Bluetooth Low Energy Sensing Technology for Proximity Construction Applications

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ABSTRACT

Safety is considered one of the most importance components that need to be successfully addressed during construction. However, dynamic nature and limited work space of roadway work zones create highly occupied working environments. This may further result in hazardous proximity situations among ground workers and construction equipment. In fact, historical incident statistics prove that the current safety practice has not been effective and there is a need for improvement in proving more protective working environments. This study aims at developing a technically and economically feasible mobile proximity sensing and alert technology and assessing it with various simulation tests. Experimental trials tested the sensing and alert capability of the technology against its accuracy and reliability by simulating interactions between equipment and a ground worker. Experimental results showed that the developed mobile technology offers not only adequate alerts to the tested person in proximity hazardous situations but also other advantages over the commercial products that may play an important role in overcoming the obstacles for rapid deployment of new technology in construction segments.

Key words: Bluetooth Low Energy, construction safety, construction equipment, iBeacon, proximity sensing

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INTRODUCTION

With the development of wireless technology in the last decade, mobile devices have become an essential component in our daily life being used for multiple purposes. The advancement in the wireless technology enabled most of the recently produced cars equipped with Bluetooth technology. The driver is then able to communicate with his/ her mobile device via a Bluetooth enabled car, triggering phone calls listening to music and radio without having to making physical contacts with the device. This has turned our daily activity of driving a car into a much safer experience, allowing the driver to better focus on the road. According to (Statista, 2015), the population of smartphone users have rapidly been increasing and the expected number of population in the U.S. is 183 million, which is more than a half U.S. population (See Figure 1).

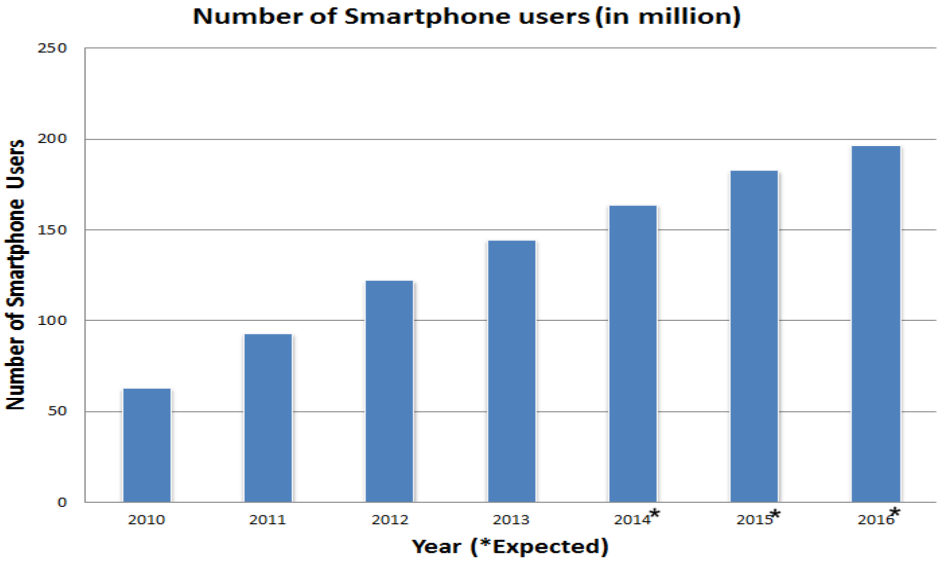

Figure 1. The number of smart phone users in the U.S.

Safety is one of the most importance components that need to be successfully addressed during construction. However, dynamic nature and limited work space of roadway work zones create highly occupied working environments. This may further result in hazardous proximity situations among ground workers and construction equipment. 962 deaths of workers were recorded at a road construction sites from 2003 to 2010. In addition, about 30% of deaths related to construction 2012 were resulted from being struck by a vehicle. These historical incident data prove that the current safety practice has not been effective and there is a need for improvement in proving more protective working environments. Recent industrial (ENR, 2015) efforts have been found with deploying cameras and motion sensors near the blind spots of a piece of equipment. Various proximity sensing devices have been discussed and evaluated by (Ruff, 2007), (Begley, 2006), (Marks and Teizer, 2012) and (Larsson, 2003). Tested and evaluated systems in the past research require external hardware, such as camera, laser scanner, tripod, power supply lines, heavy antenna, or tags. These are the major components of each of the systems to achieve communication between a hazardous source and an object that is potentially in a dangerous zone. While being major components, these requirements are barriers that limit the systems' feasibility and practicality in dynamic construction applications. In addition to the infrastructure requirement, there are other parameters that are crucial for assessing a system's feasibility and practicality, including detection area, cost, maintenance, accuracy, precision, consistency, alert method, adaptability, required power sources, ease of use, ease of deployment. Benefits and limitations of other proximity sensing systems were discussed in (Castleford et al., 2001; Goodrum et al., 2006; Marks and Teizer, 2013)

Although smart devices are already pervasive and embedded into our society, their potential uses in construction industry have not been discussed and minimal research and experimentation have not been conducted with utilizing smart devices, despite the efforts made with other technologies in the last decade. This study proposes a wireless proximity sensing technology that utilizes Bluetooth transmitters and mobile devices to create a proximity sensing and warning system. The authors consider that several characteristics of smart devices, such as pervasiveness, availability, and familiarity to end users, are the key factors to realize a feasible and practical technology. In the following sections, an extensive overview of the proposed system will be discussed, and experimental validation and conclusion will follow.

OBJECTIVE

In adopting a proximity sensing and alerting system, several factors play an important role for a system to be feasible and pragmatic. They include detection area, cost, maintenance, accuracy, precision, consistency, alert method, size of infrastructure, adaptability, required power sources, ease of use, ease of deployment, and others. The main objective of this study is to develop and validate a proximity sensing system that is economically and technically feasible and practical. The system should provide minimal infrastructure, adaptability with calibrating ability, intensifying alerts to reflect the degree of dangerousness, and real-time alerts to pedestrian workers and equipment operators during hazardous proximity situations. Widely available smart devices and low-cost Bluetooth transmitters are utilized to create a proximity sensing and alert system. Through field experimentations, their performance have been tested and assessed in various aspects.

PROPOSED PROXIMITY SENSING SYSTEM

The proposed proximity sensing system is based on Bluetooth based wireless sensing technology (iBeacon technology). This system offers various promising characteristics, including rapid connectivity, ease of deployment, low-cost hardware, minimal infrastructure and ease of integration with other systems. These characteristics are especially beneficial when considering adoption into construction industry. The system provides intensifying alerts upon creation of hazardous incidents to mitigate potential risks that will otherwise be posed upon workers and equipment. The system is composed of major components to create a basic proximity sensing and alert system, and of auxiliary components to support the system in different aspects.

System Major Components

The developed system is composed of three main hardware components, including 1) signal transmitters (Bluetooth transmitter), 2) personnel receivers (Bluetooth enabled mobile device), 3) equipment operator’s receiver (Bluetooth enabled mobile device), and the software component which provides an user interface and application function on which the system operates. A signal transmitter (beacon) is called Equipment Protection Unit (EPU) that transmits Bluetooth signal using Bluetooth Low Energy (BLE). Beacons are to create detection area from a hazard source to protect workers. Figure 2 describes an example of beacon deployments on a piece of construction equipment and a worker operating nearby. To create a symmetrical detected area, several beacons are attached symmetrically around a piece of construction equipment. A worker on the right of Figure 2 is equipped with a Bluetooth enabled mobile device, which is also called Pedestrian worker’s Personal Protection Unit (PPU). This

PPU provides intensifying sound alerts and vibration upon breach into a hazardous zone defined based on a piece of equipment considered. An equipment operator is also equipped with a Bluetooth enabled mobile device, which is also called Equipment operator's Personal Protection Unit (PPU). When a potential hazardous incident is created, this PPU provides intensifying alerts and the direction of the incident with respect to the equipment.

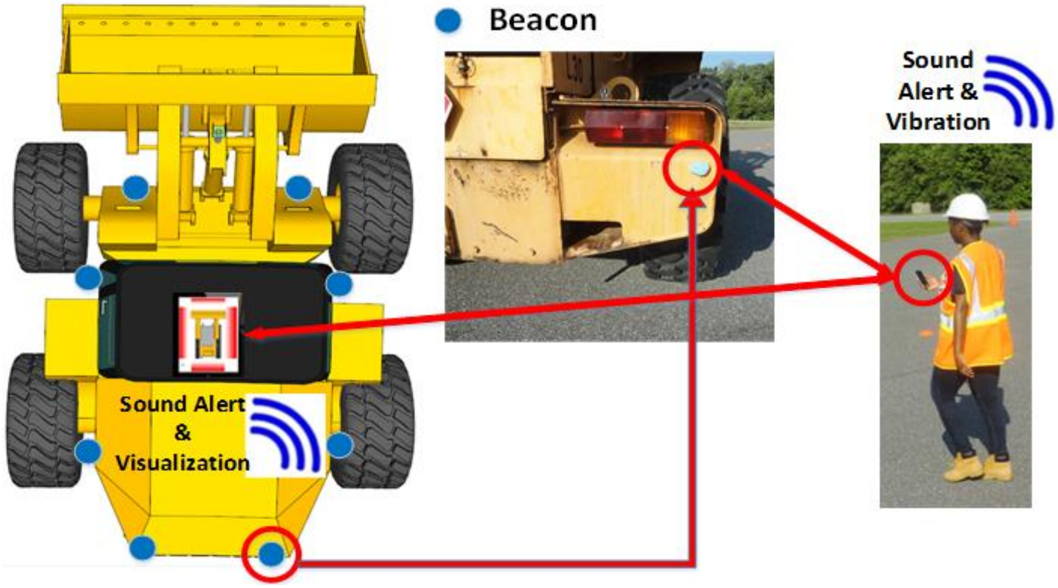

Figure 2. Major components of the proposed system

System Auxiliary Components

The proposed system is also composed of several auxiliary components to reinforce the communication and alert system especially when operating in a harsh working environment and to provide more features and opportunities for post safety analysis. Additional Bluetooth enabled devices including a smartwatch and an earpiece can be incorporated into the existing system for enhanced vibratory and sound alerts. Also, a cloud server is configured for the proposed system to gather data that indicate a potentially created hazardous situation. Whenever hazard incident is created, the system can send to a cloud server the creation of the incident for post safety analysis.

System Component Communication Flow

Previous sections described the roles of each of the components. This section explains the system work flow and details in each of the flow steps. Figure 3 shows a flow chart for one cycle of communication of the system. This flowchart illustrates one cycle of the system communication. After each cycle the flowchart points to "Keep Monitoring", which basically indicates that cycles are repeating. Each cycle starts with communication of beacons from a hazardous source (e.g., a piece of equipment) and a mobile device (e.g., a protected worker). Based on the user's distance set-up, the system determines if dangerous zone has been breached by either the piece of construction equipment or the worker during the dynamic interaction of the two. When it is determined to be breached, the system proceeds with prevention actions to provide an additional chance for the worker and equipment to escape from the scene. The prevention actions immediately take place without time delay from the hazard situation detection by the system. Audible alerts and vibration get triggered to the worker's PPU, while audible alerts and visualization of the direction of the hazard situation with respect to the equipment are provided to the equipment operator via his/ her PPU. In addition, the system support cloud based data collection to allow for post analysis.

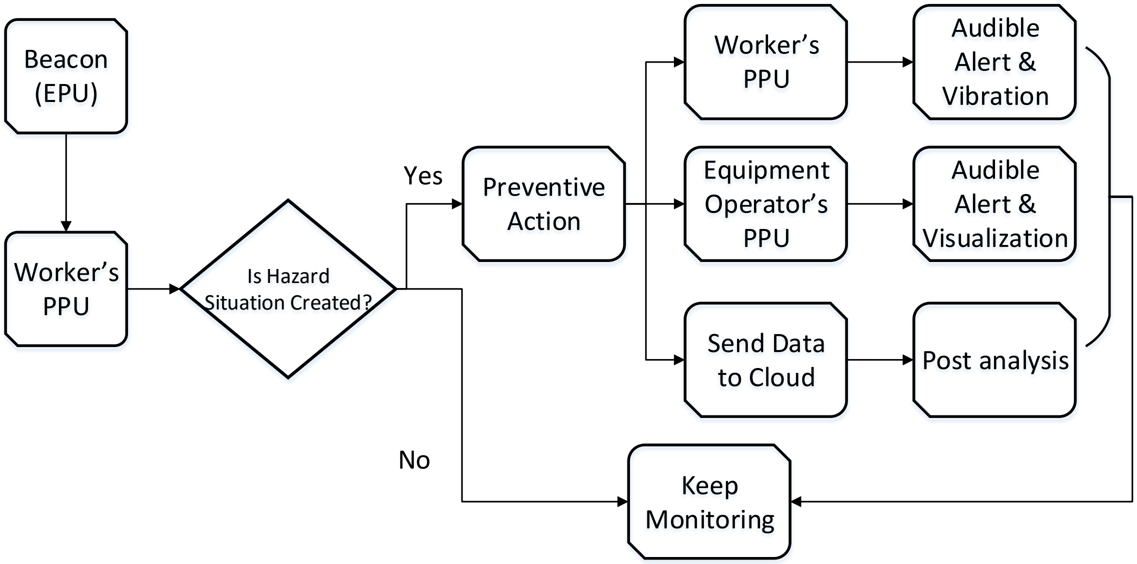

Figure 3. Communication flow for one cycle

Methods

The proposed system is a Bluetooth based system whose communication among devices is accomplished by radio signal transmission. The transmitted radio signal is recorded and the recorded Received Signal Strength (RSS) estimates the approximate horizontal distance between the beacons and receiver. The user can perform calibration to set his/ her desired distance range at which the system initiates alerts. This calibrated range is then trisected to provide intensifying alerts to indicate the degree of dangerousness of a created hazardous situation. Upon the creation of the hazardous situation, the worker's PPU immediately turns to a beacon to send out signals to the nearby operator's PPU. With this signal, alerts and visualization can be realized on the equipment operator's PPU.

System Deployment and Calibration

The key aspect in system deployment is to acquire a symmetrical coverage centered from a piece of construction equipment. To improve the quality of symmetrical coverage, multiple Bluetooth signal transmitters are deployed around the equipment. This deployment allows the communication to reply more on beacons that experience the least amount of multipath effects and signal degradation. In addition, to reduce the amount of signal interference, care should be taken when placing beacons on a piece of equipment so that the best line of sight is obtained.

Calibration is desired for two major reasons. First, the RSS is dependent on environmental conditions. For different equipment and environmental conditions, there is no guarantee for the radio communication to be in the same quality. Second, each user's may have a different desired coverage range. Per user's need for coverage range, by collecting RSS at a desired distance for each of the beacons, calibration is performed.

FIELD VALIDATION

To validate the proposed proximity sensing and alert system, a set of experimental trials were designed and conducted to evaluate the system. To assess the system reliability and effectiveness, (1) trials were performed at eight different angles centered from a piece of equipment and (2) two different pieces of equipment were tested, such as a wheel loader and a dump truck. The design of experimental simulation is to emulate real-time construction roadway work zone operations. Presented material in this paper is mobile workers and static equipment situation. Figure 4 shows the test bed and approach angles for worker and equipment interaction simulations during testing. A worker equipped with a worker's PPU approaches to a piece of construction equipment and the alert distance (at which breach into hazard zone is detected) was recorded for each of the trials. For each angle of the eight angles, 20 trials were made for statistical data collection.

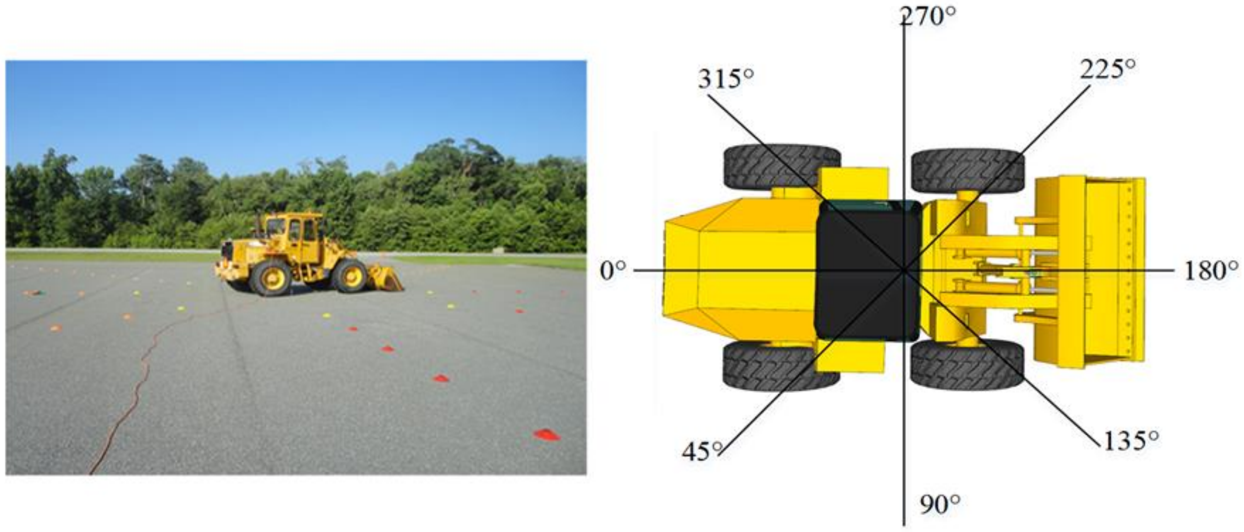

Figure 4. Test bed and approach angles during trial simulations

For these two different sets of trials, calibration was only performed for the trial with wheel loader. The purpose of this was to observe the difference in RSS behavior, thus difference in alert distance accuracy, in different environmental conditions and to confirm the needs of calibration. In the wheel loader trials, the alert distance was set to 12 meters, and the same setup was used for the truck trials. Statistically analyzed data for two complete sets of trials are tabulated in Table 1, and Figure 5 shows plots for the sets of trials. In the simulation with the wheel loader, the overall average alert distances did not deviate significantly from the set distance of 12 meters except at 135°. This drop needs be investigated considering various factors, such as battery, interference with the surroundings, or potential mal-functions of transmitter. As seen in both Table 1 and Figure 5, overall average alert distances for the dump truck simulation are, however, greater than those for the wheel loader simulation. This shows that the importance of calibration to obtain a desired distance. In this case, the RSS was more powerful with the truck simulation, and proper calibration should be able to manage this difference to set the alert distance as desired by the worker. Other than the average alert distance, the two simulations behaved similarly.

Table 1. Statistical analysis of alert distance and standard deviation

Approach angle	Wheel loader		Dump truck	
	Average (m)	Std (m)	Average(m)	Std (m)
0°	15.3	2.7	16.8	3.4
45°	12.2	3.0	17.1	2.5
90°	12.4	3.6	22.6	2.8
135°	5.3	1.8	19.2	1.9
180°	12.4	3.9	17.1	1.6
225°	13.0	3.6	18.8	1.7
270°	15.2	1.0	16.2	1.4
315°	17.3	1.0	12.5	2.9

*std is standard deviation.

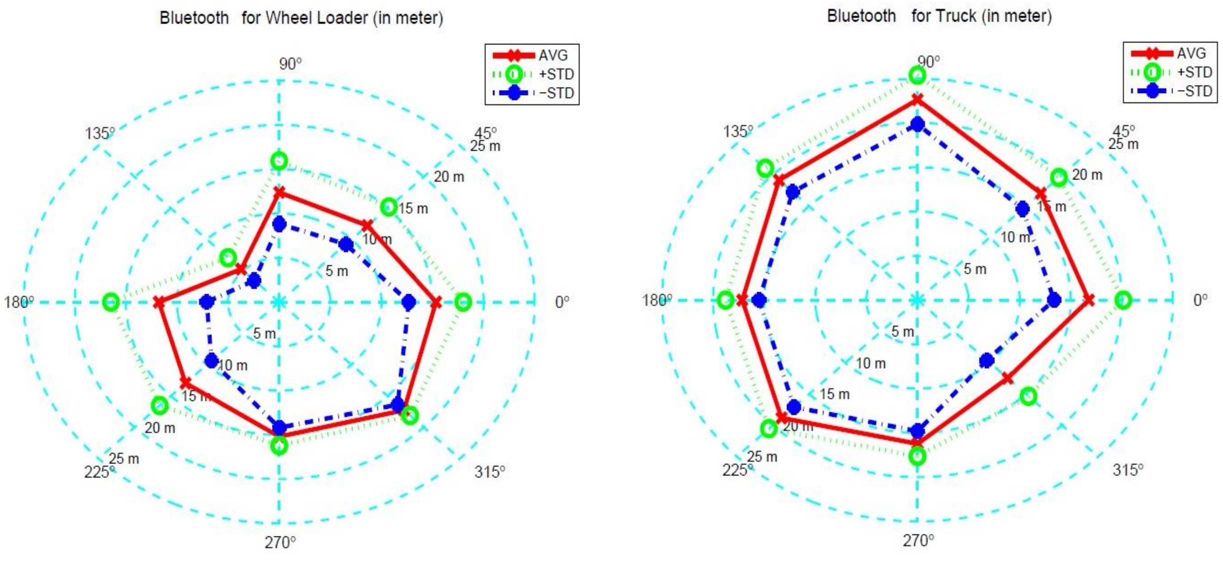

Figure 5. Field trials with a wheel loader (left) and a dump truck (right)

Table 2 displays another statistical result showing recall values. Different values of distance at failure were used to compute recall values as the definition of distance at failure may be different depending on the application. As Table 2 is read, one should keep in mind that the average alert distances of the two simulations (wheel loader and dump truck) were different, and therefore, their direct comparisons should not be made. For the entire trials, the system performed with less than 3% recall rates for less than five meters distance at failure. Five meter distance boundary seems reasonable as alerts are simultaneously provided to both the pedestrian worker and equipment operator allowing them to stop operations and take a proper action for avoidance of collision. However, if the lower distance boundary (distance at failure) is required as high as nine meters, one should consider having a higher desired distance, in this case higher than 12 meters.

Table 2. Statistical analysis of recall rates

Distance at failure (m)	Number of false negative			Recall rate
	Wheel Loader (out of 160)	Truck (out of 160)	Total (out of 320)	
3	3	0	3	0.9%
5	8	0	8	2.5%
7	25	0	25	7.8%
9	32	2	34	10.6%

CONCLUSION

This study aims at developing a technically and economically feasible mobile proximity sensing and alert technology and assessing it with various simulation tests. In order to overcome the barrier of deployment costs, a cost effective system was developed. This system is based on Bluetooth technology, which is already widely available in most of the recent smart devices. Also, the system offers minimal infrastructure, ease of deployment, calibration functionality and adaptability, compared with other similar proximity sensing and alert systems. Experimental trials were designed and performed to evaluate the proposed proximity sensing and alert system for its capability to offer real-time situational awareness via alerts to pedestrian workers and equipment operators working in proximity hazardous situations. Results of the simulated tests showed that this system was acceptable in providing pedestrian workers and equipment operators multiple forms of alerts. Upon the detection of a potential hazardous situation, immediate alerts were provided to both the pedestrian worker and the equipment operator. This can help to minimize the proximity related accidents by providing an additional chance of time and space for the workers to escape from the hazardous scenes.

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