Direction Aware Bluetooth Low Energy Based Proximity Detection System for Construction Work Zone Safety

J. Park[a], Y.K. Cho[b] and S.K. Timalsina[c]

[a] School of Civil and Environmental Engineering, Georgia Institute of Technology, USA
[b] School of Civil and Environmental Engineering, Georgia Institute of Technology, USA
[c] School of Civil and Environmental Engineering, Georgia Institute of Technology, USA
E-mail: jpark463@gatech.edu, yong.cho@ce.gatech.edu, stimalsina3@gatech.edu

Abstract

Over the last decade, the rate of fatality of workers in construction work zones has been of serious concern. One of the most frequent accidents happens due to a ground worker being struck by construction equipment. A major reason behind this is the inability of equipment operators to be aware of the existence of the nearby pedestrian worker. In this paper, we propose a direction aware proximity detection and alert system. The proposed system can detect hazardous situations caused by proximity between equipment and the ground workers. Upon detection, it notifies both the ground worker and equipment operator with audible alerts and visualization of the relative location of the hazard. This research utilizes a recent Bluetooth low energy technology to build a proactive proximity and alert system. To evaluate the effectiveness of the system, outdoor tests were conducted. The obtained results show that the equipment operators can efficiently obtain the information on potential hazardous situations to avoid collision with the ground worker.

Keywords –

proximity sensing; direction awareness; work-zone safety; Bluetooth low energy; construction

1 Introduction

Workers in the construction industry are prone to various hazardous situations, and most of these situations lead to severe and fatal accidents. In spite of the serious attention paid to accidents in the construction industry, significant occupational injuries at construction sites prevail. During 2008 to 2013, a total of 683 worker deaths was reported on road construction sites [1]. The dynamic nature of work zones comprises of situations where ground workers operate in close proximity to construction equipment. This characteristic of work zones puts the personnel in a potentially hazardous situation. Most of the fatal work zone accidents were identified as the "Worker being struck by a vehicle or equipment in a work zone". It signifies that special attention needs to be given to the safety of ground workers working in close proximity to vehicles or equipment in construction sites.

In past research, efforts have been made to detect and alert the proximity of ground workers to construction equipment [2; 3]. The hazardous proximity situation can thus be avoided to prevent worker injuries and fatalities. However, their measures fail to provide the information on direction of the event occurrence. As noted in [4], many collision accidents are due to the blind area in the field of vision of an equipment operator. Depending on the construction equipment type and operator's position, the blind area can include front, back and sides of the equipment [5]. Therefore, information on relative direction of hazardous situations is crucial to take action to avoid them. This paper reviews the current proximity detection solutions and describes the proposed direction aware proximity detection system followed by the explanation of the testing scenario and its emulation. Finally, the observed results are analyzed to evaluate the performance of the system.

2 Background

In concern of the current work zone safety status, Occupational Safety and Health Administration(OSHA) and Manual on Uniform Traffic Control Devices (MUTCD) have made efforts on implementing regulations in work zone safety [6; 7]. The imposed regulations consist of requirements, such as wearing hard hats and shiny vests, signs and signals, flaggers, traffic controlling systems and other conventional measures. However, in spite of the application of these rules, it is affected by several pitfalls. It is found with insignificant improvement in the concerned safety hazards and prevailing fatalities. A major cause of this unsatisfactory result is due to the inability to recognize in advance and avoid the potential hazard; for example, due to blind areas in the equipment operator's vision or lack of knowledge of the ground worker in proximity to the equipment [4; 8].

2.1 Proximity Detection

Over the last decade, a considerable amount of research has been conducted in applying sensing and wireless technology into the work zone safety. In [9], the sensing technologies such as Radar, video camera and Radio Frequency Identification (RFID) have been discussed as measures to implement the collision warning system by monitoring. In [3], magnetic, RFID, and Bluetooth Low Energy (BLE) technologies are discussed as potential candidates for proximity detection. These technologies were compared in terms of their performance in average distance estimation and proximity detection. An coverage area of each of the technologies was also evaluated. As mentioned in the previous section, the current state-of-the-art technologies perform efficiently in sensing the proximity but lack on identifying and providing direction information of the potential hazard. This information is critical for the equipment operator who needs to overcome a potential collision by avoiding proceeding to the direction of potential hazard. In other words, it is required not only to find out "if" there is a potential hazard, but also "where".

In [2; 8], research have been performed on the application of laser and imaging technologies in construction to mitigate the effect of blind spots in equipment operator's vision. This research utilized the Flash Laser Detection and Ranging (Flash LADAR) and a low-resolution image ranging method. Using these techniques together with learning algorithms, the researchers have attempted to scan through subject area and predict the orientation of the equipment operator. However, using the image-ranging method has a main drawback as it needs to go through several preliminary phases before the system implementation. It should be noted that the image-ranging methods additionally have requirements of complex backend to run algorithms and store the point cloud. In addition, such required process can lead to the system unable to detect the hazardous situation when applied in a new environment. Besides, as mentioned in [8], the performance of the image ranging method degrades in an outdoor scenario, which is typical to construction. Further, the quality of an image can be significantly affected by many external sources, including lights, and angles; for example, images captured at night may be of too low quality to properly process. More importantly, although this method detects the orientation of operators head and dynamically updates the blind area of the operator, it still fails to eliminate the existence of blind areas.

In order to address the issues discussed above, our study focused on building a system capable of detecting proximity and its direction relative to the construction equipment with the ground worker in a dynamic construction environment. Our primary objective was to build a system, which can cover the entire region surrounding the construction equipment to eliminate the blind areas. This enables more interactive communication about hazard incidents between associated workers; it alerts an equipment operator upon the detection of potential collision with the ground worker. The system should be minimally affected by changes in its environment. It should have least or no preliminary installation requirement.

2.2 Bluetooth Low Energy (BLE)

For fulfilling our objective, BLE has been studied in terms of its application in the proximity detection with direction awareness. BLE is a relatively new technology that differs from the classical Bluetooth technology with the capability of functioning by consuming comparatively low energy. It operates in the 2.5 GHz industrial, scientific and medical (ISM) band and was introduced in 2010 by Bluetooth Special Interest Group (SIG) along with the Bluetooth 4.0 specification [10]. The low energy consumption attribute of BLE enables it to stay alive on a coin-sized battery for months if not years. Compared to the classical Bluetooth technology, it is able to send smaller data packets, thus having specific applications, which require long-lasting connectivity but small or no data communications. Furthermore, the devices capable of detecting the classical Bluetooth can easily detect BLE as well.

With relatively small sizes (see Figures 1 and 3), low power consumption, low cost and durability, BLE can be considered an ideal tool for proximity detection for construction applications. Construction sites are very dynamic and demand not only proactive but also easy-to-use technology, which can adapt to the changes with minimum overhead. As an accessory to the construction site, its cost is reasonable, and its size is negligible to pose hassle in undergoing the construction projects. Nevertheless, incurred device and instalment costs for these devices are also low.

The devices able to detect multiple BLE sensors within a region can obtain the Received Signal Strength Indicator (RSSI) for each of the BLE sensors. The RSSI can in turn be used to estimate the relative distance to the detector. In addition, the detectors can uniquely identify each BLE sensor. The information obtained by combining these capabilities can be utilized to detect the proximity hazardous situations and obtain the relative direction of the detectors.

Figure 1. Commercially available BLE transmitters.

3 Experiment

3.1 System Architecture

The key objective of this study was to create a reliable proximity detection and alert system capable of 1) identifying proximity hazardous situations between ground workers and equipment and 2) providing, in addition to warning alerts, the associated personnel with the relative direction of the hazard with respect to the construction equipment. The setup requires less overhead in terms of the installation and maintenance, and thus, it can work as plug and play. A typical scenario of the system in construction is shown in Figure 2. The system consists of three major components, such as BLE sensors, ground worker's personal protection units (PPUs) and equipment operators' PPUs. However, there can be other auxiliary components to enhance the feature and usability of the system.

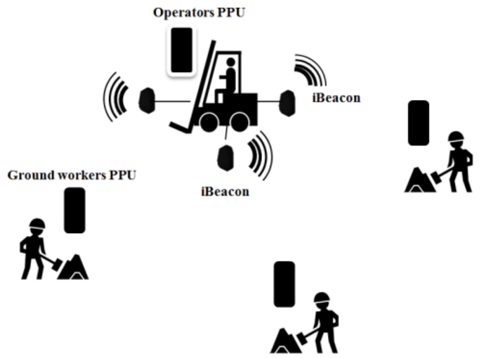

Figure 2. Typical scenario of the proposed system.

3.1.1 Location Broadcasters

Location broadcasters are the devices deployed throughout the region in order to get the knowledge on location information of object of concern. Our system uses BLE sensors to act as the location broadcasters. As described in the previous section, a BLE sensor is the radio signal transmitter, which advertises micro-location related data. The advertised data is broadcasted in Omni-direction, which can be utilized by any device capable of reading it. It is easy to install in the system by simply attaching to the equipment, whose location one wants to monitor. With its small size, the BLE sensor is easily attachable to the construction equipment while not requiring cumbersome infrastructure, including external power lines, nor interfering with the working environment (Figure 3). The sensor does not require any pre-setting to incorporate with the system as they continuously broadcast characteristic Bluetooth signals. The proposed system uses the Received Signal Strength (RSS) from these devices to estimate the relative distance to equipment.

Figure 3. A BLE sensor attached to construction equipment.

3.1.2 Personal Protection Unit/s (PPU/s)

PPU is a device, which monitors and processes the data transmitted by location broadcasters, and interprets the valuable information. The proposed system utilizes widely available smartphones to act as PPUs. Smartphones are capable of detecting the BLE signals and process it reliably. We developed software that converts the broadcasted RSSI to distance estimation. Further, the system monitors for proximity related incidents and provides alerts upon detection of such incident. This software can be configured to define the alert zones as well. The PPU can therefore alert workers through various forms such as sound and vibration when they enter the predetermined alert zones. Additionaly, PPUs can also communicate between themselves to share the local information.

3.1.3 Workers

Workers, including ground workers and equipment operators, who are prone to potential hazard situation are equipped with PPUs. The ground workers are alarmed through alerts such as sound and vibrations with intensity proportional to proximity to the equipment as shown in Figure 4. The equipment operators are also provided with the visual information regarding the hazard situation; direction of potential collision with reference to the equipment (Figure 5). This could help the operator to manoeuvre the equipment to a safer direction.

Figure 4. Ground worker with PPU.

The system comprises of the dynamic interaction between the components described previously. Ground workers are equipped with a PPU with software that alerts upon reaching proximity to hazardous situation. Similarly, the equipment operators also have a PPU, which visualizes the proximity of the ground worker in case of potential danger. The location transmitters can be attached on different parts of the equipment such that PPUs could receive signals emitted from different regions. PPU is able to uniquely identify each of the location broadcasters. Therefore, this can provide visual information with the direction of the ground worker in proximity relative to the equipment. As shown in Figure 6, the system works by continuously receiving BLE signals and providing the information to workers through their PPUs.

With the complete knowledge on proximity of the ground workers relative to the equipment in all the directions, the equipment operator can efficiently undergo collision avoidance through the direction aware alert system. In this manner, with the proposed system, the blind area of equipment operator can be virtually eliminated.

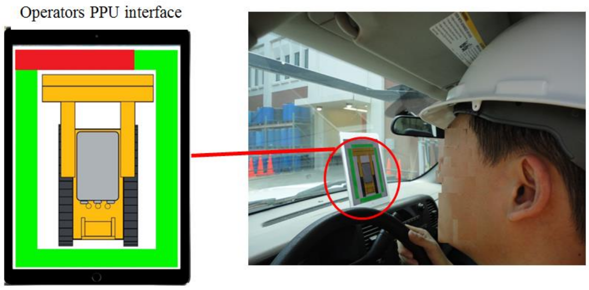

Figure 5. Equipment operator observing the PPU.

3.2 Test Setup

In order to evaluate the performance of the direction aware alert system, a simulation of scenario with a ground worker approaching the equipment was conducted. To measure the signal communication and warning responsiveness effectively, we conducted the one direction approach. The ground worker with a PPU approached stationary equipment in forward direction and raised hand to indicate the initiation of alert (Figure 4). The equipment operator then observed visualization of alert in the PPU (Figure 5), and confirmed the directional information. On moving out of the hazard zone, ground worker lowered the hand to signal the event. This was again observed by the equipment operator along with the disappearance of visual information on the PPU. Occurrences of each of these events were being logged against time. The time delay between initiation of alert and actual visualization on operators PPU (start delay) and that between termination of alert and disappearance of visual information (end delay) was also observed by the equipment operator. Observed delays were then evaluated for effectiveness of the system.

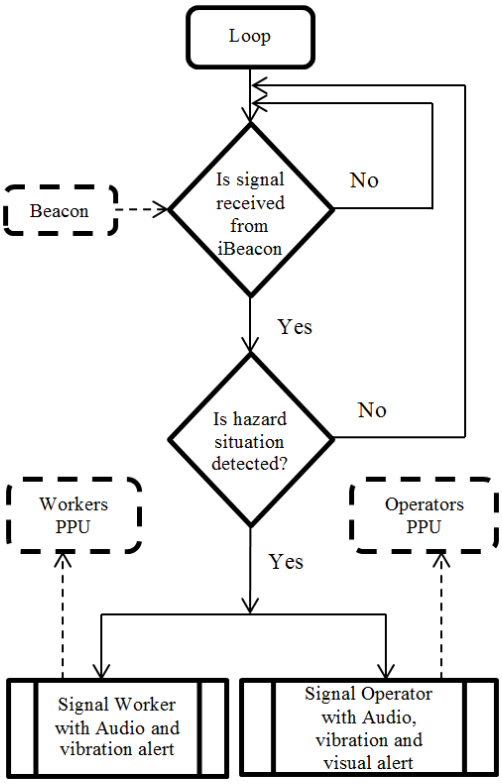

Figure 6. Working methodology of the system.

4 Results and Discussion

Figure 7 shows the result of the alert responsive rate test. The responsiveness of the system to an alert is an important metric to measure the performance of the system. The visual information in addition to the audible alerts can get the attention of the equipment operator to avoid potential collisions caused by blind spots or unawareness.

On a hazardous situation being originated at the ground worker's end, system signals operator's PPU about it. Due to the inherent nature of the system, a delay is incurred between these events. This delay in time is represented as start delay. Similarly, lag in time between a ground worker leaving the hazard zone and respective information conveyance by PPU to the operator was observed, which is represented as end delay.

Thirty trials in total were conducted on the test setup, and the obtained result is shown in Figure 6. The start delay was found to be approximately 0.1 second. However, the value of observed end delays varied in respective trials. The average end delay for the conducted trials was 8.03 seconds. Compared to start delay, end delay was found to be large. This can be attributed to the nature of radio signal transmission; the transmitted signals tend to reach the PPU in multipath. However, this outcome can be considered to have a practical importance as the operator is provided with additional time to take appropriate action to confirm the safety of workers. Importantly, the equipment operator was able to promptly receive proper information on

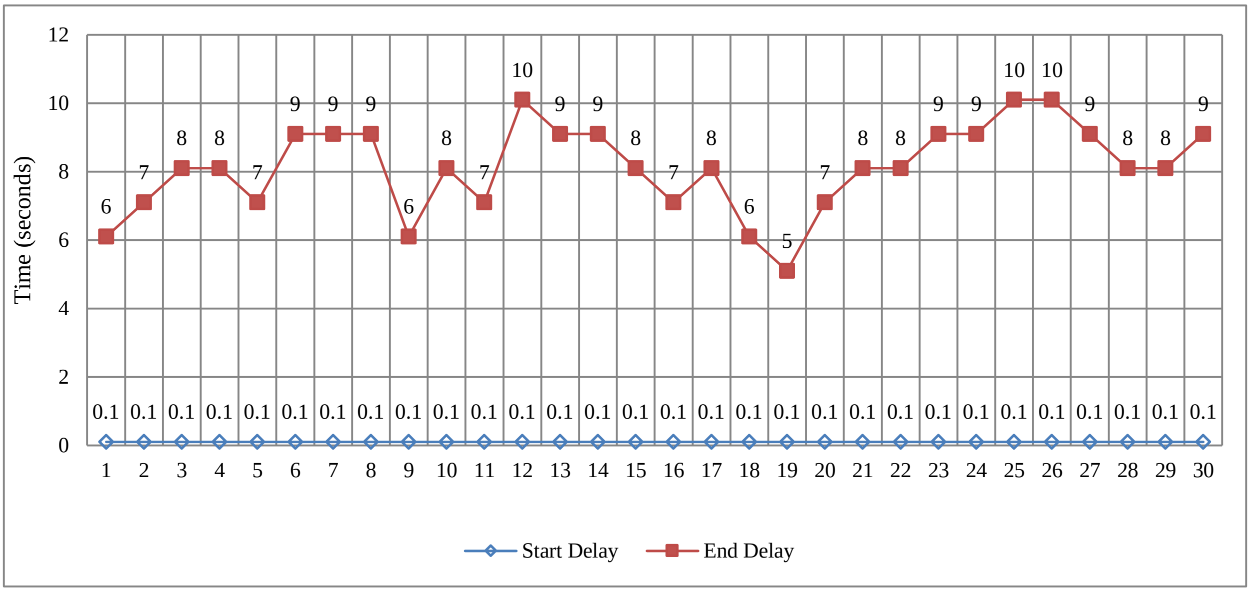

Figure 7. Alert responsiveness between ground worker and operator.

relative distance and direction of the ground worker and avoid potential collision.

5 Conclusion and Future Directions

Utilizing various proximity detection devices, many research efforts have been made to alert both the ground workers and approaching construction equipment operators regarding hazardous situations. This study focused on building a novel proximity detection system which is able to provide direction information in addition to alerts to workers and vehicle operators in vicinity. The BLE technology was used to build the direction aware proximity detection and alert system. The proposed system can synchronously provide information to the construction equipment operators regarding the potential hazard situation and its relative direction. In this way, an operator is able to avoid collisions with ground workers. Due to the simple hardware requirements, the proposed system is simple, reliable and easily adjustable to a dynamic construction environment.

In future, the system providing more granularities in the estimation of location and direction will be developed. Additionally, the improved system will be tested in more realistic and complex construction environments with a considerable number of ground workers and vehicles interacting with each other.

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