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NCHRP IDEA Program

A Low-Cost Mobile Proximity Warning System in Highway Work Zone

Final Report for
NCHRP IDEA Project 187

Prepared by:
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Georgia Institute of Technology

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IDEA Program Final Report

NCHRP-IDEA 187

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The National Academies

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CONTENTS

EXECUTIVE SUMMARY

Safety is one of the most important components that need to be successfully addressed during construction. The work environment in the U.S construction industry has proven to be one of the most dangerous work environments among many other industrial segments (*1*). A work zone is defined, in Section 6C.02 in the Manual on Uniform Traffic Control Devices (MUTCD) 2009 (*2*), as "an area of a highway with construction, maintenance or utility work activities." A workspace is provided as part of an activity area to be used for workers, equipment and construction material storage. This limited workspace may need to move with the progress of the work and this characteristic sometimes imposes highly occupied working environments, which may result in hazardous proximity situations with a high level of interactions between pedestrian workers and dynamic construction equipment. The construction industry accounts for the highest number of fatal work injuries of any industry sector in the U.S. (*3*). During a decade, approximately a quarter of all construction fatalities are caused by visibility-related issues, a majority of which involve construction equipment and pedestrian workers. United States Department of Labor and Occupational Safety & Health Administration reports that a total number of 4,405 and 4,628 fatal work injuries were recorded in 2013 and 2012, respectively. One of the most common causes of loss of life at construction sites are accidents resulting from collisions between workers and a vehicle or equipment. This type of accident accounts for nearly half (443 deaths) of 962 deaths recorded in road construction sites from 2003 to 2010 (*4*), (*5*). These historical incident data prove that the current safety practice has not been effective in providing protective working conditions, and further improvements are essential for construction safety in work zones.

Advances in sensing and equipment control technology and their integrated combinations can be considered to be an opportunity to assist construction personnel in avoiding accidents, especially hazardous proximity incidents. Significant research efforts in proximity detection systems for safety were made in other industrial sectors, such as underground mining area (*6*), the railroad industry (*7*), and manufacturing (*8*). Proactive alerting systems in hazardous proximity situations can grant the pedestrian workers with additional time and capability to escape the emergency situations.

With understanding the selection parameters for a feasible sensing technology for a roadway construction site, a new technology has been studied by the Robotics & Intelligent Construction Automation Laboratory (RICAL) at Georgia Tech, and a preliminary system was developed. The system architecture and data flow are shown in Figure 1 (*9*). The research team has been supported by the Georgia Department of Transportation (GDOT) in evaluating sensing technologies for active work zone safety. A Bluetooth proximity sensing system was developed with customized software and tested with other commercially available sensing devices at GDOT's equipment maintenance yards.

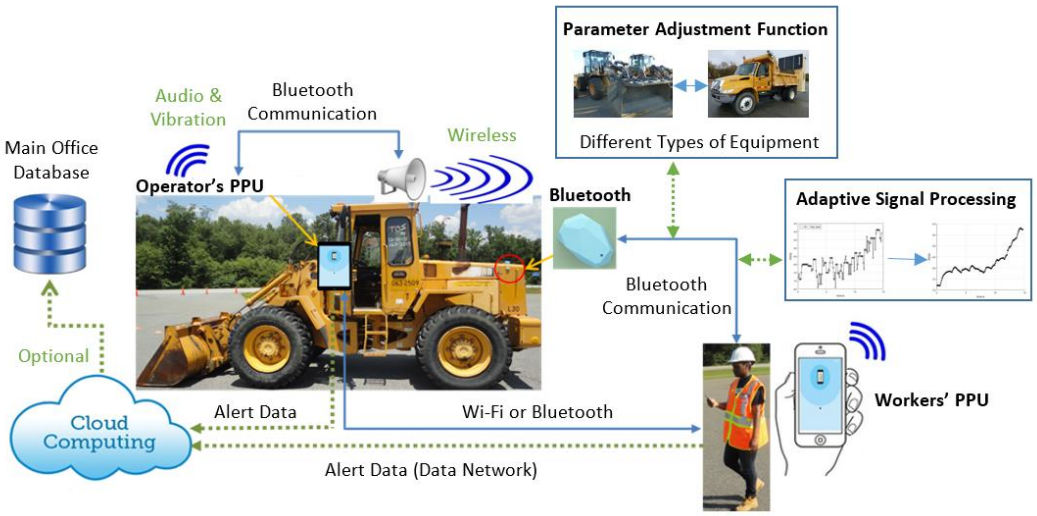


FIGURE 1 Architecture of Bluetooth proximity detection and alert system

The sensing technology used by the developed proximity sensing system, Bluetooth, is often found in mobile computing devices, but can also be used by fixed hardware. Bluetooth technology is capable of connecting to several devices in real-time simultaneously through an ad-hoc local network which does not require a cell data service nor an internet service unless the real-time remote monitoring is needed. The Bluetooth wireless technology has widely been used for point-to-multipoint voice or data transfer because of its rapid connectivity, low-cost hardware, and minimal individual infrastructure requirements (*10*). Researchers have identified these benefits for construction applications, specifically for construction topology (*11*), position tracking of construction vehicles (*12*), and information delivery systems (*13*). Furthermore, Bluetooth has been used in wireless sensor networks for resource tracking at building construction sites (*14*). The typical reliable range of one Bluetooth 4.2 enabled devices is about 30 meters (98 ft) in line-of-site, and new Bluetooth 5.0 ranges about 120 meters (394 ft). Because Bluetooth has been successfully evaluated for other construction domain applications, this research hypothesizes with high confidence that the capabilities of this system could potentially detect and alert workers during hazardous proximity situations. The wireless network and low infrastructure requirements of this technology would overcome the barriers that the current proximity sensing and alert technologies have such as 1) cost, 2) external power requirements, 3) complexity of installation, 4) security, and 5) ability to detect people versus objects.

During the research period, extensive lab tests and field trials under controlled environments were conducted to improve the functionalities of the proximity sensing and alert system. Furthermore, field tests were conducted at an earthmoving construction job site to evaluate the practicality of the system. From the test, the system performance was evaluated in real-world situations, and promising test results with positive comments were obtained from the workers who participated in the test.

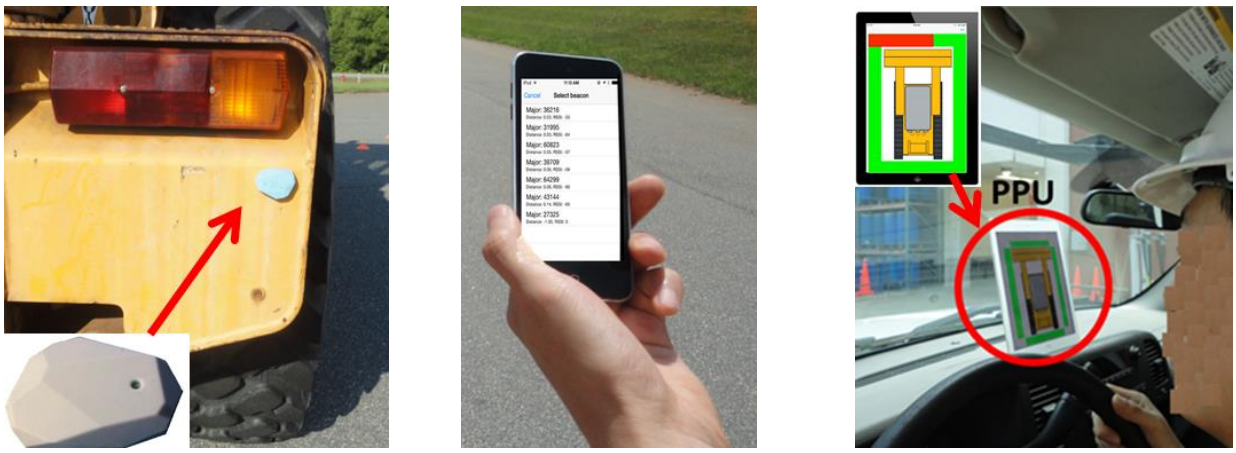
The overall primary findings throughout the research period are summarized as follows:

- Based on the test results and feedback from workers, the Bluetooth proximity alert system can provide reliable alerts during hazardous proximity situations.
- The experimental results in controlled environments demonstrate that the Bluetooth proximity sensing and alert system provides reliable results with an appropriate alarm with slight performance differences when equipment approaches a worker at various speeds.
- The adaptive signal processing (ASP) algorithm developed in this research was able to significantly reduce the signal processing delay and inconsistency of the Bluetooth system in high approaching speeds (e.g., 10 mph or greater) based on field trial results.
- The field test results show that frequencies of hazardous proximity situations highly depend on the type of equipment and type of work to be performed nearby.

IDEA PRODUCT

As shown in FIGURE 2, the Bluetooth proximity sensing and alert system is comprised of three main components that communicate in real time and provide alerts to workers in roadway work zones during hazardous proximity situations. The three system components are:

- Equipment Protection Unit (EPU) which is several beacons that are mounted to various locations of construction equipment surfaces (Figure 2a). The beacons used are radio signal transmitters. They are low cost, which is about $10-20 for each, as well as small.
- Pedestrian worker's Personal Protection Unit (PPU) which is an application that functions on any smartphone, tablet, or "smart" device that can be located anywhere on the pedestrian worker (Figure 2b). The PPU is able to process the signals for detecting a proximity hazardous situation that is created by interactions of workers and pieces of equipment nearby. This relies on a software program that was developed by the research team.
- Equipment operator's Personal Protection Unit (PPU) which is an application that functions on iPad, iPhone, or "smart" device that can be mounted in a cabin (Figure 2c). It receives a data package from the worker's PPU. This data package is used to provide audible alerts and visualization of the detected direction of workers around the equipment.



(a) EPU mounted on a wheel loader (b) PPU held by a test person (c) PPU mounted near an operator

FIGURE 2 Bluetooth proximity detection and alert system

Components of the system can be calibrated and mounted before the system can be utilized. In addition, the system may need to operate in a harsh, noisy construction environment. In that situation, an additional accessory, such as a wristwatch and an earpiece can be employed to further reinforce and assure the communication between workers and the alert system. A Bluetooth wristwatch and a Bluetooth earpiece can provide more concrete and noticeable vibrations and audible sounds to the worker in a harsh environment (FIGURE 3). From our preliminary test, the wristwatch produced clear alerts in both noisy and vibratory situations. It would be ideal for equipment or heavy tool operators.

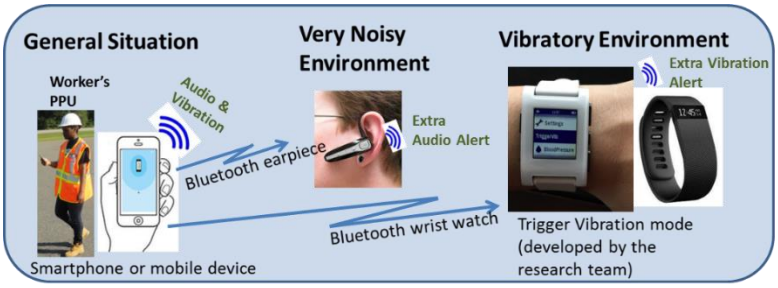


FIGURE 3 Extended warning paths to workers using Bluetooth accessories

CONCEPT AND INNOVATION

The preliminary results of our study show that Bluetooth proximity sensing and alert system has high potential to promote safety in roadway construction work zones in terms of accuracy, cost, and user-friendliness. Further, there is a clear benefit regarding the simplicity of hardware configuration (*15*). FIGURE 4 demonstrates the simplicity of the Bluetooth system compared to the current commercial proximity safety sensing systems including Orbitcoms' RFID system and Hitnot's magnetic field sensing system. The RFID system costs about $100 per personal protection unit (PPU) and $500 per equipment protection unit (EPU), and the magnetic field sensing system costs about $1,300 per EPU and $500 per PPU. The Bluetooth proximity sensing system would cost about $80 to $160 for eight beacons as EPU if workers have smartphones or a smart tablet (e.g., iPod, iPad) as PPU. All required components for the Bluetooth proximity sensing system are smartphones (or tablets) and Bluetooth beacons which can be attached to any solid surface of equipment body. The portability and simplicity of the proposed system would allow broader onsite adoption of the proposed technology and proactive safety practices between equipment and pedestrian workers at roadway construction work zones.

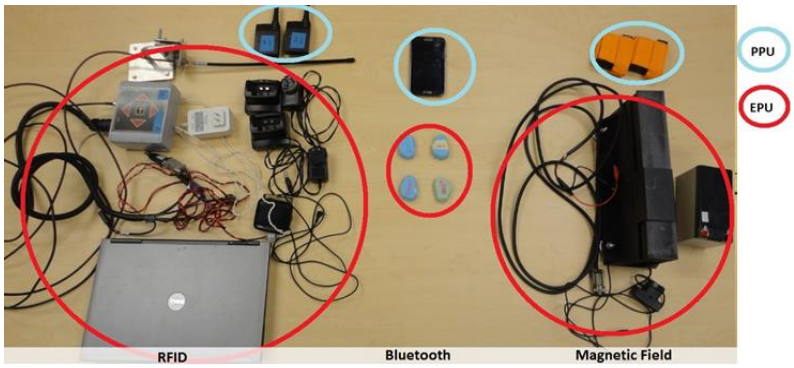


FIGURE 4 Comparisons of proximity sensing devices in size and complexity

Furthermore, the system is capable of providing three separate alert ranges for each beacon. The desired physical horizontal distance between construction equipment and a pedestrian worker is trisected with three separate equal alert distances. The alert distances allow for variations in audible alerts and vibrations depending on the location of the pedestrian worker inside the pre-calibrated hazardous proximity zone. As the pedestrian worker nears the piece of construction equipment and approaches closer to the EPU, the PPU's audible alert intensifies the frequency of beeps for the pedestrian worker and equipment operator. These alert distances can be calibrated for specific pieces of construction equipment and site conditions. The calibration process includes: 1) using a smartphone, measure a signal strength from a beacon at a known distance (e.g., 10 feet); 2) teach the system the relationship between signal strength and distance; 2) repeat Steps 1-2 for all beacons.

In addition, the alerts including vibration and beeping sounds are not only via PPUs themselves but also via additional Bluetooth enabled accessories, including a smart wristwatch and a Bluetooth earpiece (FIGURE 5). In application to construction, one of the most significant concerns raised was impractical warning capabilities of an alert system, especially in a harsh environment. To address this issue, our new development in this research included an addition of optional warning components. The ability of Bluetooth to communicate with other Bluetooth devices was useful in developing the new warning components and overcoming the raised alert limitation. These additional alerting devices can reinforce communicability of alerts in a harsh environment.

FIGURE 5 Multiple forms of alerts enabled by Bluetooth

Using Bluetooth as the signal transmission method, the proposed system is programmed to measure and record when each proximity alert is triggered and send the data to a remote server using a cloud data network. This collected data can later be used for safety hazard analyses. To sync settings of parameters and information for hazardous proximity cases, a database was built in a cloud server to facilitate information communications between various PPUs for operators, which is shown in FIGURE 6. Through the database, several PPUs are able to sync calibrated parameters for each piece of equipment. For each alert case, detailed information such as worker ID, alert time, and equipment ID are saved through both mobile platform and database in the server. New safety concepts and training could evolve from the analysis data collected from a construction site. Workers could be notified of historical hazardous project conditions, construction activities, and their safety behaviors. Further, with the aid of the proposed system, state transportation agencies can formulate a more efficient way of regulating work zone safety guidelines; thus, a lower rate of accidents and near-misses yields not only an improvement of worker's safety but also a decrease of project delays due to safety-related accidents.

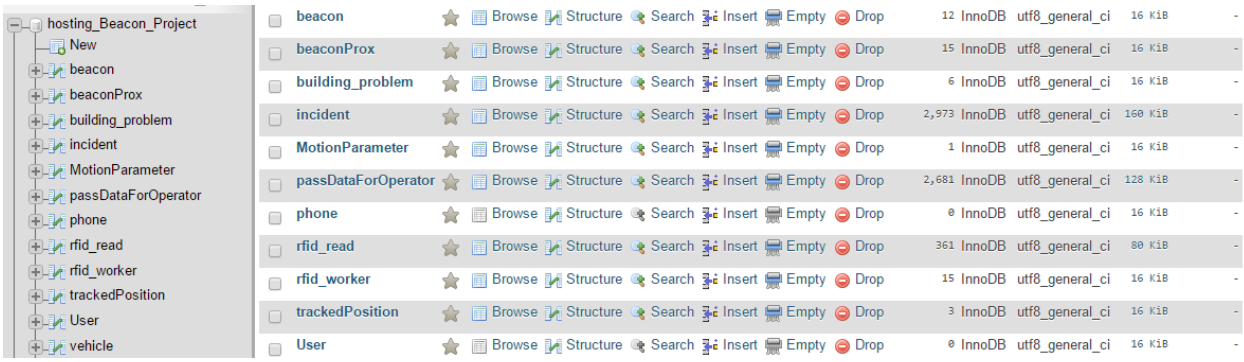


FIGURE 6 Database in a cloud server for the Bluetooth proximity detection and alerts system

INVESTIGATION

An earlier version of Bluetooth proximity sensing system was tested at a GDOT's equipment yard. The performance of the proposed Bluetooth sensing system was compared with the commercial RFID and magnetic field sensing products. As the Bluetooth sensing system possesses more favorable features, such as cost, maintenance, calibration, ease of installation, and opportunities for further developments, it was evaluated to be the more promising proximity safety sensing technology than the others. Especially, the Bluetooth system provides Internet of Thing (IoT) through its connecting and smart capabilities.

Based on previous research results, this project had two major stages: 1) system development and prototyping and 2) field testing and validation for industry acceptance. To test the accuracy and feasibility of the proposed system, we conducted field trials and tests. The detailed information of the trials and tests are described in the following sections.

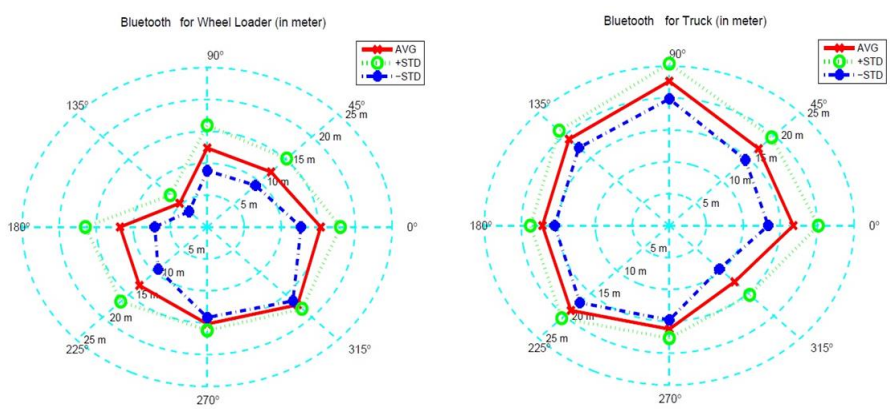
Validation Through Field Trials Under A Controlled Environment

The research team has conducted two field trials at a GDOT maintenance yard. The purpose of the trials was to test the development proximity sensing and alert system implemented in various dynamic movement scenarios under a controlled environment.

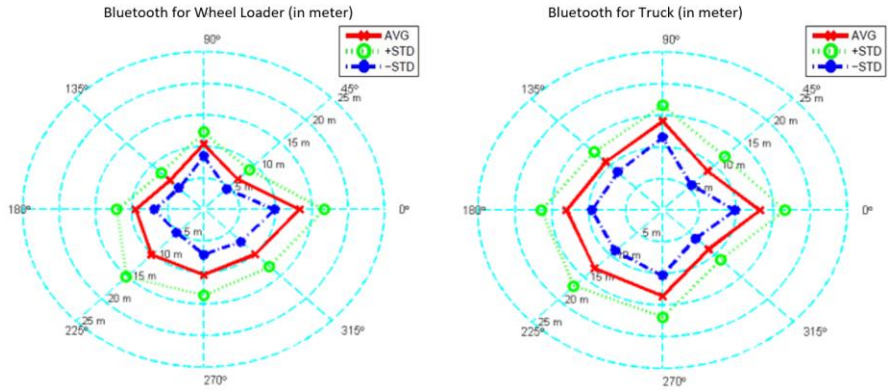
The first field trial was conducted to simulate the interaction between a stationary piece of construction equipment and a mobile pedestrian worker. This field trial used two different types of equipment, which were a wheel loader and a dump truck to assess the reliability of the system. The experimental testbed was outlined with eight equally spaced angles (i.e., 0, 45, 90, …, 315 degrees) as shown in Figure 7. To set up the system, eight EPU sensors were mounted to the equipment surfaces. Then, a subject with a PPU device approached the equipment at an approximate speed of 3 mph from each of the angles. When the proximity sensing system detected the worker's breach into a pre-set distance zone, the alert was activated, and the test subject stopped walking and measured the horizontal alert distance. The alert distance was measured from the subject's stopped position to each beacon attached to equipment. Each approach angle was tested 20 times.

FIGURE 7 Test of the first trial at GDOT's equipment maintenance yard

Figure 8 shows the test results of two field trials conducted during the period of this research. The first trial result shows that the BLE system is capable of detecting the worker's breach in real time. One challenge found from this test was the change of range when applied to a different piece of equipment (e.g., from a wheel loader to a truck). To mitigate this problem, the research team developed a calibration function and conducted another set of the same experimentations. The calibration process is conducted once as long as same beacons are used at same locations and same equipment. Based on the 2nd trial result, the BLE system shows a clear improvement in accuracy and consistency while maintaining similar levels of variability by showing the deviation, on average, to the desired setting from 5.54 m (non-calibrated) to 0.03 m (calibrated) for the 160 trials with the truck, and from 0.88 m (non-calibrated) to 0.37 m (calibrated) or the 160 trials with the wheel loader. As a note, no false negative and false positive instances were observed among all trials at the maintenance yard testbed.



(a) First Field trial (non-calibrated)



(b) Second Field trial with a calibration function for different equipment types

FIGURE 8 Test results of the field trials with a 10 m distance setting

To identify and understand the relationship among vehicle speeds, distance, and signal delay of the Bluetooth system, several tests in a controlled environment were conducted at a GDOT district yard. This set of experimental trials tested the effectiveness of the proximity detection system on a static test person and a truck. A flat, unobstructed surface was used to conduct these trials. 20 pedestrian makers were positioned at 1.5-meter intervals along the straight-line parallel to the truck's travel path (Figure 9). The truck approached a simulated pedestrian worker (traffic cone) in a forward travel direction in various speeds (i.e., 3 mph (4.8 kph), 5 mph (8.1 kph) and 10 mph (16.1 kph)) and stopped once the EPU alert was activated. For each speed, the test was repeated for 20 trials. The test was strictly controlled with safety cones and the alert system to avoid any potential incidents.

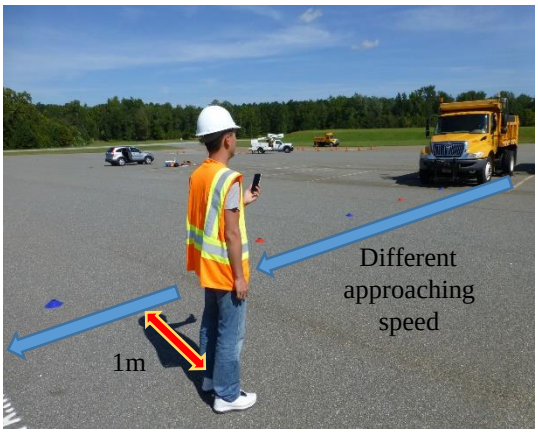


FIGURE 9 Mobile equipment and static pedestrian worker experimental testbed

Data obtained from these trials was analyzed, and FIGURE 10 presents a box plot of the results, which shows the average and the interquartile range of the data. The results show that the average of triggered distances of the Bluetooth system is decreased when approaching speeds increased. Same situations are also found in other proximity sensing and alert systems such as the magnetic field system.

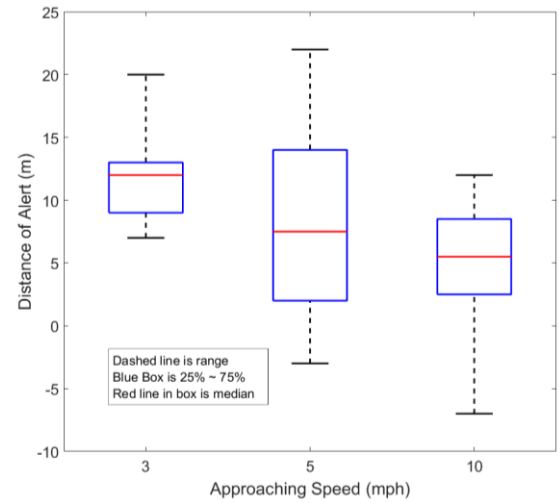


FIGURE 10 Box plot of a dump truck with various approaching speeds (Ground truth: 10 meters)

To reduce the inconstancy and delay of alerts for the Bluetooth system caused by various approaching speeds, an adaptive signal processing (ASP) function was developed by the research team. The logic of the algorithm is shown in Figure 11. The ASP method offers an adaptive feature that uniquely defines and applies a smoothing factor α used for weighted average as a dependent variable. By using this dependent variable in a decision-making process—it is shown in the *if* clauses in Figure 11—the system checks and compares the difference of signals between the processed signal value and the current datum point value. The adaptive feature provides the capability of a more responsive reaction of the system when the receiver detects signals that potentially present a hazardous situation.

Input: $Rawdata, S_1, ..., S_n$
Output: ASP(i)

```
function ASP(i)
    Diff=Rawdata(i)-ASP(i-1)
    if S1≤Diff<S2 then
        a=a1
    else if S2≤Diff<S3 then
        a=a2
        .
        .
        .
    else if Sn-1≤Diff<Sn then
        a=an
    else
        a=a1
    end if
    ASP(i)=a*Rawdata(i)+(1-a)*ASP(i-1)
end function
```

FIGURE 11 Algorithm for the adaptive signal-processing method

To test the effectiveness and functionality of the developed ASP algorithm, the same field trial was conducted using the Bluetooth system with the ASP algorithm. This scenario also performed twenty trials for each speed. FIGURE 12 shows box plots of the results for the system with the ASP algorithm. These plots suggest the same findings that are discussed in FIGURE 110. Compared to FIGURE 120, the results of ASP in Figure 12 show more reliable behaviors than those without using the algorithm. The box plots of the results using ASP have smaller interquartile ranges, and the median values of ASP are closer to the desired setting, which implies that the delay has been reduced.

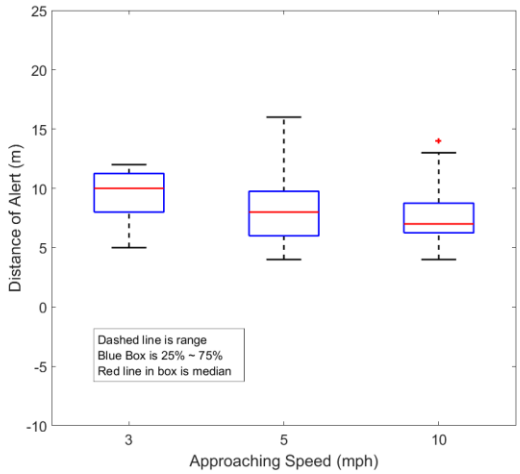


FIGURE 12 Box plot of a dump truck with various approaching speeds with ASP (Ground truth: 10 meters)

Validation With a Real-World Construction Project

The main goal of field tests was to evaluate the functional reliability of the Bluetooth proximity sensing system and obtain feedback from working crews. From the real-world field tests, the effectiveness, barriers, and benefits of the Bluetooth proximity detection and alert system were measured and analyzed. In addition, the interviews with a regional panel of experts were conducted to decide types of equipment and settings for safety distance to be used for the field test.

To determine appropriate alert distance settings for various types of equipment under both static and dynamic circumstances, the following questions were asked to the regional expert panel: (1) if a certain type of equipment is in a static status, but has a potential to move, what is the preferred safety distance? (2) If the equipment is moving toward a worker at a normal speed, what is the preferred safety distance? The answers for the interviews are summarized in TABLE 1.

TABLE 1 Preferred Safety Distance for Static Equipment

Type of equipment	Preferred safety distance settings /m
Dozer	More than 1.5
Skid Steer	More than 1.5
Truck	More than 1.5

TABLE 2 Preferred Safety Distance for Moving Equipment

Type of equipment	Preferred safety distance settings /m	
	Moving backward	Moving forward
Dozer	More than 3	More than 3
Skid Steer	More than 3	More than 3
Truck	More than 3	More than 3

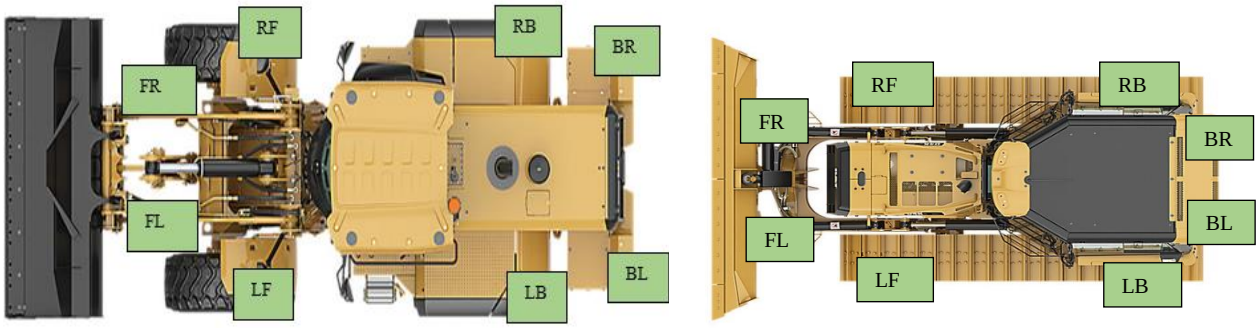
Based on the feedback from the experts, two pieces of construction equipment, a dozer and a skid-steer dozer, were used and five subjects among crew members participated in the field test. The details of the tested equipment and participated workers are shown in FIGURE 13 and 14.

FIGURE 13 Real-world validation for the proximity alert system at a building construction site

Worker ID	Worker #1	Worker #2	Worker# 3	Worker #4	Worker #5
Work Type	Traffic Control	Survey and Map	Survey and Map	Traffic Control	Truck Clean

FIGURE 14 Participated workers and work types

The system setup plans for each piece of the equipment is shown in Figure 15. For each equipment, eight beacons were mounted in various directions, where two beacons were placed an equal distance apart on every side. This allows the system to be less impacted by surface obstruction. The beacons are represented by FR: Front Right; RF: Right Front; RB: Right Back; BR: Back Right; BL: Back Left; LB: Left Back; LF: Left Front; FR: Front Right. We used 3 meters as the alert distance setting for both dozer and skid steer according to the feedbacks from field workers and the regional panel of expert.



(a) Beacon setup for dozer (b) Beacon setup for skid steer

FIGURE 15 System setup with Bluetooth sensors for the tested dozer

As can be seen in Figure 14, five subjects among crew members participated in the field test. The subjects were equipped with the PPUs (smartphones) either to arm or waist. During a10-hour test, the researchers observed 28 hazardous proximity cases, where the distance between the subjects and tested equipment was less than or equal to 3m. Among all of the recorded cases, the Bluetooth system provided 27 alerts in total, where 12 alerts were triggered by the dozer, and 15 alerts were triggered by the skid steer loaders. Alert frequencies for mounted beacons are summarized in

TABLE 3 and 4. The results indicate that types of equipment have a significant influence on the total number of alerts and the alert frequency for each direction of a certain type of equipment. Compared to dozers, skid steer loaders tend to cause more hazardous proximity situations due to its fast maneuverability.

TABLE 3 Number of Proximity Alerts for Tested Dozer in Each Direction

Beacon location	Frequency
Front Right	2
Right Front	2
Right Back	1
Back Right	1
Back Left	1
Left Back	1
Left Front	2
Front Right	2

TABLE 4 Number of Proximity Alerts for Tested Skid Steer Loader in Each Direction

Beacon location	Frequency
Front Right	2
Right Front	1
Right Back	1
Back Right	1

Back Left	1
Left Back	4
Left Front	2
Front Right	3

The result of statistical analysis of the alerts triggered by each worker is summarized in

TABLE 5. The results indicate that the number of proximity cases depends on both work types and locations. Compared to the main gate, working zones gave a large number of proximity alerts. The low counts of alerts for worker 5 is because his job duty was to clean trucks rather than the tested equipment. In this test, trucks were not equipped with sensors because of their long cycle time. The collected data can be useful to better understand individual worker's safety behavior, or design a safer job site layout if a certain area or role of worker has a higher near-miss frequency (e.g., Worker 4).

TABLE 5 Number of Proximity Alerts for Subjects

Worker ID	Number of proximity alerts	Work type	Work location
Worker 1	9	Survey and map	Main site
Worker 2	3	Traffic control	Gate
Worker 3	2	Survey and map	Gate
Worker 4	11	Traffic control	Main site
Worker 5	2	Truck clean	Main site

To find a preferred carrying position, a survey was conducted with the workers participating in the field test. First, the workers worked with PPUs on three carrying positions: armband, belt clip, and pocket, which are shown in FIGURE 16. Then, they chose the one that had a minimum impact on their regular work. Four workers among five chose a belt clip as their preferred carrying positions; the answers for the survey are summarized in TABLE 6.

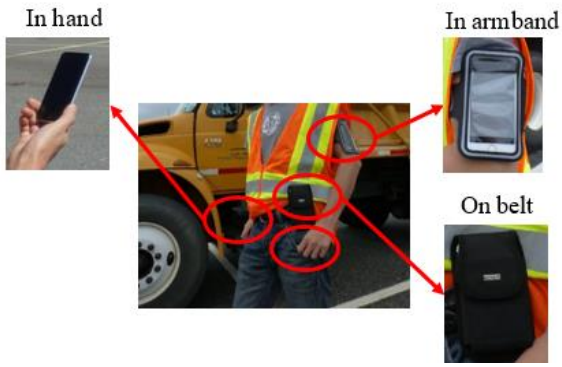


FIGURE 16 Various PPU carrying locations for workers

TABLE 6 Answers for Preferred Carrying Location of PPU for Pedestrian Workers

Worker ID	Arm Band	Belt Clip	Pocket
1		√	
2		√	
3		√	
4			√
5		√	

To find effective alert types of the PPUs for both workers and operators, another survey with the workers and operators was conducted. The workers worked with the PPU with three alert modes: audio, vibration, and audio plus vibration. Then they chose the alert mode that gave the most effective notification during their regular work. Four workers among five chose audio plus vibration as the most effective alert mode. The answers are summarized in TABLE 7. A similar survey regarding effective alert modes of the PPU mounted in the cabin was also conducted among the operators; the answers are summarized in TABLE 8.

TABLE 7 Answers for Preferred Alert Modes of Pedestrian Workers' PPU

Worker ID	Audio	Vibration	Sound & Vibration
1			√
2			√
3		√	
4			√
5			√

TABLE 8 Answers for Preferred Alert Modes of Operators' PPU

Operator ID	Audio	Vibration	Visualization	Combined
1				√
2		√		

Finally, both workers and operators participating in the test were asked to give an overall evaluation of the Bluetooth system based on whether the system provided reliable alerts during the test period. The answers are summarized in

TABLE 9. Over half of the workers thought that the system provided reliable alerts when the tested equipment was too close to them. Half of the operators commented that the system was able to provide reliable alerts and useful hazard direction information to them when pedestrian workers were too close to the equipment.

TABLE 9 Overall Evaluation of Bluetooth System

Worker ID	Low	Medium	High
1			√
2		√	
3		√	
4			√
5			√
Operator 1			√
Operator 2		√	

PLANS FOR IMPLEMENTATION

The research team plans to implement the proposed Bluetooth proximity sensing system for several projects in the future. Through continuous work with GDOT and local contractors in a variety of ways, we can utilize a large assortment of pilot field trial sites for practical aspects of the proximity alert system. Currently, we are consulting with GDOT to decide potential highway construction and maintenance projects to implement and test our proposed Bluetooth sensing system to improve their roadway work zone safety. GDOT is also very interested in providing new funds to the research team to develop another version of the proximity system which does not require a smartphone as a PPU. It is because not all employees have smartphones provided by GDOT. With their funding supports, we can conduct further studies on implementing the proximity sensing and alert technology in more practical ways.

CONCLUSIONS

Current safety practices exercised by roadway work zone personnel are inadequate to prevent contact collisions between pedestrian workers and construction equipment, which is evident from the injuries and fatalities still experienced by roadway work zone personnel. Even though several proximity alert systems have been introduced in the market, the implementation of these systems into the industry is limited because of various reasons, such as high cost, low accuracy, and complicated hardware configurations. To solve these problems, a Bluetooth-proximity sensing and alert system was developed. The test results show that the proposed Bluetooth proximity alert system has high potential to promote safety in roadway construction due to its high accuracy, low cost, and simple hardware configurations.

Using off-the-shelf Bluetooth beacons as EPU, several functions have been developed and added to the proximity system. To save battery life, for example, the developed program runs in the background of mobile devices. In addition, a communication system between pedestrian worker's PPU and operator's PPU are established through a Bluetooth communication protocol. Meanwhile, the operators' PPU can display pedestrian workers' PPU location when his/her proximity is detected. Furthermore, the detected proximity alerts are recorded within the system and optionally send to a cloud server, which can be used for future analyses.

To test the accuracy and feasibility of the developed Bluetooth sensing and alert system, field trials with construction equipment and workers were conducted under controlled environments. The test results show that the average of the triggered distance of proximity sensing and alert systems is decreased when approaching speeds increased, which also happens in other proximity systems. However, by using the developed adaptive signal processing (ASP) algorithm, the delay of the Bluetooth system was reduced. In addition, tests were designed and conducted at a real-world construction site. The test results demonstrate that the Bluetooth system provided reliable and accurate alerts when there were hazardous proximity situations between pedestrian workers and construction equipment. Also the analyzed results show that the frequency of hazardous proximity situations depended on work types, equipment types, and work locations.

Overall, the research team recommends that the Bluetooth proximity system be used for workers in work zones as a secondary layer of hazard avoidance in real time during hazardous proximity situations, while they should still primarily follow required work-zone safety protocols and always be alert and keep a lookout for any unexpected danger. Also, it is recommended to integrate the developed Bluetooth proximity alert system with an intrusion alert system to completely protect the workers in a work zone from both construction equipment and passing vehicles. As a future study, the research team plans to develop an integrated intrusion alert system which can predict driver's path and provide an alert to workers in work zones in advance.

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