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# Improving dynamic proximity sensing and processing for smart work-zone safety

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## ABSTRACT

Equipment/vehicles striking workers is one of the most frequent accidents that occur in roadway workzones. As a means of prevention, a number of active technologies have been developed to provide proximity sensing and alerts for workers and equipment operators. However, most of these systems are based on the distance/proximity level between workers and equipment and neglect the variations caused by different settings and environmental conditions, such as equipment types and approaching speeds, which can result in inconsistency and delay of the systems. As of yet, previous research has insufficiently investigated these issues. This research addresses the issues by utilizing the Bluetooth Low Energy (BLE)-based proximity sensing and alert system developed by the authors. This paper discusses the development and assessment of parameter adjustment and adaptive signal processing (ASP) methods. The research conducted field trials in various dynamic conditions and settings to assess the performance of the system. The test results showed that the parameter adjustment function reduced the inconsistency of the alert distances resulting from different types of equipment, and that the ASP method reduced the time delay resulting from high approaching speeds. The developed proximity safety alerts system provides stakeholders with better understanding of dynamic spatial relationships among equipment, operator, workers, and a surrounding work environment; thus, improving construction work zone safety.

## 1. Introduction

In construction, safety is as important as successful completion of a project. Worker safety should be addressed and managed successfully during the entire construction period. Although the issue of safety has garnered urgent attention in construction [1,2], and considerable efforts have been made, the number of fatal occupational injuries at road construction sites has remained relatively constant over the last decades. According to the U.S. Bureau of Labor [3], 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 [3,4].

Signage, traffic control systems, flaggers and other worker safety measures are used to maintain and promote safety at road construction sites. However, these passive safety devices and measures are incapable of alerting construction operators and workers in real time during a hazardous proximity situation [5]. Consequently, a variety of active technologies have been developed and applied to provide construction proximity sensing and alerts to workers and operators. Ruff [6,7] explored many technologies (e.g., radar, sonar, and infrared, UWB, GPS, and vision) for the application in the mining industry; some of these are the same technologies that are currently used in proximity sensing in passenger cars. These technologies suffer from unique limitations including light sensitivity, line of sight, form factor, cost, weight, limited field of view, and feasibility in the harsh construction environment. In addition, they generate mainly one-directional alerts for the operator not for pedestrian workers. Although these approaches provide proximity warning in certain conditions, most of them merely rely on the distance/proximity level between equipment and workers, which leads to frequent nuisance alarms [8,9]. Furthermore, most of the systems are developed and/or tested on selected equipment or at certain approaching speeds without considering inconsistency and unreliability caused by changes in these settings.

This problem indicates a need for investigating a solution that mitigates the inaccuracy of proximity sensing and alert systems caused by various types of equipment and different approaching speeds. To explore a solution to these problems, this research uses the Bluetooth Low Energy (BLE) technology-based proximity sensing and alert system that was first demonstrated as a prototype by Park et al. [10]. This BLE

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system is software-programmable that allows modification of the system. In this research, we modified the BLE proximity sensing and alert system by developing and embedding two features to it (i.e., a parameter adjustment function and a signal processing method). The purpose of these developments is to improve the consistency and reliability of the BLE proximity sensing and alert system for different types of equipment at different speeds. In the following section, an extensive review of proximity related research, in this aspect, is discussed. Then, methodologies, experimental studies, analysis, and discussion follow.

## 2. Literature review

### 2.1. Proximity sensing and alert systems

Over the last decade, researchers have attempted to use various sensing technologies, such as radar, video camera, radio frequency identification (RFID), magnetic field detection, BLE and others to provide a real-time monitoring systems [6,11–18]. Marks and Teizer [5] provided a method for evaluating proximity sensing and alert technology for safe construction equipment operation. Park et al. [10] evaluated commercially available proximity sensing and alert systems (i.e., BLE, magnetic field detection and RFID systems) through field trials, and Park et al. [19] developed a directional aware proximity system. Chae and Yoshida [17] used three tags (equipment, person, and location) to add additional location information for effectively detecting and preventing potential colliding incidents; although this method is advanced, the use of location tags in dynamic construction workzones may present challenges as previous research identified that location sensing technologies have problematic issues in many conditions (e.g., absence of line of sight, signal interference and reflection) [20–22]. Luo et al. [23] discussed the impact of workers' responses to proximity warning by conducting a series of tests at a construction site. Ruff [7] discussed the capabilities and challenges of available sensing technologies (e.g., radar, video camera, and RFID systems) for monitoring blind spots around haul trucks. Similar tests were conducted, and a guidance for evaluating and implementing proximity systems for mining equipment was developed by Ruff [6].

Although several systems have been found to be capable of providing reliable proximity alerts under certain circumstances, many systems showed inconsistency and thus unreliability in detection range, especially when environmental settings in which the systems are deployed change. Park et al. [11] conducted the coverage experience of different types of construction equipment by using three proximity sensing and alert systems, which are BLE, RFID, and magnetic field-based proximity sensing and alert systems. Their results showed that the alert range abruptly changed, although the same settings were used, when the tested equipment was changed from a truck to a wheel loader. A similar phenomenon is also found in a study conducted by Marks and Teizer [12]. In addition to these findings, Ruff [6] stated, “required detection characteristics for a system depend on the equipment it will be installed on”, which suggests the same problem. Besides the type of equipment, other parameters, such as ambient temperature and relative humidity, are also found to impact the results of proximity sensing and alert systems [5]. Similar issues of sensing technologies are also reported in a recent study [24]. These statements suggest that sensing systems can perform inconsistently even when they are applied in the same/similar manner. Such an issue has not been sufficiently studied or addressed by state-of-the-art research in the proximity sensing domain.

Previous research suggests another significant challenge other than the impacts caused by different test conditions; delays of alerts for proximity sensing and alert systems under high approaching speeds have also been found in several studies. The National Institute for Occupational Safety and Health [25] tested an electromagnet-based proximity system for mining in various testing scenarios. The test results showed clear evidence of this delay. Their tests with multiple pieces of equipment and various moving speeds revealed that the detection distance dropped in all cases. For example, one of their many tests showed that the distance dropped from 43 in. (1.09 m) to 25 in. (0.64 m) when the speed increased from 3 in./s (0.27 kilometers per hour (kph)) to 32 in./s (2.92 kph). A recent experimental study emphasizes the same finding related to the distance drop when the proximity sensing systems are subjected to various approaching speeds [11]. Ruff [6] pointed out that the parameters, such as operator and pedestrian reaction times, maximum speed of the equipment, braking distances and the equipment dimensions, must be considered when determining a detection range at high approaching speeds. In addition, researchers [18,26–28] conducted state and space modelling using 3D position, orientation and velocity to more effectively model the alert range.

Despite the previous research efforts, the literature clearly presents a strong need for exploring the problems in regard to inconsistency and delay of proximity warning systems. To overcome the discussed limitations with which currently available proximity sensing and alert systems still struggle, this study developed a parameter adjustment function and a signal processing method, which were validated through field trials.

### 2.2. Bluetooth Low Energy (BLE) technology

This section provides a brief overview of the technology, BLE, used in this research. BLE was developed and adopted in 2010, and compared to conventional Bluetooth technology, BLE offers many benefits, such as low cost, low energy usage, and minimal infrastructure requirements [29] while maintaining other beneficial characteristics of the conventional Bluetooth technology. Because of these benefits, BLE technology has recently gained in popularity with many industries. One study by Martin et al. [30] conducted tracking research. Although tested in a small, limited setting, they acquired an accurate tracking of 0.53 m accuracy. In addition, several BLE-based systems have been developed for construction safety [13,16] and tracking [31], which proved the technical feasibility of BLE technology in construction applications.

Although the potentials for BLE technology have been well recognized and actively explored in other research domains during the last decade, only limited numbers of research studies have been conducted in the construction domain. The first BLE-based proximity sensing and alert system was prototyped by the Robotic and Intelligence Construction Automation Lab at the Georgia Institute of Technology, and first introduced by Park et al. [10]. This research used the same platform to develop and test the parameter adjustment function and signal processing method to address the discussed challenges discovered in the previous literature review.

## 3. Objectives and scope

The primary objective of this study was to address the problems of inconsistent performance and potential delay of a proximity alert system by developing two methods in the BLE-based proximity sensing and alert system. This advancement will be a step forward for the system with an ultimate goal for improving worker's safety through the system. The additions of the methods were to increase both the consistency and accuracy of the system in various settings (e.g., various pieces of equipment and settings of the sensing system) and dynamic situations (e.g., various speeds), which presented challenges to previous developed and/or tested systems. The methods should overcome practical limitations, such as the inconsistency of results under different equipment settings, and the distance drop at high approaching speeds which are currently present in state-of-the-art proximity sensing and alert systems. To validate the developed methods, this study conducted various field trials to simulate hazardous situations with workers and equipment and analyzes the data to assess the performance of the proposed methods.

The scope of the study includes the development of the additional methods and incorporation into the BLE-based proximity sensing and alert system, first prototyped in Park et al. [10]. After the development of the system, several field trials were designed to assess the reliability and effectiveness of the system when it is applied to various working conditions (i.e., different pieces of equipment, different settings, and various speeds of moving equipment). Then, the subsequent analysis of the test data and discussion of the results follow. The scope was limited to proximity incidents between ground workers and construction equipment. In the analysis, the major interests are to improve the consistency—how consistently the accuracy of the alert distance is maintained—when there is a change in equipment and to reduce the delay of the alert system when there is a change in the equipment speed.

## 4. Methodology

### 4.1. System architecture

The developed mobile proximity sensing and alert system uses BLE technology as the major communication protocol that is used for detecting the proximity level between workers and equipment. Fig. 1 provides the system architecture, which shows system components, their communication network, and the methodologies proposed in the study. The distances between workers and equipment are estimated from BLE signals. The BLE signals are sent from the equipment operator units (EPUs), which are BLE beacons, and are received by the worker's personal protection unit (PPU), which is the BLE-enabled mobile device in this system. To create a symmetric coverage range, BLE sensors are mounted around the equipment, so that the sensors can reliably communicate with a mobile device at any direction with respect to the equipment. When the system detects a proximity hazardous situation, it provides continuous warning alerts to associated workers in real time until the hazardous situation is cleared.

Fig. 2 provides the flowchart of the system communication and the methods (i.e., the parameter adjustment and adaptive signal processing functions), which were developed and added to the system to address the previously discussed problems. The parameter adjustment function takes place in advance of the implementation of the system because it allows the system to adapt to the surrounding of the equipment over which the sensors are deployed. Dashed boxes in Fig. 2 indicate the two methods in the system flow. The following subsections describe each of the methods and their detailed working principles.

### 4.2. Parameter adjustment function

As the distance between the signal transmitter and the receiver increases, the BLE signal strength fades, based on signal theories, which can be used to estimate the distance between them. The relationship between distances and received signal strength indicator (*RSSI*) values used in this study is shown in Eq. (1) [32,33].

$$Dist = 10^{\left(-\frac{abs(RSSI_1)+RSSI}{10\,n}\right)} \quad (1)$$

where,

*Dist* is the estimated distance between a beacon and a receiver device;
$RSSI_1$ is a predetermined *RSSI* value that is measured at a distance of 1 m;
*RSSI* is a value that is measured in real time;
$n$ is the path loss constant.

Given the same environment, both $n$ and $RSSI_1$ are constant in theory, and the distance between the signal transmitter and the receiver mainly depends on the received *RSSI* values. However, because of the dynamic nature of a construction site and various environmental interfering conditions and variations in practice, the values of $n$ and $RSSI_1$ may not be consistent. This inconsistency may intensify when sensors operate in different conditions (e.g., different types of equipment and different test environments). To observe the behavior of *RSSI* signals, a set of sample data containing approximately 600 *RSSI* points is collected; a receiver collects *RSSI* from a transmitter at a constant distance. Fig. 3 shows the measured distance by using the *RSSI* values collected on the uncalibrated system at a distance of 1 m. The results imply that without calibration, the measured distance may not be accurate because of the variability in the environment where the signals communicate. Furthermore, the noisy nature of radio signals leads to fluctuation of signals, resulting in inconsistent data measurements even at a constant distance, which is shown in Fig. 3. To circumvent this problem, this study developed a parameter adjustment function to the BLE proximity and sensing system to reflect the unique condition of the surrounding for individual transmitters.

Fig. 4 displays a pseudo code of the parameter adjustment function. To obtain the calibrated $RSSI_1$ for a specific test condition, a certain number of data are collected through the worker's PPU where the distance between the PPU and the EPU is 1 m. The amount of collected data depends on the allowable calibration time and the requirement for accuracy. To reduce the impact of outliers (the area highlighted in Fig. 3), which can cause large deviations in the result, 80% of the

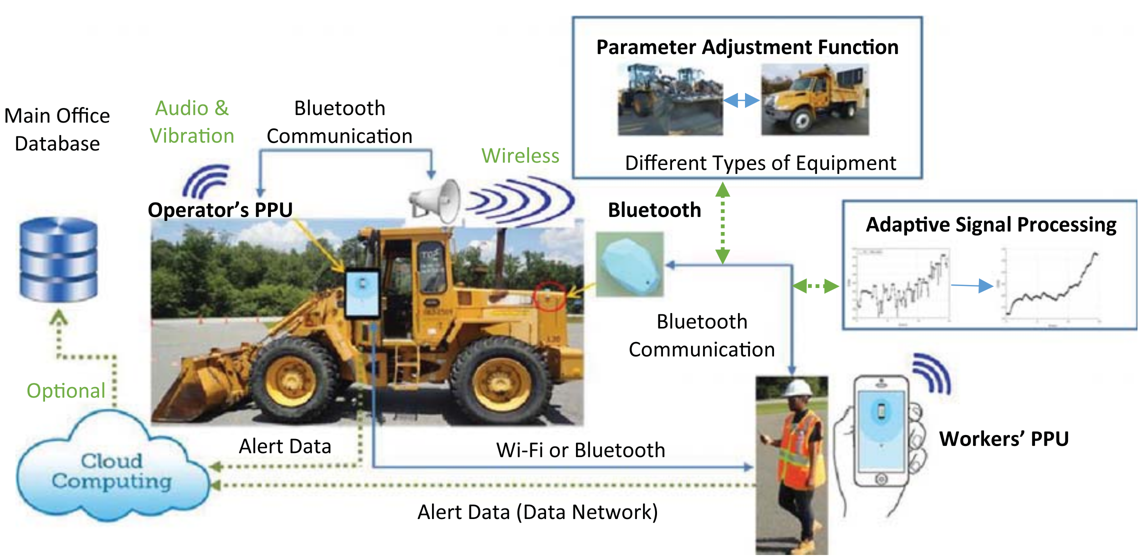



**Fig. 1.** System architecture of the BLE proximity sensing and alert system.

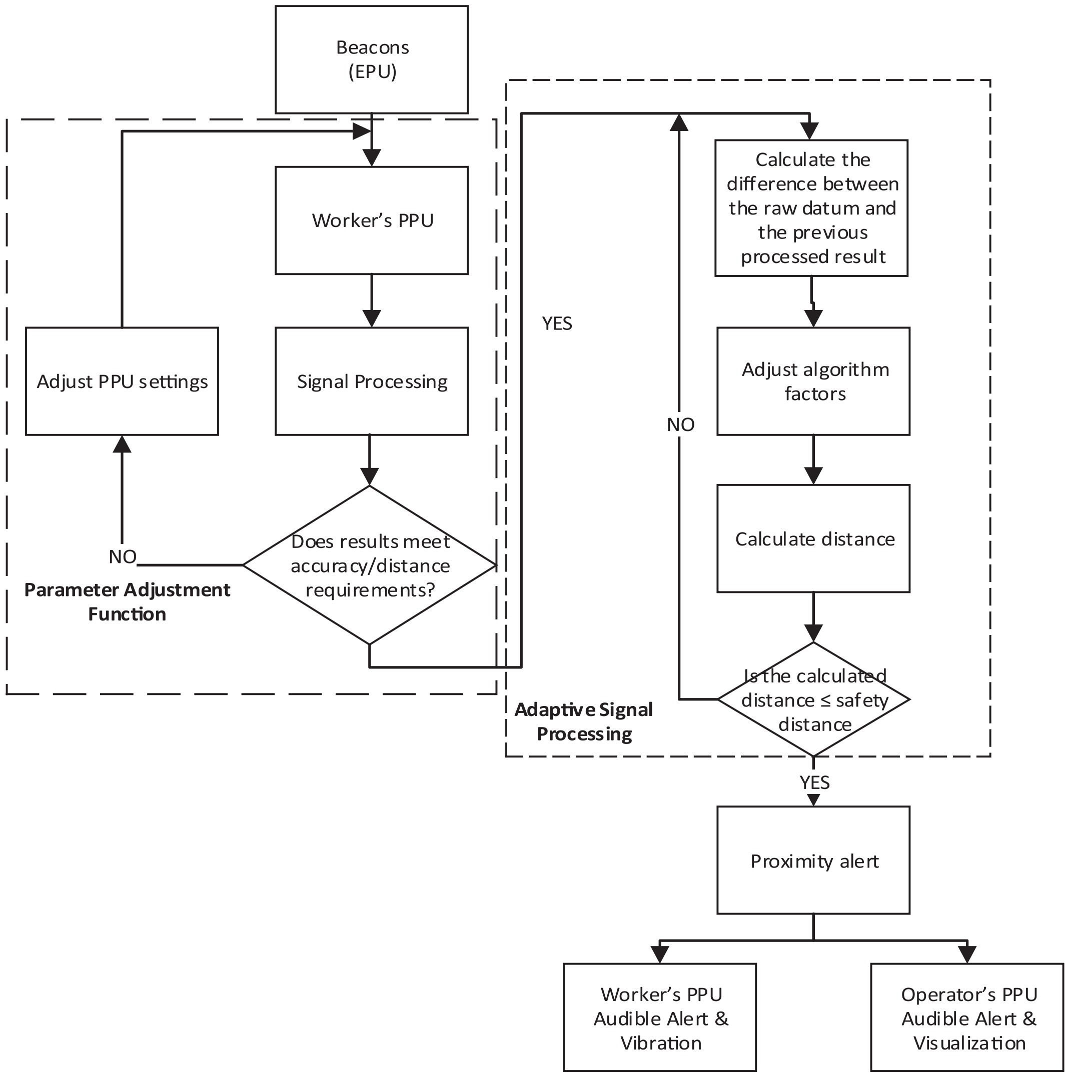



**Fig. 2.** System communication and working process.

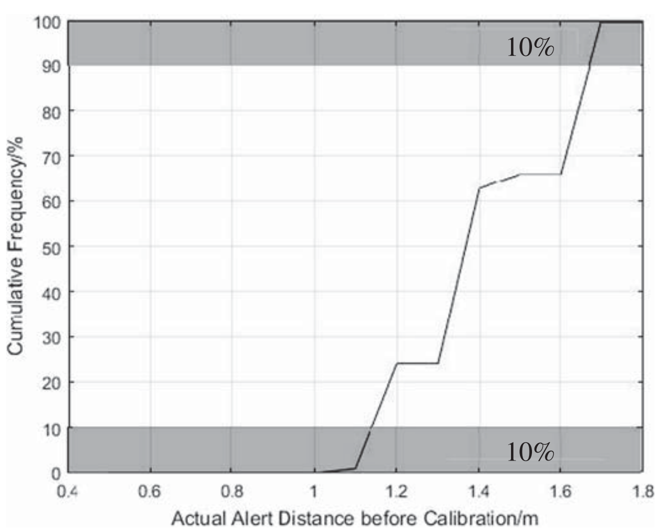



**Fig. 3.** Measured distances at 1 m without an adjustment of parameters.

**Algorithm 1** Parameter Adjustment Function

**Input:** $RSSI, N_1, N_2$

**Output:** $RSSI_1$, $n$

Collect $RSSI$ at $1/m$ for $N_1$ times
**function** $(Compute\_RSSI_1)$
    $Sort(RSSI)$
    $RSSI_1 = Ave(RSSI(0.1N_1 : 0.9N_1))$
    Output $RSSI_1$
**end function**

Collect $RSSI$ at $k/m$ for $N_2$ times $(k! = 1m)$
**function** $(Compute\_n)$
    $Sort(RSSI)$
    $AveRSSI = Ave(RSSI(0.1N_2 : 0.9N_2))$
    $n = (-abs(RSSI_1) - AveRSSI)/(10 * lg(k))$
    Output $n$
**end function**

**Fig. 4.** Algorithm for the parameter adjustment function.

collected data in the middle range are used to quantify the average value, which represents the calibrated $RSSI_1$. With this calibrated $RSSI_1$, the path loss constant $n$ can be calculated using the same process, but at a different distance. A certain number of $RSSI$ values are collected at a specific distance (e.g., 5 m, 7 m, and 10 m), which is not equal to 1 m. By applying the calibrated $RSSI_1$ and the average of the newly collected $RSSI$ values to Eq. (1), the calibrated $n$ is back-computed. By performing this process for each sensor, the proximity sensing and alert system can create more symmetric coverage range around the equipment, which will be discussed through field trials and a follow-up analysis.

### 4.3. Adaptive signal-processing (ASP) method

To mitigate the adverse impact of the noisy nature of radio signals, an effective signal-processing method is necessary so that the system can output more reliable data that can transform to a distance measure. One of the most commonly used signal-processing methods is a moving average filter (MAF) that reduces the noise of raw data by averaging a certain number of measured values—this method applies the same weight to all data points. An example of MAF is shown as Eq. (2).

$$y[i] = \frac{1}{M}\sum_{j=0}^{M-1} x[i-j] \tag{2}$$

where,

$x[]$ is the input signal value;
$y[]$ is the output signal value;
$M$ is the number of data points used in the average.

The benefit of MAF is its simplicity while being effective in certain cases. It is optimal when it is used to reduce random noise while retaining a sharp step response. However, MAF suffers two shortcomings that limit its application for a real-time proximity sensing and alert system that needs to operate in various conditions (e.g., various approaching speeds). The first limitation is that MAF needs a certain number of data points, which is the number of data that are used for averaging, to initialize the signal processing procedure. Consequently, MAF is not able to provide instant alerts when a piece of equipment starts and approaches a worker suddenly, which is one of the most common reasons that cause a struck-by accident in roadway construction sites. The second limitation is that MAF is not able to quickly reflect rapid changes in the proximity data between equipment and workers. To address these points, this study proposes the ASP method, which improves the response time (delay) of the proximity warning system by providing timely proximity alerts. The ASP method is based on the exponential moving average (EMA) method proposed by Roberts [34] and modifies EMA by adding an adaptively applied smoothing factor. Eq. (3) shows the EMA equation.

$$y[i] = (1-\alpha)\times y[i-1] + \alpha \times x[i] \tag{3}$$

where,

$\alpha$ is the smoothing factor, where $0 < \alpha < 1$.

As shown in Eq. (3), the processed result $y[i]$ is a weighted average of the current datum point value $x[i]$, and the previous processed result $y[i-1]$. The smoothing factor $\alpha$ is used to reflect the weight of the current datum point and the smoothness of the processed signal results. Fig. 5 shows a pseudo code of the ASP method. The ASP method offers an adaptive feature that uniquely defines and applies the smoothing factor $\alpha$ as a dependent variable; the values of $\alpha$ are obtained through extensive lab tests. By using this dependent variable in a decision-making process—it is shown in the clauses in Fig. 5—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. The field trials and test results will further discuss the effect of the ASP in the following sections.

**Algorithm 2** Adaptive Signal Processing

**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
```

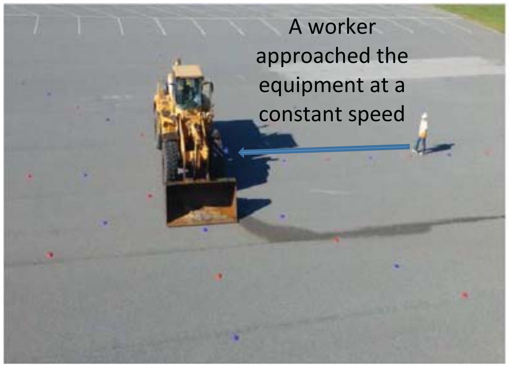
**Fig. 5.** Algorithm for the adaptive signal-processing method.

## 5. Testing method, field trials, and data collection

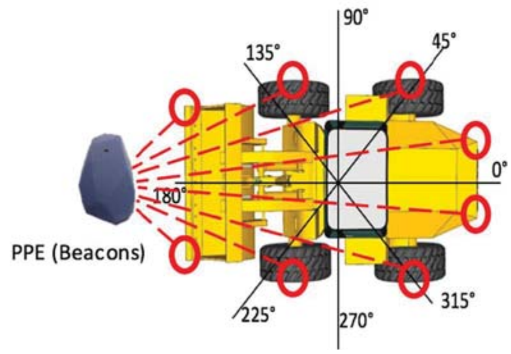
Previous research as well as our prior study [10], in which the authors compared the BLE proximity sensing and alert system with two commercially available products to comparatively assess the performance of the proximity warning systems, presented the inconsistency and delay problems in all of the systems. As new developments that attempt to address these issues have been added to the BLE proximity sensing and alert system for improvements, similar experimental trials were designed and conducted at a yard in a district of the Georgia Department of Transportation (GDOT). The trials involved two pieces of equipment including a small dump truck and a wheel loader in various scenarios that simulate different levels of dynamic working conditions.

Scenario 1 simulates an interaction between a stationary piece of construction equipment and a mobile pedestrian worker. To test the parameter adjustment feature of the system, the system was tested for two cases: one with and the other without the parameter adjustment feature. To provide strong evidence with multiple tests with different equipment, each of these cases was conducted with two types of equipment including a dump truck and a wheel loader. Fig. 6 shows the test bed of scenario 1 (a) and the system deployment plan (eight beacons) for the wheel loader (b). Fig. 7 shows selected locations of eight sensors for the truck (similar to those of the wheel loader). During the test trial, a worker is asked to hold a PPU at a waist height and approach the equipment at a constant walking speed of 3 miles per hour (mph), which is equal to 4.8 kph. When the BLE system triggers an alert, the worker stops and the distance between the worker and the equipment is measured. The test was repeated 20 times for each of the eight equally spaced angles (Fig. 6(b)).

Fig. 8 shows the test scenario 2, which is to simulate an interaction between a stationary worker and a mobile piece of equipment at different approaching speeds. In this study, 3 mph (4.8 kph), 5 mph (8.1 kph) and 10 mph (16.1 kph) approaching speeds were tested to assess the effectiveness and functionality of the proposed signal processing method. The inclusion of the 16.1 kph test posed a much more




6 (a) Test beds of scenario 1




6 (b) Beacon deployment locations for the wheel loader

**Fig. 6.** Test beds and sensor deployment for the wheel loader.

critical test environment, compared with that of the prior study discussed in [10]—twice faster interaction scenario with construction equipment. The test was strictly controlled with safety cones and the alert system to avoid any potential incidents. This scenario also performed twenty trials for each speed. During the test, we collected raw *RSSI* values, processed results using MAF, and processed results using ASP. Each result was then analyzed from the signal processing perspective. In addition to this data set, the triggered distances between the worker and the equipment were measured to analyze the performance of the ASP method.

## 6. Results and analysis

As mentioned in the Literature review, it is critical to test and demonstrate the capability of proximity sensing and alert systems with respect to inconsistency and delay. This result and analysis section is to assess the parameter adjustment function and the signal processing method that aim to address these issues. Based on the collected data from the field trials, the following analysis section discusses the effectiveness and performance of the proposed methods implemented in the BLE-based proximity sensing and alert system.

### 6.1. Performance analysis of the parameter adjustment function

The results of the scenario 1 tests without the application of the parameter adjustment function are shown in Fig. 9. Two sub-plots, which are Fig. 9(a) and (b), represent the results of the wheel loader and the truck separately, each of which are the results of 160 trials. Both of the average value and the confidence interval of one standard deviation are plotted for each of the approaching directions. The results present strong evidence of inconsistency in the alert range of the system when applied to different pieces of equipment. It shows an increase in the average alert distance when the construction equipment was changed from a wheel loader to a dump truck although the same system setting was used for the two tests. Among the various parameters—discussed in the literature review—that potentially influence the signal strength, this particular comparison analyzes the relationship between the configuration of equipment and the signal communication. The tested truck has a relatively simple configuration with flat front, side and back panels while the wheel loader had more complexity in its design with various attachments, which could intensify the effect of multipath or block the line-of-sight signal communication. Thus, it can be deduced that the complex shape of the equipment could randomly affect the system performance. The results indicate that the distance range can abruptly change for different pieces of equipment. In the following sections, the contribution of the parameter adjustment function is analyzed and discussed.

Fig. 10 displays the results of the scenario 1 tests with the application of the parameter adjustment function. Compared to those of the scenario 1 presented in Fig. 9, the results of the scenario 1 in Fig. 10 show considerably more consistent alert distances. Thus, the proposed method has successfully proven at producing consistent performance of the system for different types of equipment. Table 1 summarizes the numerical results of the same tests in aspects of the average, standard deviation, deviation to the desired distance setting. Eq. (4) shows the formula to compute the deviation to the desired distance setting. For the cases, the results indicate an improvement in consistency by showing the deviation, on average, to the desired setting from 5.54 m to 0.03 m for the 160 trials with the truck, and from 0.88 m to 0.37 m for the 160 trials with the wheel loader. Furthermore, the standard deviations for both cases are found to have a minor improvement: from 2.7 m to 2.6 m with the truck and from 3.35 m to 2.84 m with the wheel loader. As a note, no false negative instances were observed among all trials.

$$\text{Deviation to the desired distance} = \text{abs}(\text{average} - \text{desired distance}) \quad (4)$$

### 6.2. Performance analysis of the ASP method

The second analysis is associated with test scenario 2 that involves a


**Fig. 7.** Sensor deployment locations for the truck.

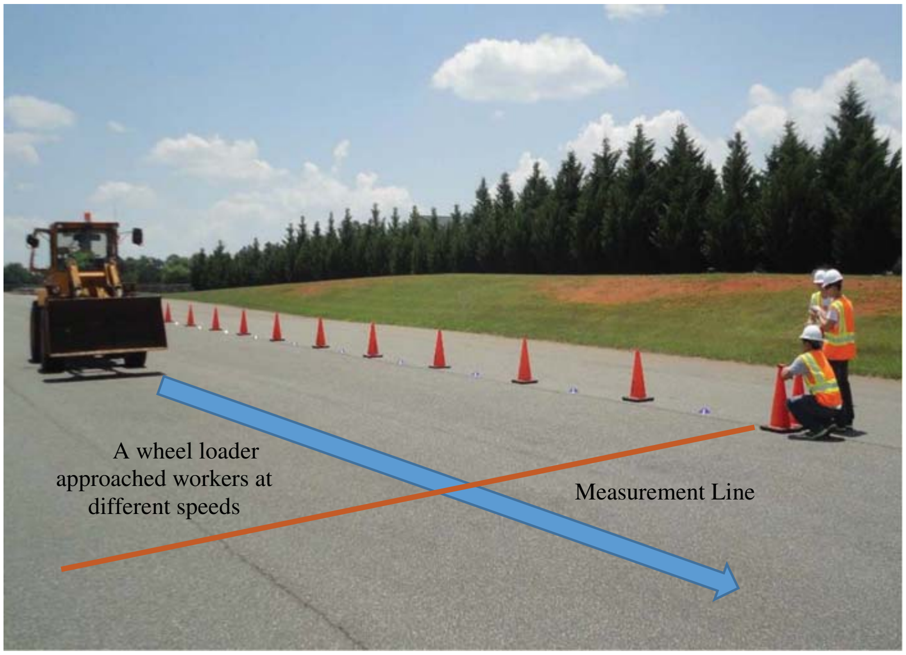


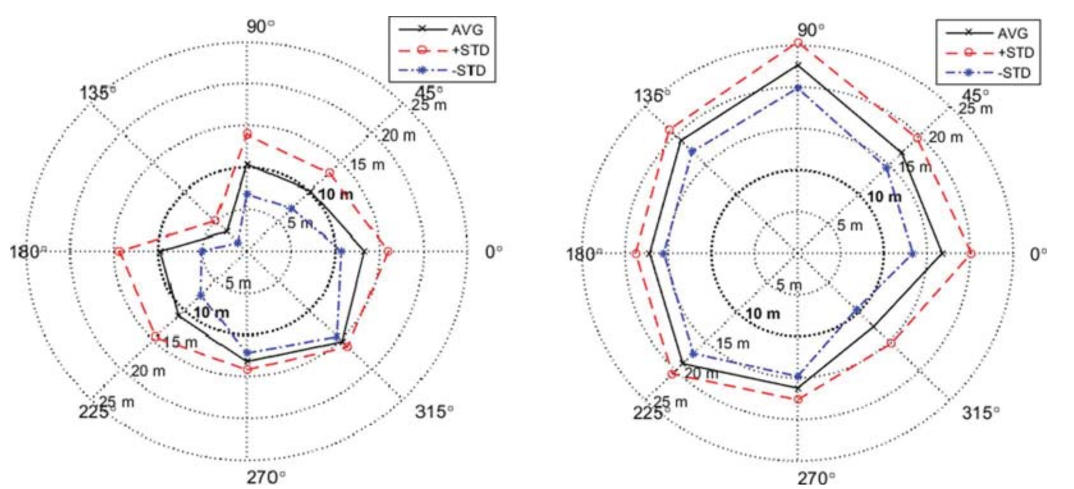

**Fig. 8.** Test scenario 2.

mobile wheel loader approaching a stationary worker at different speeds. To analyze the system behavior with respect to the delay of response, the collected raw data were processed through two signal-processing methods, MAF and ASP, and then the results were compared in micro and macro perspectives.

First, to observe the performance of the two methods in reflecting changes in increasing signals, the team collects *RSSI* data while the wheel loader approaches the stationary worker from a distance of 20 m at a speed of 3 mph (4.8 kph).

Fig. 11 shows the raw *RSSI* data values, processed results of MAF, those of ASP, and induced *RSSI* values. Note that the induced *RSSI* line is not an actual line of a plot but is only an estimated *RSSI* line assuming the specific moving scenario as mentioned above, which is made for a comparison purpose. The parameters used to calculate the *RSSI* values are estimated by using the parameter adjustment function as proposed in Algorithm 1. The plots clearly indicate that both of the MAF (blue line) and ASP (red line) significantly reduce the noises of the raw data, which is a positive effect. However, the two methods differ with respect to the response of delay. By analyzing the data in a macro level, the ASP offers less alert delay than the MAF, which was the primary goal in the development of the ASP method. In addition, the mean square error, generated by ASP, corresponding to the induced *RSSI* is considerably smaller than that by MAF (3.34 dbm vs. 7.95 dbm). This comparison suggests that the signal output fits better to the estimated *RSSI* line. Furthermore, the ASP method maintains the quality of the data and mitigates the negative effect of signal noises.

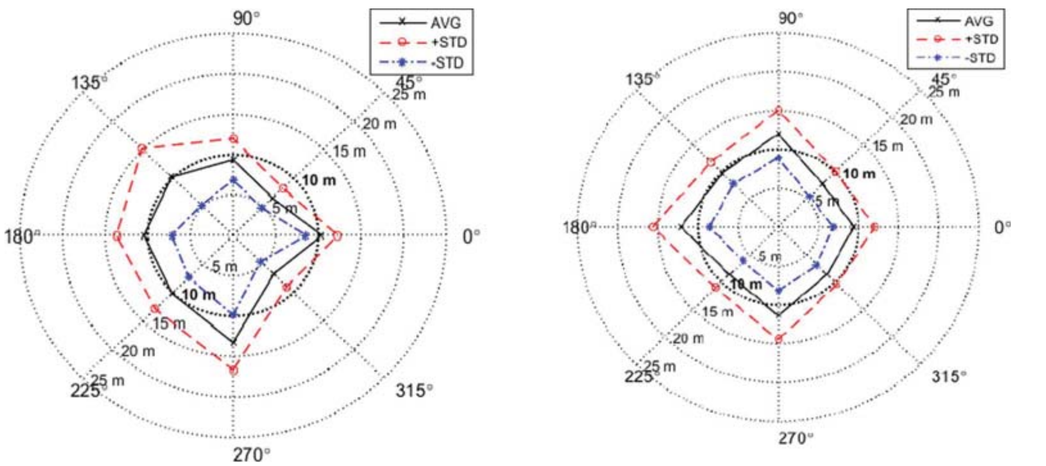
To further understand the behavior of the system with respect to various speeds of moving equipment, we analyzed the data collected from cases in which the equipment operates at different speeds (i.e., 3 mph (4.8 kph), 5 mph (8.1 kph) and 10 mph (16.1 kph)). When measuring the actual alert distance, the stopping location of equipment is measured with respect to the worker (e.g., 10 m indicates the equipment stops at 10 m in front of the worker). Figs. 12 and 13 plot the test results for each trial, representing MAF and ASP, respectively. For both methods, the average alert distances have the tendency to decrease when the system is subjected to higher approaching speeds. While this




(a) Active proximity alert zone of a wheel loader without parameter adjustment (10m setting)

(b) Active proximity alert zone of a truck without parameter adjustment (10m setting)

**Fig. 9.** Test results of the BLE system without parameter adjustment function.




(a) Active proximity alert zone of a wheel loader with parameter adjustment (10m setting)

(b) Active proximity alert zone of a truck with parameter adjustment (10m setting)

**Fig. 10.** Test results of the BLE system with the parameter adjustment function.

**Table 1**
Test results of scenario 1.

| Equipment | | Average (m) | Deviation to setting (m) | Standard deviation (m) |
|---|---|---|---|---|
| Truck | Without calibration | 15.54 | 5.54 | 2.70 |
| | With calibration | 9.97 | 0.03 | 2.60 |
| Wheel loader | Without calibration | 10.88 | 0.88 | 3.35 |
| | With calibration | 9.63 | 0.37 | 2.84 |

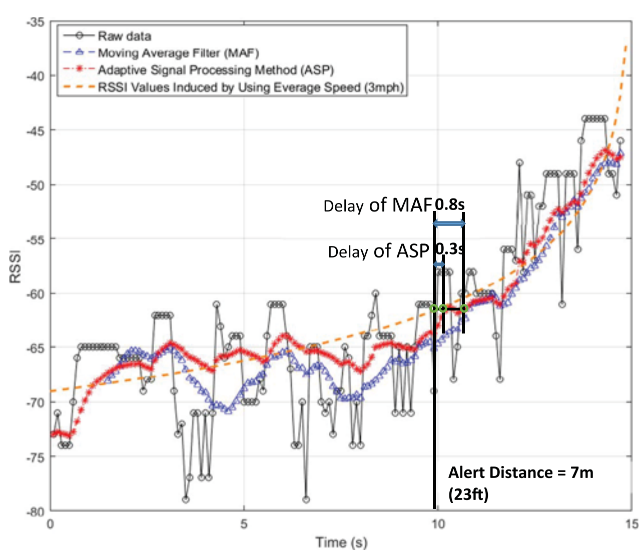



**Fig. 11.** Signal processing under 3 mph (4.8 km per hour) approaching speed. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

is true, the decrease of the alert distance with the application of ASP is slightly smaller than that of the alert distance with the application of MAF. This indicates a minor improvement offered by ASP. Furthermore, a significant difference is observed between the methods with respect to consistency of the alert distance. The fluctuation of the results with ASP is considerably reduced, compared to that of the results with MAF.

Fig. 14 shows box plots of the results of scenario 2; it shows the average and the interquartile range of the data. These plots suggest the same findings that are discussed with Figs. 12 and 13. The results of ASP show more reliable behaviors than those of MAF. The box plots of ASP have smaller interquartile ranges than those of MAF, and the median values of ASP are closer to the desired setting than those of MAF, which implies that the delay is reduced. In addition, the smaller range of ASP arguably suggests that the potential for false alerts is less.

## 7. Conclusion and discussion

Accident statistics have shown that the safety issues in road construction work zones have not been successfully addressed and managed in protecting construction workers. Equipment or vehicles striking construction workers in a work zone is one of the most detrimental types of accidents with the most frequent rate of occurrence. Previous research in the area of proximity sensing and alert technology has progressed considerably through methodological and experimental studies. Although previous research studies have identified problems of inconsistency and delay of proximity warning systems, they have not been adequately investigated for improvement.

To address these problems, this study developed and tested the working processes involving the parameter adjustment function and the ASP method using the BLE-based proximity sensing and alert system. The research conducted field trials by simulating interaction scenarios between ground workers and equipment in various dynamic conditions and on different types of equipment to assess the performance of the system in regards to the additional methods. The test results showed that the parameter adjustment function reduced the inconsistency of the alert distances resulting from different types of equipment, and that the ASP method reduced the time delay resulting from high approaching speeds. The developed processes demonstrated the potential to overcome the discussed problems found in other proximity sensing and alert systems.

The testing of such a system can be an extremely dangerous task if an unverified system is used or if the test is not properly controlled. The developed system is still in an improvement phase as previous research found potential problems that this research attempted to overcome. For this reason, the test was conducted in limited conditions and resources as described throughout the paper. For one, calibration was conducted by collecting a large number of data sets to eliminate potential bias. As to this matter, future research will investigate the relationship among calibration time, advertising rate, and system accuracy. Also, for further validation of the system in various working environments, as a future study, the system should be tested with additional types of equipment,

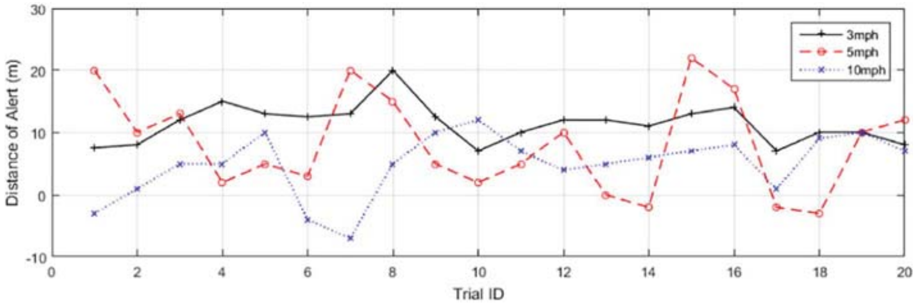



**Fig. 12.** Alert distance of wheel loader with various approaching speeds using MAF (10 m setting).

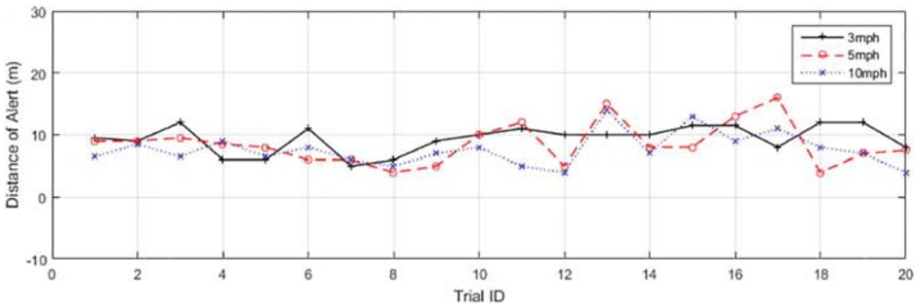
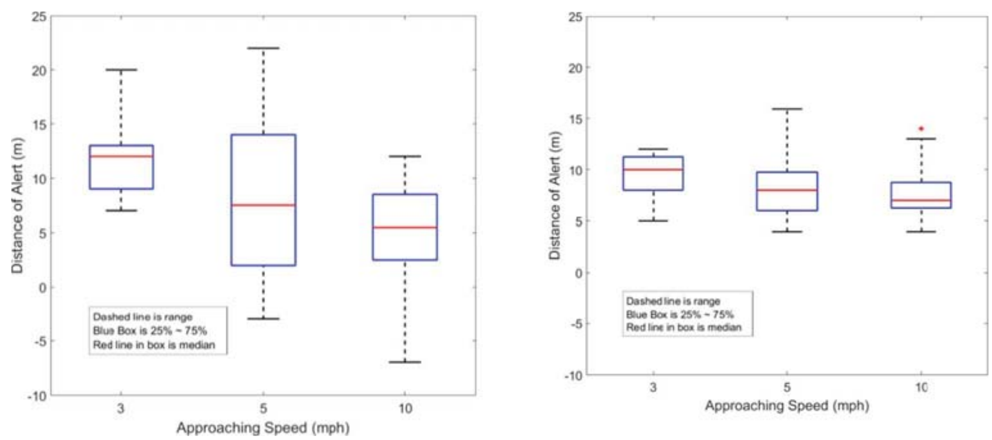



**Fig. 13.** Alert distance of wheel loader with various approaching speeds using ASP (10 m setting).




(a) Box plot of a wheel loader with various approaching speeds by using MAF (Ground truth: 10 meters)

(b) Box plot of a wheel loader with various approaching speeds by using ASP (Ground truth: 10 meters)

**Fig. 14.** Box plots of test scenario 2.

different system deployment settings, and more extensive field environmental and dynamic conditions (e.g., uphill and downhill) that can be commonly encountered in construction work zones. Although the research included various speeds in the test scenarios, each scenario relied on an assumption of a constant speed. However, on construction sites, the speed of equipment changes and different speeds would require different alert distances. To address this challenge, future research will be conducted for defining safety zones based on different factors such as approaching speeds. With continuous improvement on the system, the ultimate goal of the research team is to implement the system in an actual construction project, such as highway paving construction, for possible industry acceptance.

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