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Improving Work Zone Safety Utilizing a New Mobile Proximity Sensing Technology

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CPWR Small Study Final Report

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Improving Work Zone Safety Utilizing a New Mobile Proximity Sensing Technology

Final Report

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CPWR small study

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ABSTRACT

Safety is one of the most important components to be addressed during construction. During the past decade, approximately a quarter of all construction fatalities have been caused by visibility-related issues, a majority of which involve construction equipment and pedestrian workers. To provide alerts to both operators and workers in real time during a hazardous proximity situation, a new proximity sensing and alert system utilizing Bluetooth Low Energy (BLE) technology was investigated, and a proof-of-concept system was developed by the Robotics & Intelligent Construction Automation Laboratory (RICAL) at Georgia Tech. The major objective of this study was to identify and understand the relationship among vehicle speeds, distance, and signal delay of the system through several tests in a controlled environment. A new algorithm was developed to reflect dynamic movements of construction equipment and workers. Also, real-world field tests and surveys were conducted to analyze the reliability and accuracy of the system. The test results were promising, and the system was also positively evaluated by the participating equipment operators and pedestrian workers. Overall, it was validated that the Bluetooth proximity safety alert sensing system can provide an additional layer of collision avoidance in real time during hazardous proximity situations in dynamic construction work zones.

KEY FINDINGS

- The Bluetooth proximity system provided reliable performance results in real-world field tests.
- Experiments in controlled environments demonstrate that Bluetooth proximity sensing provided reliable results with an appropriate alarm, with slight performance differences when a piece of equipment approached a worker at various speeds.
- An adaptive signal processing algorithm reduced the signal processing delay and inconsistency of the Bluetooth system in high approaching speeds during field tests.
- Field tests showed that frequency of hazardous proximity situations is highly dependent on the type of equipment used and type of work performed nearby.
- The participating subjects in the field tests, including equipment operators and pedestrian workers, agreed that there is a need for such a system and reported and rated the system positively evaluated the need and practical usability of the system.

INTRODUCTION

During the last decade, out of 639 worker deaths related to road construction, nearly half resulted from being struck by a vehicle or mobile equipment (Health 2015; Pegula 2010), making this one of the leading causes of injuries. According to CPWR, fatalities related to vehicles and heavy mobile equipment have resulted in a total of 7,681 deaths between 1992 to 2010 (CPWR 2013). These historical safety statistics and reports prove the need for further improvements for construction safety in work zones. In addition, the current practices do not pro-actively protect or warn construction workers to prevent potentially hazardous situations caused by approaching equipment. Current safety regulations and standards mandated by the Occupational Safety and

Health Administration (OSHA) require passive safety devices such as hard hats, reflective safety vests and other Personal Protective Equipment (PPE). These passive safety devices are incapable of alerting construction operators and workers in real time during a hazardous proximity situation. Although there exist several proximity warning systems, including radar, sonar, RFID, GPS, magnetic marking fields, and cameras, they are not widely adopted by the construction industry for safety hazard protection. A number of limit adoption of a new technology for construction safety.. Several studies (Goodrum et al. 2006; Lazaro et al. 2009; Park et al. 2015b; Ruff 2007) found such limitations including accuracy, size, weight, cost, non-adjustable range, nuisance alerts, power supplies, and complicate calibration processes. The research team has studied commercial proximity detection and alert products. Table 1 shows the details of commercially available proximity sensing technologies, which we have also studied and tested in fields (Park et al. 2015a, 2015b).

Table 1: Characteristics of Proximity Sensing Devices (Ruff 2007)

Feature	**Sonar**	**Radar**	**Magnetic**	**RFID**
Adjustable range	No	Yes	Yes, but limited	Yes
Maximum range	3 m	8 ~ 17 m	18 m	80 m
Two-way alarm	No	No	Yes	Yes
False alarm frequency	Medium	Medium	Low	Low
Nuisance alarm frequency	High	High	Medium	Medium
Installation and setup difficulty	Low	Low	Medium	Medium-High
Cost	Low	Low to Medium	Very high	Low

Sonar and radar systems are not ideal options mainly due to their limited capabilities, such as short range and high level of nuisance alarms. A great deal of metal interference was observed in the range reads of the radio frequency identification (RFID) technology (Goodrum et al. 2006). Also, construction equipment and other ambient environmental conditions may influence the RFID system via multipath and other obstructions (Marks 2014). The magnetic field sensing technology has been used in underground mining and shows relatively good performance (Park et al. 2015b). However, the downside of this device is that the installation and setup are difficult, the cost is relatively high, and it does not offer calibration ability but requires a change of expensive antenna to change the range limit, which adds more cost (Park et al. 2015b). Thus, there is a strong need to identify a more effective, economical, and easy-to-use tool for safer work zones where construction workers are often exposed to struck-by incidents associated with vehicles.

Understanding the parameters for a feasible sensing technology for a roadway construction site, researchers developed a new proximity sensing and alert system, utilizing Bluetooth Low Energy (BLE) technology has been investigated by the Robotics & Intelligent

Construction Automation Laboratory (RICAL) at Georgia Tech. The system architecture is shown in Figure 2.

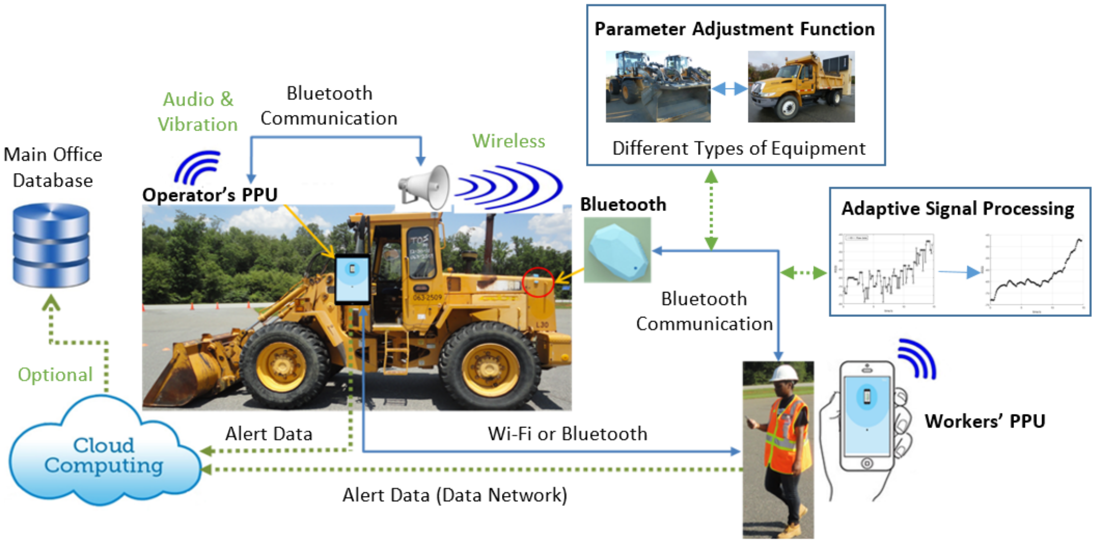
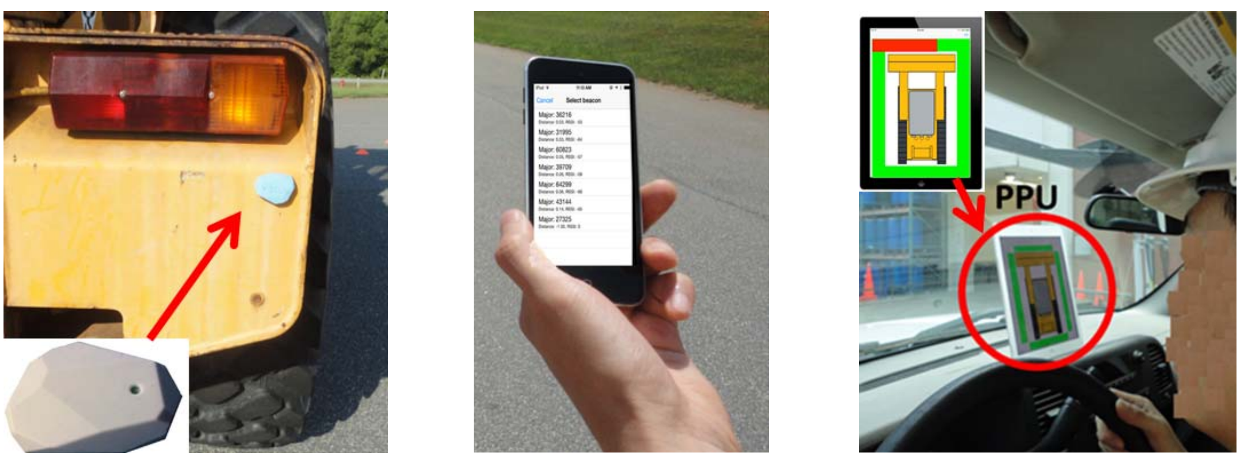


Figure 2: Bluetooth proximity detection and alert system

Components of the system must be calibrated and mounted before the system can be utilized. An Equipment Protection Unit (EPU) and PPUs for workers and operators are shown in Figure 3.



EPU mounted on a wheel loader | PPU held by a test person | PPU mounted near an operator

Figure 3: Bluetooth proximity detection and alert system

As shown in Figure 3, the Bluetooth proximity detection and alert system is composed of three components that communicate in real time and provide alerts to workers in work zones during hazardous proximity situations. The three components are:

- The EPU, composed of several beacons mounted at various locations on a piece of construction equipment. The beacons used are Bluetooth signal transmitters.
- A pedestrian worker's PPU which is an app for any smartphone, tablet, or "smart" device that can be worn or carried by the pedestrian worker. The PPU can process the signals for detecting a proximity hazard situation that is created by interactions of workers and pieces of equipment nearby. The research team developed the mobile app software program..
- Equipment operator's PPU which is an application that functions on any "smart" device that can be mounted near the operator in a cabin. It receives a data package from the worker's PPU, which contains the universally unique identifier (UUID) of the Bluetooth transmitter. This data package provides audible alerts and visualization of the detected location of workers around the equipment.

The results of our study show that Bluetooth-based mobile proximity detection and alert system has high potential to promote safety in construction work zones: it is accurate, affordable, and user-friendly. Further, there is a clear benefit regarding the simplicity of hardware configuration. All required components are smartphones (or tablets) and Bluetooth beacons which can be attached to any solid surface of equipment body. The portability and simplicity of the system will allow broader onsite adoption of the proposed technology and proactive safety practices between equipment and pedestrian workers at construction work zones. Also, the system can be 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 analysis.

Several field trials were conducted under controlled situations. Based on test results, delay of the system was found when equipment approached a worker in high approaching speeds, as in other proximity sensing systems. To reduce the delay, an adaptive signal processing algorithm was developed in this study, reducing the signal processing delay of the Bluetooth system at high approaching speeds. From real-world field tests at an ongoing building construction project, the Bluetooth proximity system provided reliable performance results and was positively evaluated by participating equipment operators and pedestrian workers.

OBJECTIVES

The main goal of the research was to better understand and reduce situation-specific proximity safety hazards from the interactions of pedestrian workers and construction equipment in work zones utilizing a newly developed mobile proximity warning sensing prototype system. The specific objectives of this research include:

1) Identify and understand the relationship among vehicle speeds, distance, and signal delay through extensive tests in a controlled environment,
2) Develop a new algorithm for the proposed proximity system to better reflect dynamic movements of construction equipment and workers, thus improving accuracy,
3) Identify and categorize hazard zones for construction equipment based on the type of equipment, type of work to be performed nearby, and dynamicity between pedestrian workers and equipment from real-world field tests, and

4) Evaluate performance of the mobile proximity alert sensing system based on the workers' practical inputs and feedback regarding alert strength, user-friendliness, nuisance alerts, and practicality.

METHODS

To identify and understand the relationship between vehicle speeds, distance, and signal delay of the Bluetooth system, several tests in controlled environments were conducted. This set of experimental trials tested the effectiveness of the proximity detection system on a stationary person and a mobile wheel loader. A flat, unobstructed surface was used to conduct these trials. 20 ground markers were positioned at 1.5-meter intervals along the straight-line parallel to the wheel loader's travel path. The wheel loader approached the simulated pedestrian worker (traffic cone) in a forward travel direction in various speeds (i.e., 3 mph, 5 mph and 10 mph) and stopped once an alert was activated, which is shown in Figure 4. For each speed, the test was repeated for 20 times.

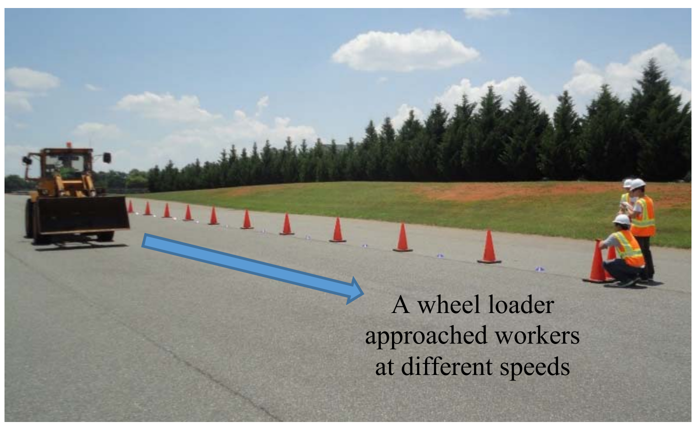


Figure 4: Mobile equipment and static pedestrian worker experimental test bed at a Georgia DOT's test yard

Data obtained from these trials was analyzed, and Figure 5 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 decrease when approaching speeds increase. Similar trends were also found in other proximity sensing and alert systems such as magnetic field systems.

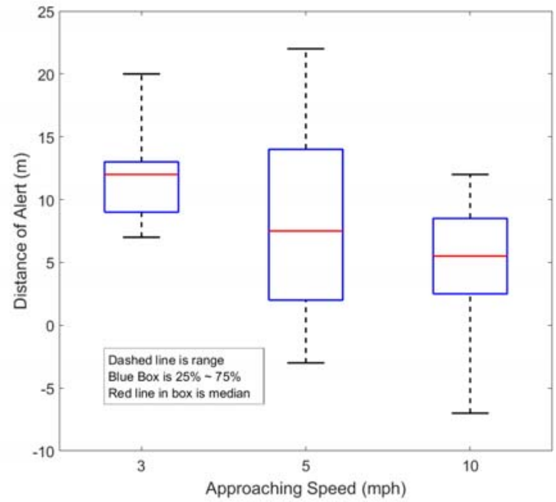


Figure 5: Box plot of a wheel loader with various approaching speeds (Ground truth: 10 meters)

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. The algorithm is described in Figure 6. 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, 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 $S_1 \leq$Diff$< S_2$ **then**
        $a = a_1$
    else if $S_2 \leq$Diff$< S_3$ **then**
        $a = a_2$
        .
        .
        .
    else if $S_{n-1} \leq$Diff$< S_n$ **then**
        $a = a_n$
    else
        $a = a_1$
    end if
    ASP(i)=a*Rawdata(i)+(1-a)*ASP(i-1)
end function

Figure 6: 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 7 shows box plots of the results for the system with the ASP algorithm. These plots suggest the similar trends that are shown in Figure 5, but the results of ASP 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.

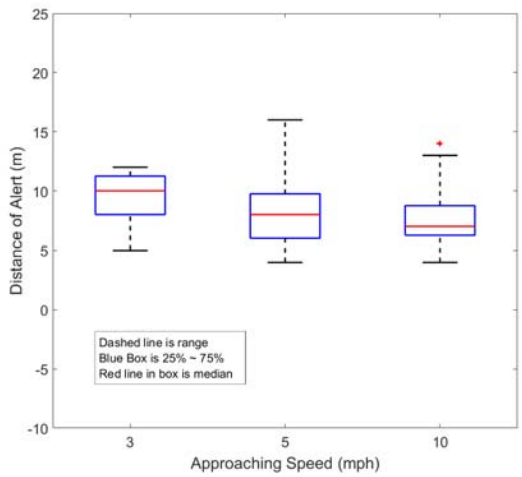


Figure 7: Box plot of a wheel loader with various approaching speeds with ASP (Ground truth: 10 meters)

Another main sub-objective of this study was to identify and categorize hazard zones for construction equipment through real-world field tests, where the effectiveness, barriers, and benefits of the Bluetooth proximity detection and alert system could be measured and analyzed. Interviews with local experts identified appropriate alert distance settings for various types of equipment under both stationary and dynamic circumstances, based on the following questions:

(1) If a certain type of equipment were at rest but had a potential to move, what would be the preferred safety distance for an alert?
(2) If the equipment were moving toward a worker at a normal speed, what would be the preferred safety distance for an alert?

Responses to the interview are summarized in Tables 2 and 3.

Table 2: 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 3: 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 field workers, two pieces of construction equipment, a dozer and a skid steer loader, were used in field test. Seven crew members participated. The details of the tested equipment and participated pedestrian workers are shown in Figure 8 and Table 4.

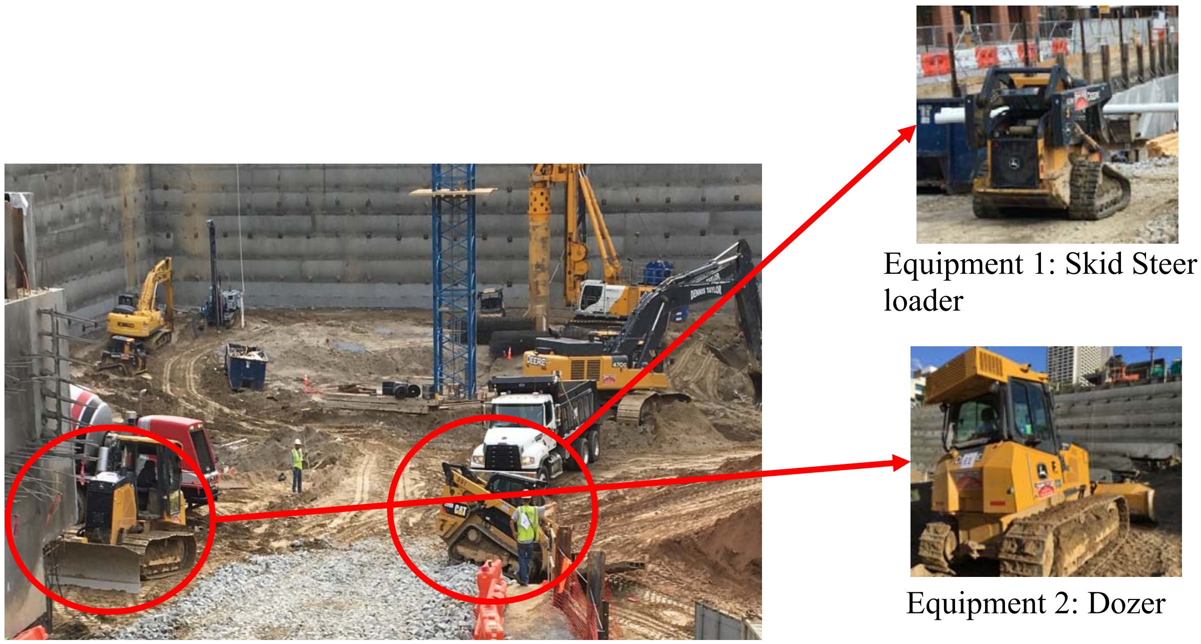


Figure 8: Types of equipment for field test at a building construction site in Atlanta, GA

Table 4: Participated pedestrian workers and work types

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

The system setup plans for the two pieces of construction equipment are shown in Figures 9 and 10. For each piece of equipment, eight beacons were mounted in various directions, where two beacons were placed at 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 3m as the alert distance setting for both dozer and skid steer loader according to the preferred safety distance in Table 3.

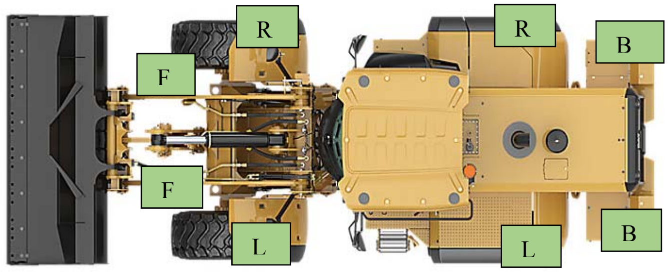


Figure 9: System setup with Bluetooth sensors for the tested skid steer loader

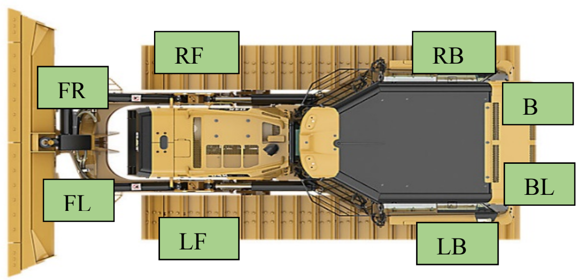


Figure 10: System setup with Bluetooth sensors for the tested dozer

The subjects wore the PPUs (smartphones) either to arm or waist. During two sets of 5-hour test, the researchers observed 28 hazardous proximity cases (near-misses). 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 loader. Alert frequencies for mounted beacons are summarized in Tables 5 and 6. The results indicate that types of equipment have a great influence on the total number of alerts and the alert frequency for each direction of a certain type of equipment. Compared to the dozer, the skid steer loader tends to cause more hazardous proximity situations due to its fast maneuvering capability.

Table 5: 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 6: 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 **Error! Reference source not found.**7. The results indicate that the number of proximity incidents depends on both work types and locations. Compared to the main gate, a larger number of proximity alerts were detected. The low count of alerts for worker 5 is because his job duty was to clean trucks which were not equipped with EPU in this trial due to their long cycle times.

Table 7: Number of Proximity Alerts for Each Subject

Worker ID	Number of proximity alerts	Work type	Work location
worker1	9	Survey and map	Main site
worker2	3	Traffic control	Gate
worker3	2	Survey and map	Gate
worker4	11	Traffic control	Main site
worker5	2	Truck clean	Main site

To find preferred carrying positions, a survey was conducted with the workers participating in the field test. First, the workers worked with PPU on three carrying positions: (1) arm band, (2) belt clip, and (3) pocket. Then they chose the one with minimum impact to their regular work. Four workers out of five chose a belt clip as their preferred carrying position.

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: (1) audio, (2) vibration, and (3) audio plus vibration. Then they chose the alert mode that gave most effective notification during their regular work. Four workers among five chose audio plus vibration as the most effective alert mode. Their responses are summarized in Table 8. A similar survey regarding effective alert modes of the PPU mounted in the cab was also conducted among the operators; their answers are summarized in Table 9.

Table 8: Answers for Preferred Alert Modes of Pedestrian Workers' PPU

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

Table 9: Answers for Preferred Alert Modes of Operators' PPU

Operator ID	Audio	Vibration	Visualization	Combined
1				√
2		√		

ACCOMPLISHMENTS AND RESULTS

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. Their responses are summarized in Table 10. Over half of the workers thought that the system provided reliable alerts when the 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 10: Overall evaluation of Bluetooth system

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

Overall, the Bluetooth proximity system had validated its capability to provide additional layers of hazard avoidance in real time during hazardous proximity situations. More real-world tests with various tasks and equipment types for an extended testing time would help further validate the practical aspects of the Bluetooth system.

DISCUSSION

Although this study validated a proof-of-concept system for proximity safety sensing and alerts, there are several practical improvements needed for industry adoption and deployment. For example, the current prototype system cannot measure speeds of approaching vehicles with the off-the-shelf Bluetooth Low Energy (BLE) beacon that we used as an Equipment Protection Unit (EPU). Thus, we used specific vehicle speeds known a priori to develop the adaptive signal processing algorithm. An added sensing function with a speed sensor or a GPS module would resolve this issue. Another limitation of the current system is smartphone's battery life. In our tests, the battery lasted about six hours while the software app continuously ran. To cover full day working hours (e.g., 8 hours), the app needs to be further improved with an energy-saving function, or a small external battery (e.g., power bank) needs to be connected to a smartphone.

CHANGES/ PROBLEMS

No changes or problems were encountered during the study.

FUTURE FUNDING PLANS

The research team plans to seek additional funding from state Department of Transportations (DOTs) and local construction companies to improve the current prototype system and further this research.

LIST OF PUBLICATIONS

Publication:

(1) Park, J., Xiaoyu Yang, Cho, Y. K., Seo, J. (2017). "Improving Dynamic Proximity Sensing and processing for smart workzone safety," Automation in Construction, in press

Presentation:

(1) JeeWoong Park, Yong Cho (2016). "Sensing Technology in Construction", research seminar, the University of Texas at Austin, Texas, Aug.12, 2016
(2) Yong Cho (2017). "Construction Safety & Productivity with Mobile Technologies" FIATECH Technology Conference & Showcase, Orlando, FL, April 10-12.
(3) JeeWoong Park and Yong Cho "Direction Aware Bluetooth Low Energy Based Proximity Detection System for Construction Work Zone Safety", 33rd International Symposium on Automation and Robotics in Construction (ISARC), Auburn, Alabama, Jul. 18-21, 2016

DISSEMINATION PLAN

Lessons learned from this project and its follow-up future research, if any, will be broadly disseminated through:

- Journal publications in top journals such as Safety Science, Automation in Construction, and ASCE Construction Engineering and Management
- Conference papers or posters in the field of transportation, construction, and automation (i.e., TRB meeting, ISARC, IWCCE, or ICCCBE)
- Industry seminars and workshops through FIATECH annual conference, and the biannual Digital Building Laboratory (DBL) meetings at Georgia Tech

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