communication devices or external noise due to its high bandwidth and signal modulation. Furthermore, the cost of UWB equipment is low and it consumes less power than other competitive solutions" (14).

Upon selecting UWB as the localization technology, the team completed a review of available off the shelf UWB systems and brands. Based on this review, the team chose the DecaWave TREK1000 Evaluation Kit (Two-Way-Ranging Real Time Location Systems IC Evaluation Kit) and felt that this system would best fulfill the criteria outlined (15).

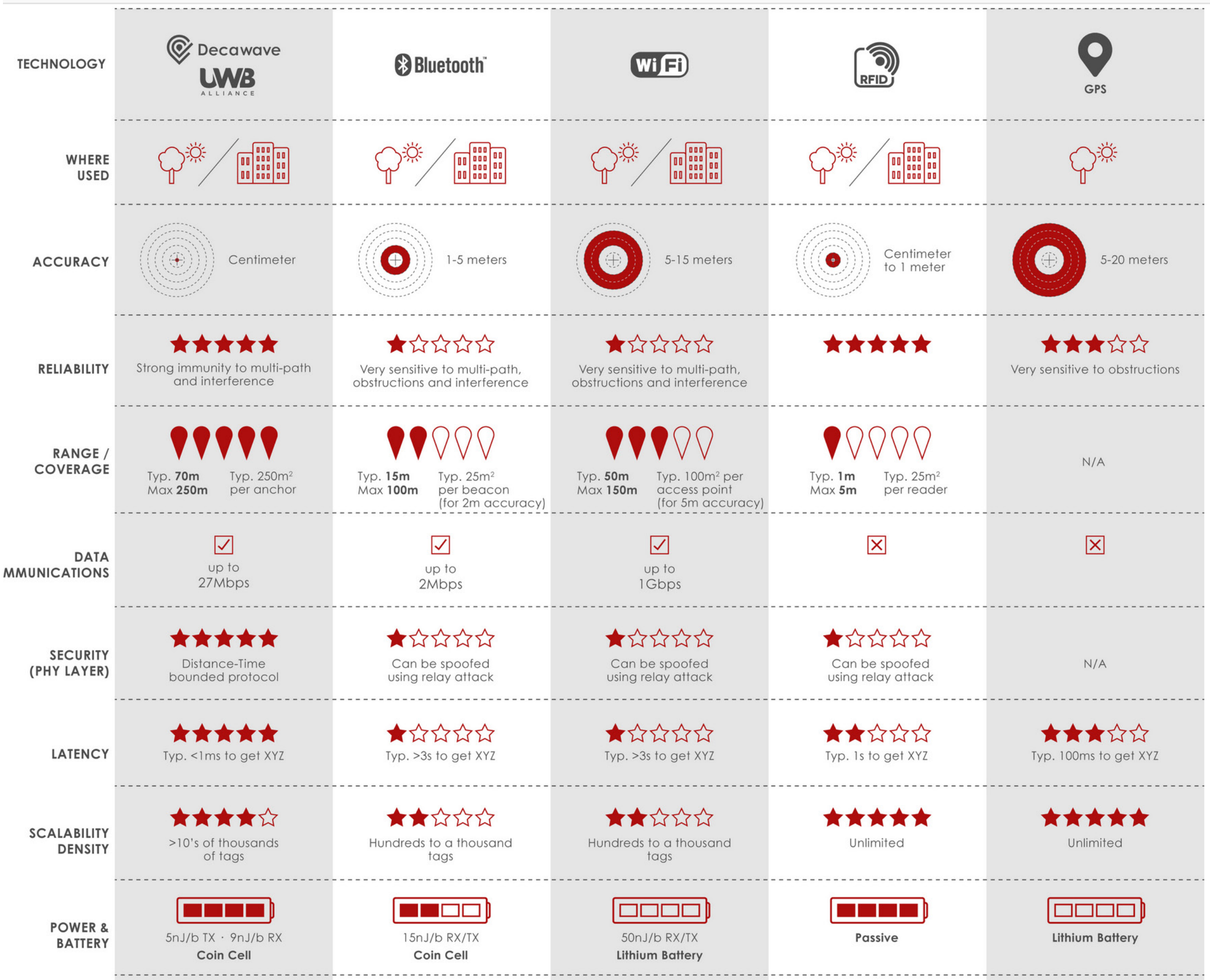

Figure 12: Decawave UWB specs (https://www.decawave.com/technology1/)

As seen in Figure 12, the DecaWave system advertised a range of 250 m, which was much better than other systems that were researched that were only around 60 m. The DecaWave also advertised precision of 10 centimeters. The system can support up to eight mobile "tags" and three anchors. Multiple other options were considered (infsoft, BeSpoon, Pozyx, Redpoint), but ultimately passed on for various reasons, including availability, accuracy, technical specifications (range limitations) and price.

Work Zone Intrusion Alarm Technology (WZIAT)

One of the most important issues that needs to be addressed to improve highway construction safety is to warn workers of dangerous situations to allow workers enough time to react before an accident occurs. Previous studies have indicated that even though essential safety training has been put in place to improve construction workers' safety awareness, the unsafe behaviors of construction workers in addition to their lack of situation awareness remained a major cause of many accidents at highway work zones [6]

Work Zone Intrusion Alarm Technology (WZIAT) was invented in an effort to solve this problem. The technology integrates proximity detection and an alarm system to send audible alerts to workers, taking into account the reaction time needed for workers to act on the received warning

[7]. WZIAT was first introduced in 1995 by a study that focused on evaluating Strategic Highway Research Program (SHRP) work zone safety devices [8]. SonoBlaster and Intellicone are two common WZIAT devices available in the market. The SonoBlaster device is placed on traffic cones and can be activated when the traffic cone is tilted during an intrusion [9]. Intellicone is another type of WZIAT device that consists of motion sensors and portable site alarms. If a vehicle comes close enough to the work zone, it can be detected by motion sensors and the alarm system will be triggered. A portable site warning device will then produce an audio-visual alarm to warn workers of potential danger [2].

Wearable Technology Combined with WZIAT

Wearable technology has a wide range of applications and in recent years there has been a trend to combine wearable technology with WZIAT to provide workers with a more convenient and efficient device to ensure their safety. Traffic Guard Worker Alert System (WAS) [2] is a great example of the combination of wearable technology and WZIAT. The WAS is a pneumatic-based alarm system consisting of an audio-vibratory personal safety device (PSD), pneumatic tubes and other devices. When an unplanned vehicle intrudes into the work zone, pneumatic tubes are compressed and simultaneously activate the PSD attached to worker’s belt that would subsequently release an alarm to alert workers of the dangerous situation [2].

The real-time information delivery, convenience, and portability characteristics of wearable devices in addition to their ability to be connected to networks and/or other equipment, caused them to be commonly used in healthcare industry for continuously monitoring patients’ physiological status [10]. These advantages also make wearable technology a viable solution for upgrading construction safety devices. Since the wearable devices usually are in direct contact with the human body, they can effectively transmit warning to the workers without consideration of effective distance. It could also integrate some advanced functions to further increase highway work zone safety, such as communication, worker localization and movement tracking, or even monitoring worker’s physical status for medical and insurance purposes.

Given the benefits of wearable technology, it has a great potential to elevate the safety level for highway workers when combined with WZIAT. However, in order to effectively employ wearable devices to enhance construction safety a number of questions need to be addressed; including the type of wearable device that fits the purpose, the type of alarm that can be provided without interrupting the work underdone as well as user preferences in terms of factors that would affect comfort, convenience, working process, and user habits. Sections 2 and 3 will discuss various types of available wearable devices, alarm signals, and their applications in construction and other areas. These factors will be discussed in Section 4. The last two sections will discuss some available wearable alarm devices at current stage and their limitation.

Types of Wearable Devices

Smart Watch/ Wristband

Smart watches are one of the most common types of wearable devices. There are various smart watch products available in the market. Most smart watch products connect to other smart devices and networks. Researchers have been using smart watches to collect physical data in construction related studies. A wristband-type wearable activity tracker was introduced in a study to monitor construction workers’ heart rates with an embedded photoplethysmography (PPG) sensor [11]. A Basis Peak smart watch was used to collect heart rate, skin temperature, steps, and calories burned to identify if the worker's physical status qualified for specific tasks [6]. In another research study, a wrist-worn accelerometer was employed to track the motion of masonry workers [12].

By integrating location services such as GPS, smart watches have been helpful location tracking tools. Some studies also adopt location technologies other than GPS for specific purposes. MagTag is a new type of smart localization device based on Wi-Fi used for monitoring of patients at home [13]. WristQue is another type of wearable wristband device similar to MagTag that provides precise indoor localization [14]. Hybrid Technology Smart Wristband was developed to approximately locate dead and live injured people for a quicker rescue operation in cases of traffic accidents in highways [15]. Overall, wearable wristband devices are widely preferred by different industries since they have the highest consumer interest level among other wearable devices [16]. However, despite its potential for improving workers' safety, no specific use of wearable wristbands have been reported for highway projects.

Construction Helmets

Construction helmets are essential personal protection equipment (PPE) required of construction workers while at work. As a result, integrating WZIAT into construction helmets has the potential to provide a sensing device for workers without unnecessarily adding extra equipment to them. Teizer [17] developed a safety device called Self-Monitoring Alert and Reporting Technology for Hazard Avoidance and Training (SmartHat) as a real-time hazard proximity alarm and communication system prototype that was embedded in a hard hat. Through several field experiments, the SmartHat proximity detection and alert system was proved to be reliable and effective to provide sufficient alerts for construction workers in various hazardous proximity cases. A study on underground mining safety also used smart helmets as a part of an intelligent sensing and warning system [18]. In the study, multiple mine environment parameters were monitored by various sensors, such as temperature, pressure, and humidity. When the sensors detected that any parameter exceeded the safety limit, a locating system was activated to locate the workers.

Smart Safety Glasses

Safety glasses are also required at many construction worksites as mandatory PPE while performing certain activities and accordingly could be transformed as a type of wearable alarm device without adding to the worker's burden. Lightweight and easy-wearing, smart glasses can integrate cameras, touchpads, speakers, microphones, as well as advanced functions like navigation, sound control or other smart functions for various operations[19]. VisAural is a wearable sound-localization device for people with impaired hearing [20]. This device can convert audible signals into visual cues and use the visual signal to guide users to the source of the sound. This study showed a successful application of smart glasses in localization. However, no similar research was found in construction safety area.

Belt

The Traffic Guard Worker Alert System (WAS) discussed in section 1 employed belts as wearable alarm devices which were attached to workers' bodies [2]. However, belt is not a fixed option in the study, other comfortable positions can also be considered. Although security belt could be used as wearable device for patients to support other implantable medical devices, [21] it is not common as part of alert system especially in construction area.

Vest

Similar to other construction projects, highway construction workers are also required to wear safety vest to ensure visibility to construction machinery as well as passing traffic. Usually safety vest features bright colors such as yellow/lime and orange. Since safety vest is required in construction environment, it is feasible to conveniently use vest as wearable alarm device for WZIAT. Furthermore, since safety helmets were usually worn inappropriately, vest could be a better choice for alarm device [22]. In fact, several studies have delved into the possibility of vest alarm device, and developed prototypes for vest alarm device.

Virginia Tech engineers, led by Tom Martin, since 2013, have developed InZoneAlert vest. It is a safety-zone vest with sensors, which would warn not only workers but also driver of an unplanned vehicle if it gets too close proximity to construction workers. Connected and Automated Vehicle (CAV) technology has also been used in this new type of alarm technology. Wireless sensor technology enables vehicle communication with one another to avoid collision. Early tests shown about 90% successful rate for the InZoneAlert vest [23]. In 2015, Redpoint Positioning Corporation provided a new safety alert solution which also used safety vest as wearable device. Redpoint Real Time Location System (RTLS) has a very high precision and is able to alert workers accurately. When construction workers enter hazardous area, RTLS system embedded in safety vest would be triggered and use visual and audible alarm to warn workers of potential hazards (PRWeb Newswire, 28 Apr. 2015).

Some safety researches in other areas also indicated vest as a feasible choice of an alarm system. For example, Body-worn Antenna Vest (BWAV) has demonstrated its efficiency in a military program. BWAV could facilitate hands-free operation of man-portable radio communications and threat warning equipment while minimizing impairments due to human body interaction [24]. Consequently, vest is a viable choice of personnel alarm device as it can generate little impairment to workers' daily work performance and minimize the required equipment which construction workers have to use during their work. Also, vest has enough space for placing sensors and alarm devices.

Others

Besides wearables fixed at specific locations, there are some other new types of wearable devices that can be attached to workers at different body parts including joints to monitor physiological status. Occly Blinc ™ is one of the examples that is mainly used for personal security purposes. It is a wearable alarm system which is able to initiate alerts during an imminent accident, then send the in-danger person's location and real-time images or messages to alert his/her family and friends. Occly Blinc ™ could be worn wherever you want. Because of its small size, it could be placed on the arm, attached to handbag/backpack or any other accessory (Professional Services Close-Up, 24 June 2017. Business Collection). In fact, wearable alarm devices such as Occly Blinc ™ have the potential to be widely used in near future, because there is no requirement for device location, making it flexible for users to choose a location based on their own comfort. However, it would be easily lost by users due to its small size and flexible locations.

Alarm Type

Generally, alarm signals include auditory, haptic or visual elements. It is also common to combine two or even more alarm signals. The following paragraphs discuss three major signal types which are successfully used in safety devices.

Visual Signal

Visual alarm signal is a common signal type in construction field. Examples include flashing stop/slow paddle or all-terrain sign and stand. Visual alarm plays an important role in various unsafe situations, especially in alerting drivers at night. Effective alarm signals should be easily noticed by users. A salient visual alarm could use color, hue, saturation, intensity or combination to convey an urgency situation [25]. Intrusion alarms made by Traffic Management Corporation and Columbia Safety Sign Company included flashing strobe light in the system. In some intrusion alarm systems, visual signal is combined with auditory signal.

However, a major disadvantage of visual alarm is that it needs workers' uninterrupted attention to the alarm otherwise users may miss the alarm since stimuli locates away from central vision [25]. Unlike passing drivers, construction workers generally focus on their own work instead of situations on the road. Visual signal may not be enough to generate sufficient alarm. In a study on alerting options of vest, many participants stated that it was hard to see the light warning since they were looking forward or upward for working [22]. As a result, for visual alarm design, lights should be placed as close as possible to human body, and a bright light is also needed. However, increasing the brightness of alarm could increase the harm to workers' eyes. Different means of demonstration such as safety glasses can also be used instead the visual lights, to transmit the required warning to the workers.

Audible Signal

Audible alarm is the most common type of alarm which is widely used by many electronic devices. Unlike visual alarm, audible alarm does not have many requirements for location, which allowed the alarm system to be placed more flexibly. In construction safety field, audible signal has been widely used for alarming. In WZIAT, auditory alarm is more common than visual alarm. In a study of Kenneth Agent which aimed at evaluation of SHRP work zone safety devices, all five intrusion alarm products tested used audible alarm ranging from 110 dB to 150 dB to provide siren warning [8].This study has proved that audible alarm is more efficient than visual alarm. In the study of alerting method on vest-worn system, an audible signal which was a mix between a beep at 3kHz and a ramp signal going from 2.5kHz to 4kHz was tested. The outcomes have shown that participants responded faster to audible alarms than other types of alarms. In fact, audible alarm was the only one that caught participants' attention within 2.5 seconds [22].

Despite their outstanding performance in providing efficient alerting, audible alarms have some disadvantages. Audible alarm could only be effective when it is heard by workers. In a highway construction site, noise level could be higher than general conditions. Auditory alarm needs to be salient in a noisy background without irritating construction workers. Typically, about a 30 dB difference above the noise level could guarantee detection [26].

Haptic Signal

A haptic/tactile signal is another common type of alarm signal. Vibration is the most common haptic alarm signal being used in alarm devices. Usually, vibration sensors are placed on a low movement area to ensure measurement consistency between sensors and skin, e.g wrist, neck, and shoulder [27]. Vibro-tactile design was found to be useful since its various features such as small size, light weight, and being salient. A flexible vest could be an ideal platform for vibro-tactile technology [27]. In the research of alerting method on vest-worn system mentioned in 3.1and 3.2, tactile technology has also been evaluated. Sawtooth waveform ranging from maximum to minimum vibration strength has been used in the study. Tactile sensors were placed on shoulder and neck area on the vest. However, vibrating signal might not be effective if participants wear thick closing [22]. Also the threshold of vibration sensation needs to be considered. In construction worksites, daily activities such as drilling, walking or other movement could result in vibration of the body that could possibly reduce the efficiency of vibro-tactile alarm. The result of vest-worn alerting method research showed that participants could react faster than visual alarm after receiving vibration, but it would also depend on user perceptions [22].

Multi-modal Alarm

To ensure the efficiency of alarm system, several alarm types could be combined. Study by Wickens has revealed that multimodal information would decrease the perception time [28]. Some following studies further approved this theory and found that response time was reduced with multimodal signals. Multimodal could even reduce the error rates [29-31]. Although a common idea is that combined signals should be better than single signal alarm, the efficiency for specific use should be investigated.

Based on the literature review of Herring & Hallbeck, multimodal visual and tactile alert system wearables are the best viable combinations. It also highlights the importance of selecting body location for tactile sensors [25]. Results achieved by [22] showed that auditory-visual-haptic alerting method is similar to auditory-haptic, both of which have a shorter response time than visual-haptic alerting method. Furthermore, participants completed secondary tasks faster under audible-haptic combination [22].

In conclusion, multimodal alarm works better then single signal alarm. Participants with multimodal alarm including audible alarm perform better than without audible alarm. Considering user perception, auditory-haptic would works better than other multimodal alarming systems.

Other Factors

Besides selection of different types of signals and wearable devices, other important factors which may influence efficiency of wearables or subjective feeling of construction workers also need to be considered when developing an alarm system. According to a literature review by Awolsi, four safety performance metrics need to be considered: 1) physiological monitoring 2) environmental sensing; 3) proximity detection; 4) location tracking [16]. To satisfy those requirements, sensors are needed to monitor both construction workers and vehicles' trajectory, and the communication technology should be precise, reliable and real-time.

Besides the performance of wearable technology, other elements should also be considered including:

- Size and weight of device: The size of the wearable technology has direct impact on the experience of workers and their willingness to use it; because workers need to carry other necessary tools for work. Notice that battery's capacity is directly related to its size and weight. Before designing or choosing the wearables, how powerful the device need to be should be determined [16].
- Perceived usefulness and risk: Subjective thoughts from workers themselves also can influence their acceptance of new technology. It is necessary to learn their own thoughts about new alarm product. Probably it could help design education of new wearable technology.
- Social influence: Usually a new technology would raise discussion in industry, what other workers would think probably could also impact the usage of new wearables [10].

Conclusions

Based on the results of the literature review, the team concluded that haptic and auditory alarms would be the most effective in the roadside work zone use cases. Regarding the haptic alarm type, the location of the HMI device on the body is important, as it must be in a low-movement area to ensure measurement consistency between sensors and skin, such as the wrist, neck, or shoulder. Furthermore, for the roadside work zone use case, the alarm should address directionality (i.e., the direction from which the potential hazard is coming from and/or which direction the worker should retreat to in order to avoid the hazard) as well as the level of threat (i.e., an advisory versus a warning indicating a more imminent threat).

Literature Review References

1. NIOSH, *Preventing injuries and deaths of workers who operate or work near forklifts*. 2014, The National Institute for Occupational Safety and Health (NIOSH).
2. Nnaji, C., et al., *Developing a Decision-Making Framework to Select Safety Technologies for Highway Construction.* Journal of Construction Engineering and Management, 2018. 144(4): p. 04018016.
3. Gambatese, J.A., F. Zhang, and A.M. Vahed, Implementing speed reductions at specific interstate work zones from 65 mph to 35 mph: appendices to final report. 2013, Oregon. Dept. of Transportation. Research Unit.
4. Shen, X., J. Dumpert, and S. Farritor, *Design and control of robotic highway safety markers.* IEEE/ASME Transactions on Mechatronics, 2005. 10(5): p. 513-520.
5. Esmaeili, B. and M. Hallowell, *Integration of safety risk data with highway construction schedules.* Construction Management and Economics, 2013. 31(6): p. 528-541.
6. Guo, H., et al., The availability of wearable-device-based physical data for the measurement of construction workers' psychological status on site: From the perspective of safety management. Automation in Construction, 2017. 82: p. 207-217.
7. Nnaji, C., J. Gambatese, and H.W. Lee, *Work Zone Intrusion: Technology to Reduce Injuries and Fatalities.* Professional Safety, 2018. 63(04): p. 36-41.
8. Agent, K.R. and J.O. Hibbs, Evaluation of SHRP work zone safety devices. 1996.
9. Transpo Industries, I. *SonoBlaster® Work Zone Intrusion Alarm*. 2017 [cited 2017; Available from: https://www.transpo.com/roads-highways/safety-products/wz-intrusion-alarm.
10. Choi, B., S. Hwang, and S. Lee, What drives construction workers' acceptance of wearable technologies in the workplace?: Indoor localization and wearable health devices for occupational safety and health. Automation in Construction, 2017. 84: p. 31-41.
11. Hwang, S., et al., Feasibility analysis of heart rate monitoring of construction workers using a photoplethysmography (PPG) sensor embedded in a wristband-type activity tracker. Automation in Construction, 2016. 71: p. 372-381.
12. Ryu, J., et al. Action recognition using a wristband-type activity tracker: Case study of masonry work. in Construction Research Congress 2016. 2016.
13. Silva, S., P.M. Mendes, and L. Domingues. Magtag-A wearable wrist device for localization applications. in Pervasive Computing Technologies for Healthcare (PervasiveHealth), 2010 4th International Conference on-NO PERMISSIONS. 2010. IEEE.
14. Mayton, B.D., et al. WristQue: A personal sensor wristband. in Body Sensor Networks (BSN), 2013 IEEE International Conference on. 2013. IEEE.

15. Kamruzzaman, M., et al., DESIGNING AN INFRASTRUCTURE BY RFID BASED HYBRID TECHNOLOGY SMART WRISTBAND (HTSW) TO ENHANCE THE QUICK RESCUE OPERATION IN INDUSTRIAL ACCIDENT.

16. Awolusi, I., E. Marks, and M. Hallowell, Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices. Automation in Construction, 2018. 85: p. 96-106.

17. Teizer, J., Wearable, wireless identification sensing platform: self-monitoring alert and reporting technology for hazard avoidance and training (SmartHat). Journal of Information Technology in Construction (ITcon), 2015. 20(19): p. 295-312.

18. Shabina, S. Smart Helmet Using RF and WSN Technology for Underground Mines Safety. in Intelligent Computing Applications (ICICA), 2014 International Conference on. 2014. IEEE.

19. Wei, L. and Q. Zhang, Real-Time Traveling Information System Based on Wearable Technology, in ICTE 2015. 2015. p. 441-447.

20. Gorman, B.M. VisAural:: a wearable sound-localisation device for people with impaired hearing. in Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility. 2014. ACM.

21. Kulaç, S., *Security Belt for Wireless Implantable Medical Devices.* Journal of medical systems, 2017. 41(11): p. 172.

22. Hines, K.P., Exploration of alerting methods on vest-worn systems. 2016, Virginia Tech.

23. Grose, T., *SMART SAFETY VESTS.* ASEE Prism, 2015. 25(2): p. 13.

24. Kohls, E., et al. A multi-band body-worn antenna vest. in Antennas and Propagation Society International Symposium, 2004. IEEE. 2004. IEEE.

25. Herring, S. and M. Hallbeck, *Conceptual design of a wearable radiation detector alarm system: A review of the literature.* Theoretical Issues in Ergonomics Science, 2010. 11(3): p. 197-219.

26. GORDON-BECKER, S.E., et al., *An introduction to Human Factors Engineering.* Google Scholar, 2004.

27. Gemperle, F., N. Ota, and D. Siewiorek. Design of a wearable tactile display. in Wearable Computers, 2001. Proceedings. Fifth International Symposium on. 2001. IEEE.

28. Wickens, C.D. and J.G. Hollands, *Attention, time-sharing, and workload.* Engineering psychology and human performance, 2000. 3: p. 439-479.

29. Liu, Y.-C., Comparative study of the effects of auditory, visual and multimodality displays on drivers' performance in advanced traveller information systems. Ergonomics, 2001. 44(4): p. 425-442.

30. Chan, A.H. and K.W. Chan, Synchronous and asynchronous presentations of auditory and visual signals: Implications for control console design. Applied Ergonomics, 2006. 37(2): p. 131-140.

31. Doyle, M.C. and R.J. Snowden, *28 The effect© f auditory warning signals on visual target identification.* Engineering Psychology and Cognitive Ergonomics: Volume 4: Job Design, Product Design and Human-computer Interaction, 2017: p. 245.