IMPROVING SAFETY IN WORK ZONES BY USING REAL-TIME TRACKING OF WORKER FIELD OF VIEW AND PROXIMITY TO HAZARDS

FINAL PROJECT REPORT

by

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16. Abstract

This research focused on the use of equipment telematics, sensor analytics, and virtual modeling to positively impact construction sites by providing real-time field of view monitoring of the worker-on-foot and by automating safety warnings on the work site. The automation of safety warnings will allow an alert to be delivered to affected personnel so that changes can be made to improve safety relationships between entities on site. The line-of-sight monitoring will allow management teams to eliminate visibility issues and reduce the numbers of fatalities and injuries due to struck-by object incidents. A construction site where human laborers work alongside heavy equipment will be virtually created in the Virtual Robot Experimentation Platform (V-REP) to enable the researchers to experiment with rules-based systems that automatically deliver safety warnings on the basis of proximity and orientation between equipment and workers-on-foot. This virtually simulated experiment will allow the researchers to determine the type of equipment telematics data that need to be collected to implement a similar system in the real world. Because of a lack of access to proprietary data for construction equipment, the real-world implementation of the system to track equipment proximity and worker orientation was demonstrated by using a hardware system that is made up of an Arduino board, Pozyx board, and a GPS board. This research provides a framework to incorporate the use of telematics and sensor data first in virtual environments to determine parameters before their application in the real world for safety applications, to monitor the field of view of workers on site to eliminate hazardous visibility issues, and to allow management teams to plan for hazardous situations. The use of real-time progress tracking systems is also expected to reduce the number of extraneous personnel on construction worksites and to reduce the travel time required to monitor safety and productivity on large construction projects.

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Abstract

This research focused on the use of equipment telematics, sensor analytics, and virtual modeling to positively affect construction sites by providing real-time field-of-view monitoring of the worker-on-foot and by automating safety warnings on the worksite. The automation of safety warnings will allow an alert to be delivered to affected personnel, so changes can be made to increase safety between the entities on site. The line-of-sight monitoring will allow management teams to eliminate visibility issues and reduce the numbers of fatalities and injuries due to struck-by object incidents. A construction site where human laborers work alongside heavy equipment was virtually created in the Virtual Robot Experimentation Platform (V-REP) to enable the researchers to experiment with rules-based systems that automatically delivered safety warnings on the basis of proximity and orientation between equipment and workers-on-foot. This virtually simulated experiment allowed the researchers to determine the type of equipment telematics data that need to be collected to implement a similar system in the real world to produce the most effective results. Because of a lack of access to proprietary data for construction equipment, the real-world implementation of the system to track equipment proximity and worker orientation was demonstrated by using a hardware system made up of an Arduino board, Pozyx board, and a GPS board. This research provided a framework to allow telematics and sensor data to be first incorporated into virtual environments to determine the relevant parameters before their implementation in the real world for safety applications, to monitor the field of view of workers on site to eliminate hazardous visibility issues, and to allow management teams to plan for hazardous situations. The use of real-time progress tracking systems is also expected to reduce the number of extraneous personnel on construction

worksites and to reduce the travel time required to monitor safety and productivity on large construction projects.

Executive Summary

This report outlines information on research focused on improving visibility and proximity issues at construction work zones to reduce the number of struck-by object incidents and other hazardous situations and accidents. The line-of-sight of workers-on-foot was monitored with a device that was made up of three different boards: Arduino, Pozyx, and GPS boards. Each board contributed a certain aspect to the hardware system. Ultimately, the device will be used to monitor the location and orientation of a worker on site to understand detection issues between workers and equipment. A literature review was conducted to collect work zone safety statistics, gather background on previous studies that have used sensors and equipment telematics to improve on-site safety, and understand how companies are using these technologies to monitor safety on their sites.

There were four main steps to this research, which included

- obtaining equipment safety information from contractors' best practices and organization regulations,
- using a safety model to create a rules-based system to deliver safety warnings,
- observing a virtual model to initially analyze proximity and visibility issues on site,
- conducting monitored experiments in the real world to determine whether the virtual model's safety warnings were applicable and to utilize the sensors and telematics data to pinpoint areas that produce unsafe conditions.

To validate this methodology, the device was applied to a case study scenario to help the researchers identify and observe areas in an equipment-intensive construction operation that could create unsafe working relationships between workers-on-foot and heavy equipment. The information gathered from the device was implemented into a virtual environment to observe

worker field-of-view and visibility issues that could occur without creating any liability issues. The case study in which the device was used involved typical work zone equipment moving in reverse while being in close proximity to workers-on-foot, with the worker oriented toward and away from the equipment. By observing this scenario, the researchers were able to develop safety warnings based on the visibility issues found during the case study. With the device collecting data on line-of-sight of workers-on-foot, management teams can create solutions to eliminate hazardous visibility issues.

The limitations of this research included not having access to heavy equipment to conduct realistic tests, not having accurate real-world situations to observe because of liability issues, and the improper enforcement of the safety warnings and the gathered device information when it was used on site.

The main contribution of this research is to provide management teams with a tool to help them monitor the safety relationships and fields-of-view of workers-on-foot and equipment operators to reduce their fatality rates in the work zone. In addition, this research used an analytical approach to objectively examine safety conditions, which contradicts the normal perception that safety is a subjective topic and hard to quantify.

To further this research, the hardware system could be applied to generic operations in work zones and applied to a wider range of case studies.

Chapter 1 Introduction

Construction sites are notorious for being hazardous environments because of their dynamic nature, the continuous movement of the entities within them, the uniqueness of each worksite, and the differing site conditions involved with each project. This dynamic state results in close proximity interactions between various entities, such as workers-on-foot and heavy equipment, which can potentially lead to struck-by object incidents on site. The unsafe proximity of workers-on-foot to construction equipment, or equipment to equipment, has been identified a safety issues distinct to construction jobsites (Pradhananga and Teizer 2013; Wang and Razavi 2016). Statistics published by the Occupational Safety and Health Administration (OSHA) showed that from 1995-2008 struck-by equipment hazards accounted for 58 percent of all struck-by object accidents (Wu et al. 2010).

In 2015, according to the Bureau of Labor Statistics (BLS), 937 recorded fatalities occurred in the construction industry, approximately 19 percent of the total fatalities in all industries (CFOI 2015). Of those fatalities, 162 were struck-by object incidents involving vehicles, equipment, and other objects. Approximately 59 percent were struck-by object incidents caused by equipment and 41 percent were vehicle collisions (Safety Health Magazine 2017). This number has increased over the past couple of years, which is alarming particularly because of the technological advances that should have been implemented to reduce these fatality rates. In 2016, according to the Occupational Safety and Health Administration, the "Fatal Four" (defined as falls, struck-by object accidents, electrocutions, and caught in/between accidents) were responsible for more than half of all construction worker deaths, approximately 63 percent (OSHA 2016). Struck-by object incidents were responsible for 9.4 percent (93/991) of construction industry fatalities. According to the Bureau of Labor Statistics, 31 percent of pedestrians killed by vehicles in work zones were struck when a vehicle was operating in reverse gear, a situation that produces in line-of-sight obstructions and lack of hazard detection and awareness (BLS 2016).

These issues have been considered in previous studies through the implementation of different technological advancements, such as sensors to improve construction site proximity safety. The unprepared and dynamic nature of a construction site, and the hazards and difficulties presented by on-site work, also necessitate the use of intelligent ways to support on-site construction staff and personnel (Behzadan et al. 2008). A large number of proximity avoidance systems utilizing various technologies have been developed (Wang and Razavi 2016), such as radio frequency identification sensing technology, laser scanning to pinpoint blind spots, radar-based proximity warning systems, ultra-wideband (UWB) sensor technology, hybrid transmitting sensors, and global positioning systems (GPS) to monitor and observe proximity issues to prevent contact collisions and struck-by equipment incidents (Chae and Yoshida 2009; Marks et al. 2013; Cheng et al. 2012; Lee et al. 2008; Choe et al. 2013).

Nonetheless, the frequency of false alarms created by current proximity and contact collision avoidance systems has limitedon their implementation in real-world construction environments. The construction industry statistics mentioned above show that proximity and struck-by object incidents still remain a major issue, and changes are needed on site to provide workers with a safer working environment. To reduce these issues, research needs to focus on minimizing the occurrence of false alarms (Wang and Razavi 2016).

The research presented in this paper developed a safety model that monitors the worker-on-foot's position, along with his/her orientation/heading, and transmits the data collected to a virtual model to allow researchers to pinpoint areas that are deemed unsafe because of potential interactions with heavy equipment. This safety tool will allow workers to be more aware of their surroundings, and it will allow management teams to create proper solutions to prevent struck-by object incidents and enforce those solution appropriately and in a timely manner on site to further reduce high fatality rates.

The next section focuses on research that has been previously conducted on proximity detection systems and the research gap that the authors found. Chapter 3 introduces the methodology for the research presented in this study that focuses on two modules: worker proximity and orientation. Chapter 4 discusses evaluation of the performance of the system created by the researchers through various case studies, simulations, and field experiments. Finally, the results are discussed, as well as limitations, contributions, and future work.

Chapter 2 Literature Review

This research focused on reducing and injury fatality rates in work zones by preventing potentially hazardous interactions between heavy equipment and workers-on-foot . To date, different technological applications have been developed and tested in the field to track the positions of workers and equipment with the goal of identifying potentially hazardous situations and delivering appropriate safety warnings. This chapter provides a review of research that has been conducted in this area to provide context for the current research. Incorporating alternatives into the practices of the construction industry, such as technological advances to improve the visibility of interactions and the proximity between workers-on-foot and heavy equipment, can ultimately reduce the high injury and fatality rates.

This research focused on improving the safety of construction sites by developing a safety tool/system that can prevent potentially hazardous situations, such as contact collisions, between various entities on site. Currently, different technological applications have been tested in the field to observe and track the positions of workers and equipment, with the main goal of identifying and monitoring imminent hazardous situations and delivering appropriate safety warnings to the affected personnel. This section reviews the research and studies that have been conducted to improve worker-on-foot and heavy equipment safety on construction sites to provide a context for the current study.

First, this chapter discusses work zone statistics to understand issues related to real-world hazardous situations. Second, it discusses state tracking applications observe the impact these studies have had on improving safety interactions between various entities on site. Next, it presents a summary of various proximity detection-related studies. The final section identifies gaps in the literature.

2.1 Work Zone Safety Statistics

In 2014, a total of 669 fatalities occurred from crashes in the work zone, approximately 1.8 work zone fatalities per day (FHWA 2017). In addition to these fatalities, approximately 40,000 injuries occurred in work zones, with 162 large trucks and buses involved in work zone crashes (FHWA 2017). Because of the constantly changing nature of work zones, fatalities are caused by various interactions on the worksite between equipment and workers. In the past few years, the most common causes of worker fatalities in work zones have included run-overs/back-overs by dump trucks, collisions between vehicles/mobile equipment, and workers caught in between/struck-by construction equipment and objects.

The category of run-overs/back-overs has the highest percentage of fatalities at 48 percent, which has increased in the last couple of years (FHWA 2017). These rates cause concern for management teams because worker safety is a top priority for them. To prevent these rates from increasing, researchers have focused on automating construction tasks and observing the interaction between workers-on-foot and heavy equipment. Furthermore, researchers have analyzed the implementation of sensors and telematics to improve safety in work zones.

Figure 2.1 shows the number of fatal struck-by object injuries among highway maintenance workers for both struck-by vehicles, indicated by blue bottom bars, and struck-by other objects or equipment, indicated by the red top bars.

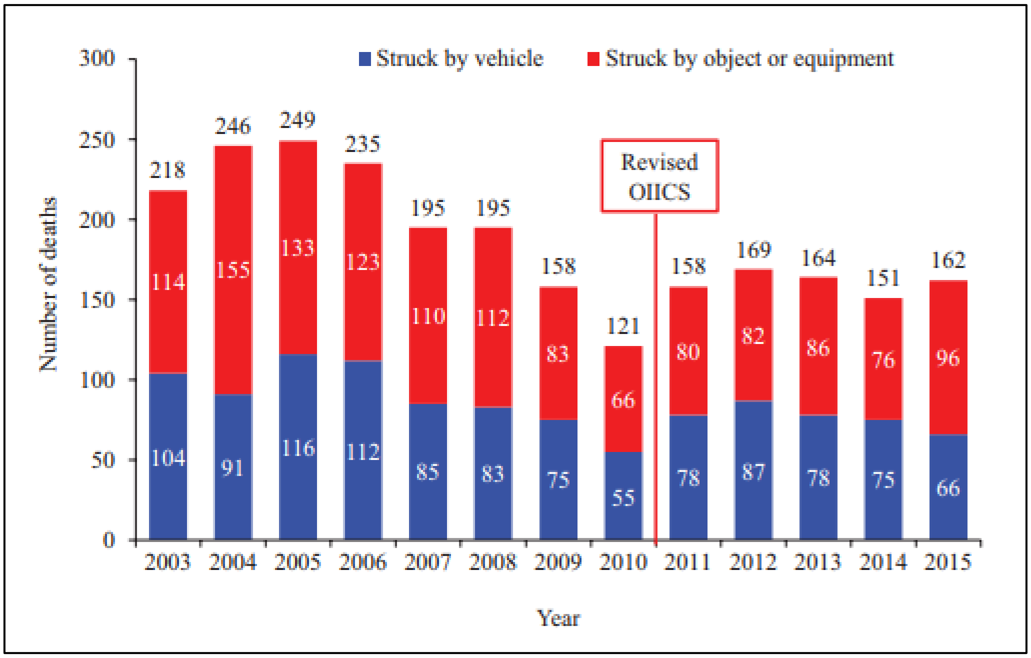

Figure 2.1 Number and rate of fatal struck-by object injuries among highway maintenance workers from 2003 to 2015 (Centers for Disease Control 2017)

This increase over two years (from 2013 to 2015) in struck-by object injuries justifies the need to improve work zone worker proximity and visibility constraints to reduce fatalities. Construction equipment may not always be the source of the incident in every scenario because work zones are prone to passenger vehicle collisions, but with the current research, the orientation of workers can be monitored to determine unsafe situations and to improve their field of view to any potential hazards on or off site.

Figure 2.2 shows the number and rate of fatal struck-by object injuries in construction from 2011 to 2015. The red bar graph shows the number of fatalities per year, and the blue line placed on top of the bar graph shows the rate progression throughout the four years of observation.

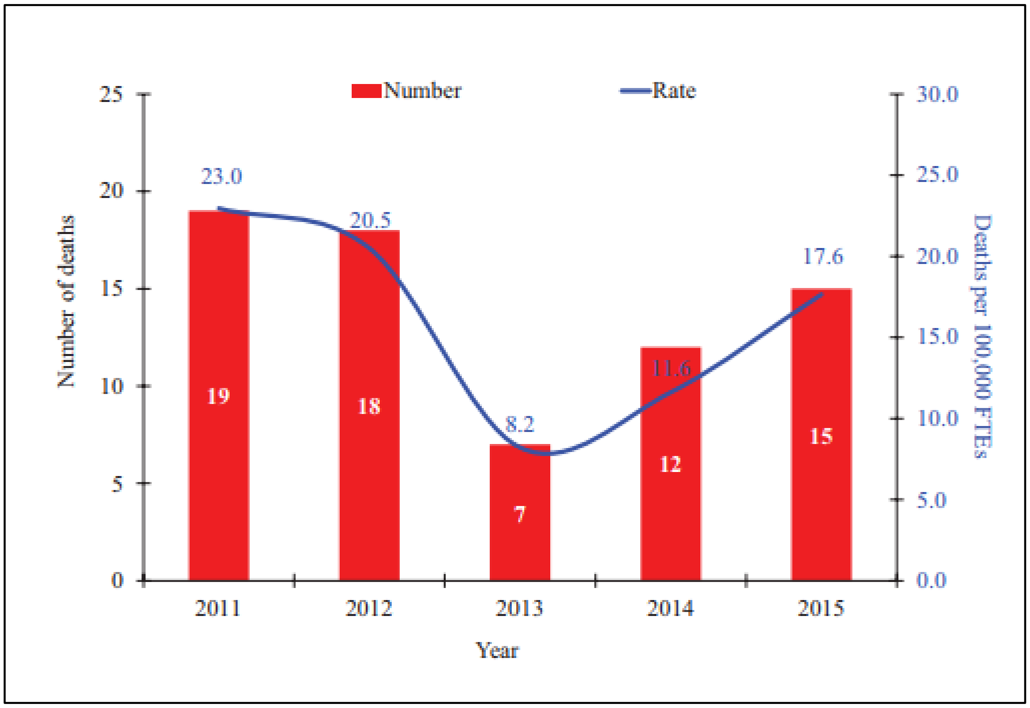

Figure 2.2 Number of fatal struck-by object injuries in construction from 2011 to 2015 (Centers for Disease Control 2017)

This figure shows a slight increase from previous years (2013 to 2015) due to construction site struck-by object incidents. This current study will work to improve safety in work zones and construction sites by delivering safety warnings to the work site through real-time data collection.

2.2 State Tracking Implementations and Research

The National Safety Council's "2016 Injury Facts" chart books showed that struck-by object incidents involving backing vehicles and equipment still remain a serious occupational hazard (National Safety Council 2016). Given that the number of struck-by object incidents on construction sites is still high and the consequences of those accidents is so severe, the states of construction entities should be properly monitored and analyzed so that potential collisions can be prevented and reduced (Wang and Razavi 2016). The ability to track construction entities on site has improved construction management techniques by allowing teams to create solutions for issues that have occurred or have the potential to occur. The ability to automatically detect the locations of items can improve the performance of material distribution and monitoring to ultimately improve overall project performance (Razavi and Haas 2010). When the state of a construction entity is considered, various components must be observed through the use of multiple devices all performing different functions. The state of a construction entity includes its position, heading, speed, orientation, characteristics such as idle time, and other safety-related information (Wang and Razavi 2016). The research conducted on the tracking and monitoring of various entities on site has contributes to improving the safety of the construction industry by allowing management teams to access information that can pinpoint areas on site that are hazardous and unsafe for workers-on-foot.

The accurate collection of construction entity state information has affected various areas of construction site safety, such as increasing situational awareness to help prevent struck-by object incidents between workers-on-foot and heavy equipment (Wang and Razavi 2016). For example, Park et al. (2017) used a combination of Bluetooth low-energy (BLE)-based location detection technology, building information modeling (BIM)-based hazard identification, and a cloud-based communication platform to create a low-cost automated safety monitoring system to assist management teams in identifying hazards on site and monitoring workers-on-foot. Hazardous areas were first defined and registered in the system, and an imminent hazard area was set automatically and manually by using BIM. A set of seven scenarios was designed to assess the real-time safety monitoring capability of the system. The results from these experiments indicated that the proposed approach can assist in construction site monitoring and can potentially improve construction site safety (Park et al. 2017). Although the authors did not use their system on construction equipment directly, the system can still be applied to track equipment and workers-on-foot by identifying and monitoring hazardous situations between those two entities on site.

The real-time locating system (RTLS) developed by Lee et al. (2012) aimed to locate workers and equipment on dynamic and busy construction sites and to identify and prevent hazardous situations between workers-on-foot and heavy equipment on site. Their experiment contributed most by giving management teams a system, comprising localization and tracking technology, that can monitor workers and other objects to alert workers when they are in danger (Lee et al. 2012).

Razavi and Haas (2010) developed a fusion model and used it as an integrated solution for automated identification, location estimation, and dislocation detection of construction materials. This model can improve location estimation and movement detection, which can be directly related to monitoring the relationship between workers-on-foot and heavy equipment on construction sites by allowing management teams to accurately monitor the interactions between those entities and prevent unsafe situations from occurring. In addition to this system, various other methods have been researched, such as a study that presented an enhanced boundary condition method that incorporated tag-reader angles and reader geometric configuration factors to control and monitor the accuracy of a locating system that integrated radio frequency identification (RFID) and a real-time kinematic (RTK) global positioning system (GPS) (Su et al. 2014). This study showed that incorporating the proposed configuration factors into the boundary condition–based methods of RFID locating could significantly increase locating accuracy, and the corresponding quality control filters based on these two factors could achieve an accuracy level required to meet specific application needs, such as identifying unsafe situations between workers-on-foot and heavy equipment (Su et al.

2014).

The use of automated materials management systems can provide construction management teams with the communication and information tools required to identify, locate, and track materials to improve safety on site, along with other engineering project controls (Razavi and Haas 2010). Research conducted on state tracking has laid a solid foundation for the development, improvement, and proper implementation of proximity warning systems (Wang and Razavi 2016). For example, Teizer et al. (2010) used real-time construction object location information to enable proximity analyses that aid management teams and research groups in preventing deadly and disastrous accidents such as workers struck by equipment (Su et al. 2014).

The next section of the literature review looks at various proximity detection devices currently being researched or used in the construction industry to improve interactions between workers-on-foot and heavy equipment and to prevent unsafe situations from occurring on site.

2.3 Proximity Detection in Practice

Construction sites are defined as structured spaces consisting of multiple interacting resources, such as personnel, equipment, and materials, that are involved in dynamic work tasks unique to each site (Teizer et al. 2010). When these resources are in motion and interacting to complete daily tasks, many close-proximity situations occur. These situations contribute to the high injury and fatality rates the construction industry is known for. Since zero incident and zero collateral damage are overall project safety objectives, technology can assist existing safety best practices (Teizer et al. 2010).

To reduce high fatality rates due to close proximity situations between workers-on- foot and heavy equipment, advancements in sensing technologies and state tracking have been developed and have prompted the improvement of collision avoidance systems (Wang and Razavi 2016). Proximity detection studies have been conducted in the past decade to assist construction workers and management teams in reducing fatalities on site. For example, Chae and Yoshida (2009) used RFID technology to prevent collision accidents with heavy equipment. Functions for the collision prevention system were defined, and a final collision prevention system was designed, composed of working area estimation, collision risk analysis, and warnings to relevant persons. The radio frequency remote sensing and actuating technology developed by Teizer et al. (2010) can also improve construction safety by sending appropriate warnings or alerts to workers-on-foot and equipment operators in a proactive, real-time module once specific equipment get too close to other entities on site.

A study conducted by Teizer and Marks (2012) used similar technology but different field testing conditions to improve close proximity encounters between heavy equipment and workers-on-foot. The results of this second study showed the ability of the system to detect close proximity hazards and further record when a proximity alert was activated, which could later be used to analyze "near-misses" to prevent the same type of situation from occurring in the future (Teizer and Marks 2012). A new safety approach was developed that used small GPS units attached to hard hats to collect continuous location data about the safety performance of workers near equipment or other hazards (Pradhananga and Teizer 2013). This system demonstrated how potential users can measure the safety performance of construction resources automatically to prevent hazardous interactions between workers-on-foot and heavy equipment and to use the information for safety education (Pradhanaga and Teizer 2012). Marks and Teizer (2013) also contributed to proximity detection studies by evaluating the capabilities and reliability of low-cost (semi-)passive RFID technology as the main component of a proactive, real-time personal protection unit (PPU). The results indicated that both the position and orientation of the PPU impacted the reliability of the system's ability to activate appropriate alerts during hazardous proximity encounters and that by implementing this system in the construction industry, workers-on-foot could be provided an alert during close proximity situations (Marks and Teizer 2013).

A framework for implementing a sensor-based proximity warning system used to minimize backing accidents was created and developed by Choe et al. (2013). In addition, a study by Luo et al. (2015) focused on workers' responses to proximity warnings about static safety hazards on construction sites by using a location-based proximity warning system called the Proactive Construction Management System. Park et al. (2016) also created and evaluated a proximity detection and alert system that used Bluetooth sensing technology to prevent and analyze hazardous proximity situations between pedestrian workers and construction equipment. These safety technologies may provide workers with a second chance at a safe environment by creating an additional layer of protection for workers-on-foot and are necessary when organizational commitment, supervisory influence, and personal protective equipment (PPE) fail (Teizer et al. 2010).

2.4 Gaps in the Literature

All of these studies have contributed to making the construction environments safer by developing techniques and alternatives to address proximity and visibility issues between workers-on-foot and heavy equipment. However, despite all of the benefits that previous proximity detection research has provided to the construction industry, a common limitation to these studies has been the high potential for the systems to generate false alarms. Frequently generated false alarms can result in workers disabling the alert system to prevent distractions and even ignoring the alarms, whether or not they are helpful. The generation of frequent false alarms that occurred in previous studies has restrained real-world implementation of the developed devices and methods(Teizer et al. 2010, Wang and Razavi 2016).

The main reason for the frequent generation of false alarms was that distance was the only factor \ considered in the previous studies, while other factors such as the speed and orientation of the entities were ignored. There are two noticeable situations in which distance could trigger a false alarm. The first is when a worker is close to the heavy equipment because their task on site requires them to be closer to the equipment than other tasks. Spotters tend to be in close range to equipment so that they can guide equipment operators to appropriate areas on site. This close proximity duty could generate a false alarm and could cause a distraction to the worker, leading to the worker ignoring the alert. The second is when the distance between two entities could be considered as unsafe because it is smaller than the predefined distance threshold, while in reality the entities are moving apart from each other with no risks present (Wang and Razavi 2016).

Under the above two conditions, a false alarm may be generated. To reduce the number of false alarms due to a focus on distance alone, Behzadan et al. (2008) suggested that position combined with other information, such as orientation, can define a user's spatial context with much greater precision than position alone. Li and Jobes (2012) determined that simply sensing the proximity between entities is inadequate for safety control because it limits the information and study to one factor.

To address these limitations, the main objective of this study was to create and develop an innovative safety device that analyzes and collects data on the basis of both the proximity and orientation of the entity under examination to prevent hazardous proximity situations between entities on site (workers-on-foot and equipment) with a low to zero false alarm generation rate.

Chapter 3 Methodology

The objective of this research was to use real-time equipment telematics, sensor analytics, and virtual modeling to positively impact highway work zone safety. This research was intended to enable management teams to monitor the real-time status of equipment fleets and automate safety warnings on the worksite throughout the construction phase of the project. This section describes the proposed methodology to deliver safety warnings to the worksite through real-time data collection, and it provides the experimental set-up that was used to validate the research. Figure 3.1 shows the proposed methodology for this study. The figure shows four main steps, with step two containing two sub-steps, all of which addressed the overall goal of increasing safety on construction sites and in work zones by reducing visibility issues between workers-on-foot and equipment operators.

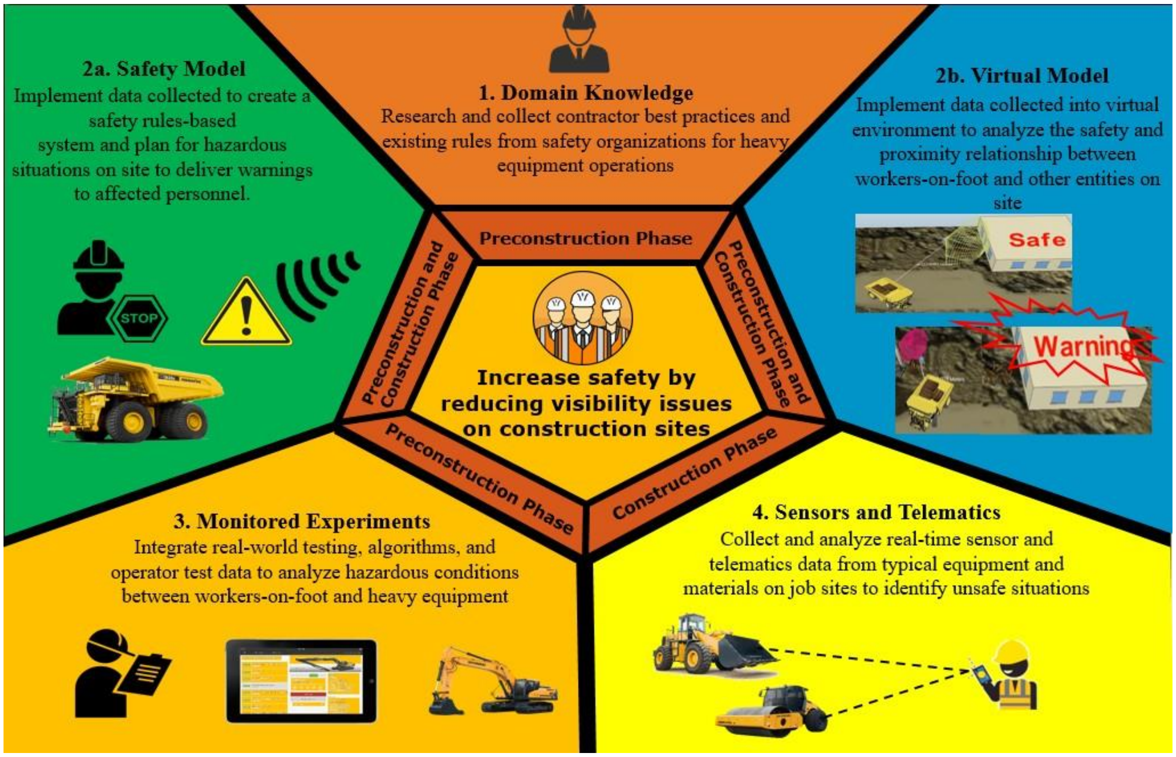

Figure 3.1 Methodology for increasing visibility and proximity issues on site

Each step is separated into different sections of the figure and can be identified as in the construction phase, pre-construction phase, or both. The ultimate goal of this methodology is to increase safety on site for workers-on-foot by reducing the number of visibility issues and false alarms in the work zone identified in previous research.

3.1 Domain Knowledge

To obtain a better understanding of the types of incidents and unsafe conditions that cause fatalities on construction sites and in work zones, whether equipment-related or not, an analysis of reports produced by organizations such as the National Institute for Occupational Safety and Health (NIOSH) and Occupational Safety and Health Administration (OSHA) was performed. The reports provided by NIOSH contained detailed summaries of what occurred during an incident, who the incident affected, and recommendations to prevent similar future scenarios. In analyzing these reports and OSHA statistics, the authors found that struck-by object incidents produced the majority of reported injuries and fatalities on construction sites and in work zones. According to OSHA, these incidents have caused approximately 940 fatalities in the construction industry and are considered to one of the Fatal Four. .

OSHA has named the four on-site incident categories with the highest rate of fatalities the “Fatal Four.” These four categories are falls (38.8 percent), struck-by objects (9.6 percent), electrocutions (8.6 percent), and caught-in between objects (7.2 percent) (OSHA 2016).

Because struck-by object incidents have one of the highest rates of fatalities, this type of hazardous scenario was chosen to be analyzed through this case study. In addition, contractor best practices and existing rules were researched, and contractors were interviewed to allow the researchers to obtain a better understanding of how management teams enforce safety regulations on site. This information was filtered to pick out the regulations and rules of thumb that were applicable to the equipment that would be present on the construction site or throughout the study. From the information gathered in this step, a rule-based system was developed to provide management teams with a safety model to implement on construction sites to reduce fatality and injury rates, as well as create a safer working environment.

3.2 Safety Model

The second step in the methodology involves developing two different models applicable to the preconstruction and construction phases of a project: a safety model and a virtual model.

These models will be developed from the best practices information and incident reports collected and studied by the researchers. The advantage of using both of these models and real-time automated data collection is that they will enable the programs used to self-update in response to changes in the project environment (Akhavian et al. 2012).

The safety model will be used in the preconstruction phase to create a rules-based system to utilize the data collected from subject matter experts and other sources to analyze hazardous situations in the work zone. This rules-based system will deliver a safety warning to affected personnel on site when a hazardous situation is detected so that appropriate changes can be made in a timely manner. This safety model will allow management teams to make appropriate changes to safety regimens on site, provide workers with safety alternatives, and pinpoint areas that need attention to creating a safer work environment.

3.3 Virtual Model

The virtual model component will focus on modeling different hazardous work zone situations involving heavy equipment during the construction phase through a virtual environment called Virtual Robotic Experimentation Platform (V-REP). V-REP is a platform that provides a 3D robot simulator that concurrently simulates actions such as control, actuation, sensing, and monitoring (Freese et al. 2010). This program is ideal for complex scenarios in which sensors and actuators operate asynchronously at various rates and with differing characteristics (Freese et al. 2010). Because of factors such as liability issues, the methodology for this research will be difficult to validate. Potentially hazardous situations cannot be investigated on a real construction site because they put lives at risk (Chan et al. 2017). This platform and experiment will also be used to focus on analyzing the interactions between human workers and heavy equipment on site. To avoid liability issues, the domain knowledge gathered from the first task will be applied in the virtual world, rather than tested in the real world, to evaluate the safety relationships between entities on site. With both the safety and virtual models, researchers will be able to analyze the visibility, safety, and proximity relationships between workers-on-foot and equipment operators without encountering liability issues.

The researchers assigned a mannequin to symbolize a worker-on-foot, a rectangle to symbolize a truck that could be detected, a safe or warning sign to represent the worker detecting the equipment approaching too close and not visible to the worker, and a sensor attached to the back of the mannequin's head to symbolize the worker's field of view. The reason for the sensor being at the back of the worker's head is that it represents the worker not having a clear view of the equipment and being in a dangerous situation. By having the sensor on the back of the worker's head, the researchers were aiming to reduce the number of false alarms by focusing on the most dangerous situations, such as the worker not seeing approaching equipment. The researchers can also observe visibility and proximity issues and hazardous situations in extreme scenarios without putting real-world workers in danger. The data obtained from these models will provide management teams with ways to produce safety alternatives and solutions to current visibility and proximity issues on site.

3.4 Monitored Experiments

When the safety and virtual models have been developed, real-world testing can begin to allow the researchers to observe the effectiveness of contractor best practices and how the proposed models affect work zone and construction site safety. This testing will use a hardware system comprising an Arduino board, a Pozyx board, and a GPS board, as shown in figure 3.2.

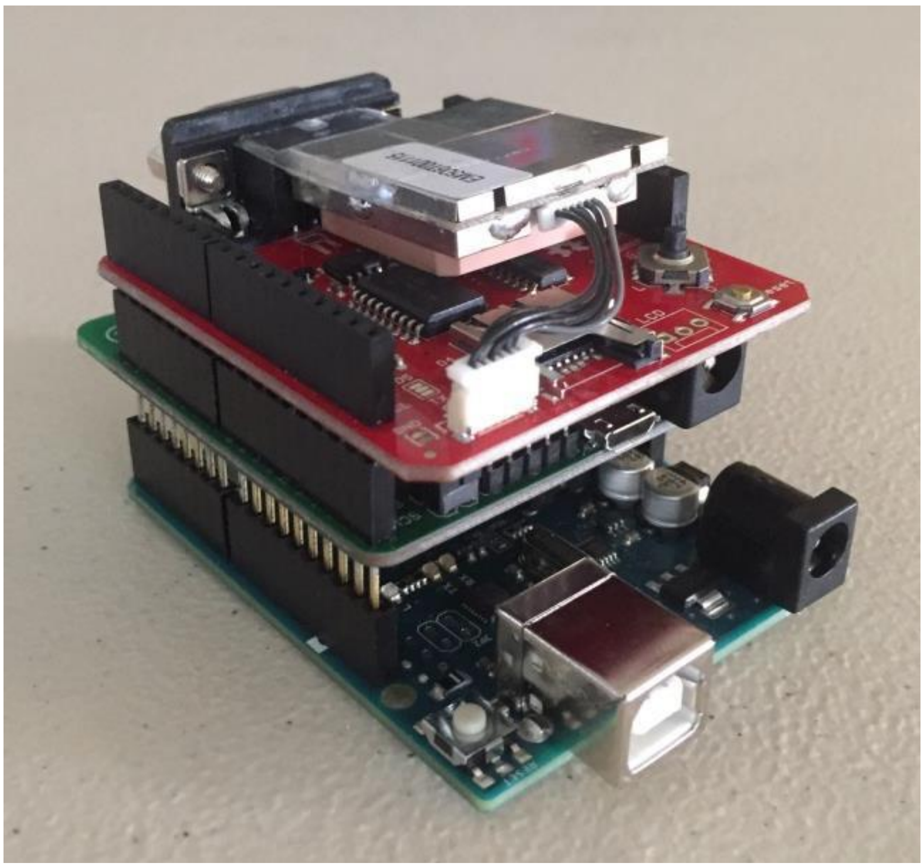

Figure 3.2 Safety device made up of three boards: Arduino, Pozyx, and GPS

The Arduino board is an open-source electronics platform based on easy-to-use hardware and software. The board senses the environment by receiving inputs from other sensors, and it can affect its surroundings by controlling lights, motors, and other actuators. The Arduino works with a code written in the Arduino programming language.

The Pozyx system is a hardware solution that provides accurate positioning and motion information. In order to achieve the positioning accuracy of a few centimeters, the Pozyx system relies on a novel wireless radio technology called ultra-wideband (UWB). This technology uses short pulse radio frequency waveforms and is capable of providing location precision in an indoor environment of less than 30 cm, as well as resistance to multipath effects in indoor applications (Teizer and Castro-Lacouture 2007). Applications of UWB include high-speed communications networks and data links, collision and obstacle avoidance, precision systems for personnel location, asset tracking and inventory control, and intelligent transportation systems (Teizer and Castro-Lacouture 2007). UWB technology is also used to detect construction equipment, risk areas, or workers and is capable of positioning these entities with a great level of accuracy, thereby relating their positions with Computer Aided Design (CAD) information and identifying potential hazard areas at the construction site (Teizer and Castro-Lacouture 2007).

The accuracy achieved with this ultra-wideband technology is better than traditional positioning systems based on WiFi, Bluetooth, RFID, or GPS signals. This system will be used to monitor the orientation of the workers-on-foot and equipment operator to observe whether the workers have the equipment in their field of view to prevent visibility issues on site. This hardware will be used on site by attaching the three boards to a worker’s hard hat, as shown in figure 3.3, so that the field of view can be analyzed on the basis of data collected when the worker moves on the site or moves his/her head throughout his/her daily tasks.

Figure 3.3 Field of view, worker-on-foot, and truck in real-world testing

With these tools, this step will focus on using the virtual environment to test operator movements, observe worker's line-of-sight, and develop algorithms to observe safety relationships to analyze hazardous situations mainly between human laborers and heavy equipment operators during the preconstruction phase. These experiments will aid the researchers in understanding how equipment operators and workers-on-foot function, the typical line of sight measurements for both of these entities, and how their movements affect their line of sight when they are in the work zone.

3.5 Sensor and Telematics Implementation

The final step will be performed in the construction phase. It will consist of collecting and analyzing real-time sensor and telematics data from typical equipment and construction labor-intensive operations to identify heavy equipment states and, again, monitor their relationships with workers-on-foot. This step will be implemented by using telematics, sensors, and monitoring on heavy equipment to obtain field data that describe the operations in which heavy equipment is used and to provide general insight into the various safety issues in the real world.

The hardware system described previously will be used by workers-on-foot and equipment operators as sensors to monitor the lines of sight of both entities and to observe their actions when working with one another. Site observations and telematics will be used to obtain a better understanding of equipment characteristics and operator behaviors. This information will help the researchers determine areas during the construction phase that need improvement in visibility and proximity issues between on-site entities. The real-world testing conducted in the previous step will help researchers narrow this study to scenarios that are common on site and have the greatest safety and visibility issues. With these components, information gathering, and sensors and telematics data collection, the line of sight for operators and workers-on-foot can be properly analyzed and observed to improve the safety relationship between these two entities and to further reduce the fatality and injury rates between heavy equipment and laborers.

Chapter 4 Study Site and Data Collection

Visibility and proximity issues, which cause many hazardous situations on site, may be caused by blind spots, poor communication, and the lack of an effective flagging system. By using sensors and telematics data collection tools, researchers can study hazardous situations related to line-of-sight for workers-on-foot and equipment operators. Along with observing the safety situations arising from worker-equipment interactions, the locations of these hazardous areas will be observed to determine how these situations affect work zone safety. The objective of this study will be to use various sensors and telematics to observe the line-of-sight of equipment operators and workers-on-foot to better understand how line-of-sight affects the movements of the two entities and to produce solutions to reduce fatality and injury rates between workers-on-foot and heavy equipment.

4.1 Struck-by Object Incidents

Struck-by object incidents are a leading cause of construction-related deaths. Of those incidents, approximately 75 percent involve heavy equipment such as trucks or cranes because of the proximity and visibility issues between equipment and workers-on-foot (OSHA 2009). As mentioned in section 2.1, struck-by object incidents are the second highest cause of fatalities on construction sites. In addition to these statistics, the researchers reviewed fatality reports produced by the National Institute of Occupational Safety and Health (NIOSH). These reports contained detailed summaries of on-site hazardous situations that have resulted in fatalities. The locations reported in these summaries ranged from work zones to high-rise construction. The scenarios chosen to test the developed telematics and sensors safety system in this study included reports from May 29, 2003, and June 29, 2004. The first scenario involved a 23-year-old male Hispanic pipe layer. He was struck by the bucket teeth of an excavator while installing a concrete drain pipe alongside a public roadway with four other workers. The excavator operator was assigned to extend the trench to accommodate another piece of the pipe, but when making the cut, the bucket teeth struck the worker in the chest and neck area. This caused immediately fatal injuries.

The second scenario involved a 34-year-old flagger who died after being run over by a partially filled dump truck. The truck was transporting materials to a hopper on site that would dispense onto a conveyor that would deposit the material onto the northbound lane shoulder, where a worker would smooth it with a rake. When it was time, the truck was instructed to move the material. The dump truck operator had a flagger to control traffic and a flagger to control the area on site. The coworker (spotter) signaled by hand for the truck driver to raise the bed to allow the UCL to be dispensed into the hopper and then motioned for the driver to pull forward. As the truck moved forward, the coworker saw the rear sway and the truck operator felt a bump. The coworker rushed to the passenger side of the vehicle and saw the victim under the truck's rear passenger-side tandem wheels. With implementation of the appropriate telematics and sensor tools, these fatalities could have potentially been prevented.

From the report analysis for struck-by object incidents, it was clear that many accident scenarios are caused by heavy construction equipment backing over workers-on-foot. This research will use those findings and focus on an unsafe situations involving workers-on-foot and heavy equipment in reverse. The case studies mentioned above will be observed in the real world and in the virtual model, as a real-world study may be limited by the proprietary rights of the equipment and liability issues. Dump trucks have been present in most of the have equipment back-overs that have caused fatalities. Given this observation, their common utilization in the construction industry, and their visibility constraints, a dump truck will be used for the virtual model in this research. The virtual operation will take place in a typical work zone and will include a worker-on-foot donning the hard hat with the hardware system and a dump truck in close proximity moving in reverse toward the worker. This virtual model simulation will allow the researchers to make line-of-sight observations based on collected sensor and telematics orientation and proximity data without putting lives in danger. Because of proprietary and liability issues related to the use of heavy equipment and laborers, the real-world testing will be done at a lower scale: a passenger car and a student from Oregon State University will simulate a dump truck and a construction worker-on-foot. The movements of the entities will be similar to those that occur on construction sites, allowing the researchers to directly use the data collected from the experiments in the virtual model to provide a visual representation to management teams of the various proximity and visibility issues that actually occur on site. The worker will be positioned in two orientations—facing the equipment, as shown in figure 4.1, and facing away from the the equipment, as shown in figure 4.2—with different proximities.

Figure 4.1 Worker-on-foot facing the equipment with the safety device attached to the PPE

Figure 4.2 Worker-on-foot facing away from equipment with safety device attached to the PPE

The study will focus on improving the field of view of workers-on-foot and limiting the emission of false alarms to prevent dangerous situations from occurring in work zones and construction sites and to reduce the number of extraneous distractions on site.

4.2 Research Components

To observe how line-of-sight affects the safety relationships between heavy equipment and workers-on-foot, a safety tool was developed. This safety tool uses telematics to communicate the locations and orientations of workers-on-foot and equipment operators on site.

The tool comprises three main components—an Arduino board (Arduino), a Pozyx Real-Time Location System (Pozyx), and a GPS board—that focus on obtaining the location of both the worker-on-foot and the equipment. The Pozyx monitors orientation. This system offers localization to achieve 3D positioning with centimeter accuracy, motion sensing, wireless communication, and compatibility with other hardware.

The Pozyx and a battery pack are both attached to the Arduino board through the proper ports. Along with the Pozyx board, a GPS board focuses on proximities and locations on site. The system is attached to a worker-on-foot's PPE and to a piece of equipment involved in the construction task to monitor both their locations and orientations to observe how line-of-sight affects the safety relationship between the two entities. Because of proprietary issues, actual equipment could not be used for the research study, but Oregon State University's (OSU) facility services allowed a 5-ton dump truck to be pictured with the device for this portion of the experiment, as shown in figure 4.3.

Figure 4.3 Five-ton dump truck provided by OSU for real-world simulation

The researchers attached the system to a student's hard hat and monitored the orientation of the student's line-of-sight movements. The scenarios chosen for this study could be reenacted and observed by using a student with the proper PPE, a passenger car, and another student to represent a spotter.

Chapter 5 Results

The methodology will be validated by applying the system to a case study scenario to identify and observe areas in an equipment-intensive construction operation that could create unsafe conditions. To determine those areas, the line of sight of workers-on-foot will be observed by using a hardware system to monitor the position and orientation of workers on site. This approach will focus on improving safety during various phases of a construction project by potentially reducing the number of struck-by object fatalities that occur in work zones.

The collected best practices data will be used to create a safety model that uses a rules-based system to analyze and observe a site to evaluate the enforcement of regulations. A virtual model will also be used to model case studies to observe the effects that field of view have on the safety relationship between heavy equipment and workers-on-foot. Monitored experiments involving real-world testing and algorithms will be used to observe workers-on-foot and heavy equipment to locate areas in need of field of view improvements. Furthermore, sensors and telematics will be used to track and pinpoint areas that compromise workers' fields of view in work zones when they are in close proximity to heavy equipment.

Contractor best practices have a great effect on workers' safety on site. To gather background information on best practices, the research team plans to create a short survey, conduct interviews with local contractors, obtain safety check lists from safety managers, and research established organizations' rules and regulations. The resulting information will describe how safety on site is being monitored and enforced. Workers' field of view can also be studied in relation to these best practices, as the check lists and interviews may pinpoint areas where the contractors recognize a need for safety improvements. In addition, the safety checklists and best practices can be reenacted in a virtual environment to determine whether their application to the safety relationship between workers-on-foot and equipment operators suffices. Furthermore, the reenactment of situations that test the applications of best practices can allow the research team to develop appropriate warnings and recommendations.

The proposed system comprising the Arduino, Pozyx and GPS boards will be attached to a worker-on-foot's hard hat to monitor his/her orientation and position when in close proximity to equipment on site. The results will ultimately show the how the field of view of each worker affects safety levels and how safety in work zones, where many struck-by object incidents occur, can be altered to improve the fields of view and safety relationship between these two entities. The Pozyx board implementation will also provide management teams with an option to accurately monitor positioning and motion information.

This system will allow users to navigate throughout an environment while tracking position and orientation, allow the environment to respond to the user's presence, and measure distances in the test zone. The hardware solution will be attached to a worker's hard hat to monitor his/her orientation to provide data on how field of view affects the safety and proximity relationship between workers-on-foot and equipment operators. By attaching the device to the hard hat, the research team can monitor the worker's orientation and track what the worker is able to see when his/her head is turned. This will help management teams develop appropriate warnings to deliver to affected personnel.

The sensor system on the worker's hard hat will send orientation and positioning data to sensors anchored around the study area. These will then relay a signal to the virtual environment, V-REP, so that movements in the real world can be tracked and developed in the virtual environment to pinpoint areas during the construction phase that can benefit from more efficient warnings in the work zone. V-REP will also be used to recreate scenarios in the pre-construction phase to observe the relationship between the workers and equipment operators without putting workers' lives in danger. The scenarios will be reenacted through robots in the virtual environment, which will help eliminate liability issues and determine the accurate points in time to deliver warnings based on the worker's field of view. Through this virtual simulation, the researchers will be able to locate problem areas and make observations on how field of view should be improved to reduce the fatality rates in work zones during both the construction and pre-construction phases. This will validate the proposed methodology to observe worker field of view in the work zone, reduce the amount of stress that management teams have currently in manually processing collected data, and create a more efficient way for management teams to handle large-scale projects.

The researchers have worked on fine-tuning the communication between the safety device and the virtual platform. To improve the communication between the two entities, the researchers have eliminated the use of the Pozyx anchors because they limit interactions in indoor construction situations. GPS has been selected because of its ability to receive a stronger signal for outdoor construction, which is where this type of device is needed the most in the industry.

There are three different systems used to make up this study. The first system is attached to the worker-on-foot and monitors his/her location and orientation when performing daily tasks, as shown in figure 5.1.

Figure 5.1 Worker-on-foot with device for monitoring location and orientation

The second system is attached to a piece of equipment to monitor its location and orientation on the basis of the movements it makes on site, as shown in figure 5.2. The third system communicates the signals received from the worker-on-foot and the heavy equipment to V-REP, where a virtual mannequin represents the worker and a proximity sensor represents the worker’s line of sight.

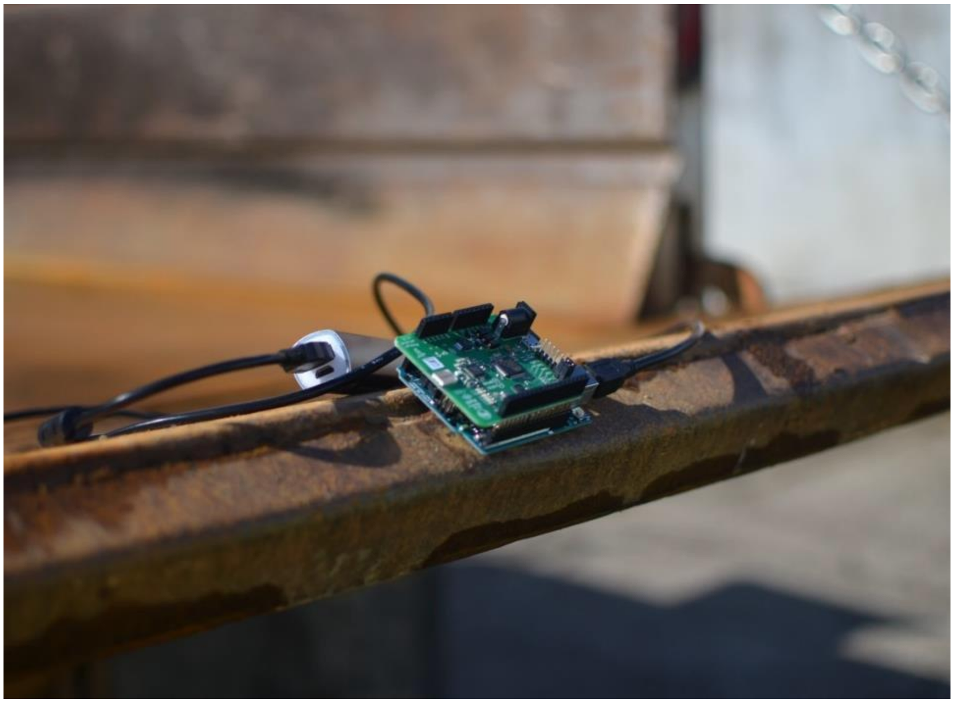

Figure 5.2 Safety device attached to heavy equipment to monitor location and orientation

In V-REP, the proximity sensor is attached to the back of the mannequin’s head because this study’s scope of work focused on reducing false alarms and visibility issues in situations where equipment travels in reverse. When the worker is at a safe distance from the equipment, V-REP sends a safe alert to the user, as shown in figure 5.3. If any object, including the equipment, intersects with the sensor attached to the mannequin, it represents the worker not seeing the object because his/her back is to the entity. In V-REP, a warning is emitted when the equipment or any other object intersects with the sensor from the signals sent from the safety device attached to the worker, as shown in figure 5.4.

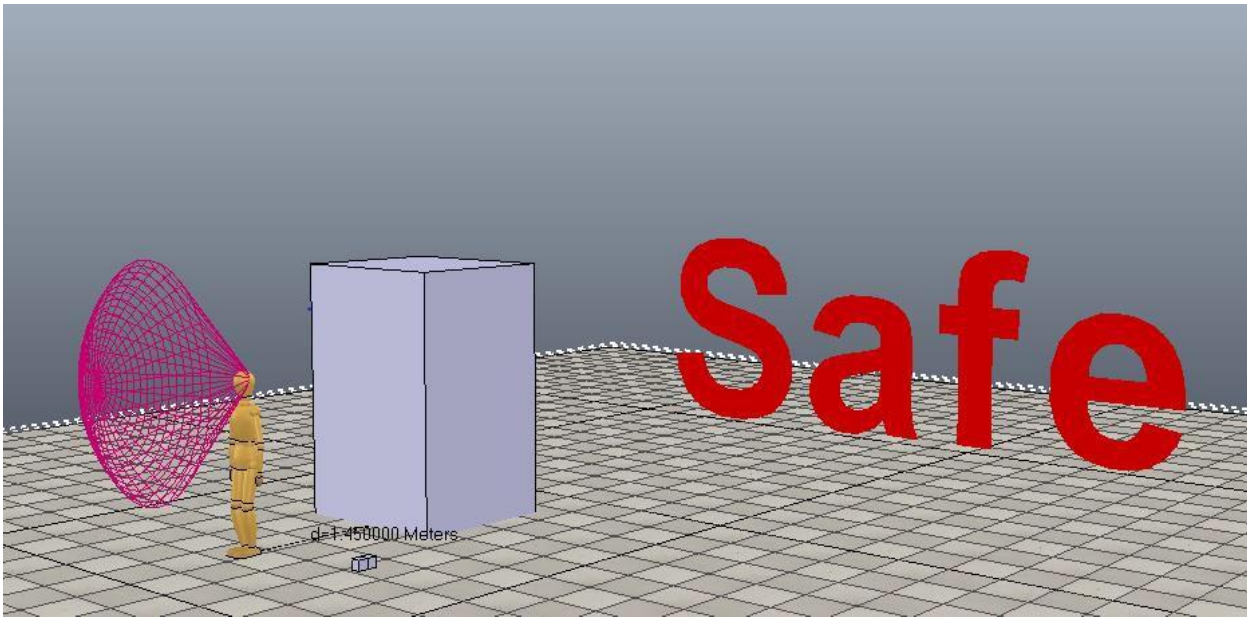

Figure 5.3 Worker-on-foot is in safe proximity to the equipment and does not have the equipment in his/her line of sight

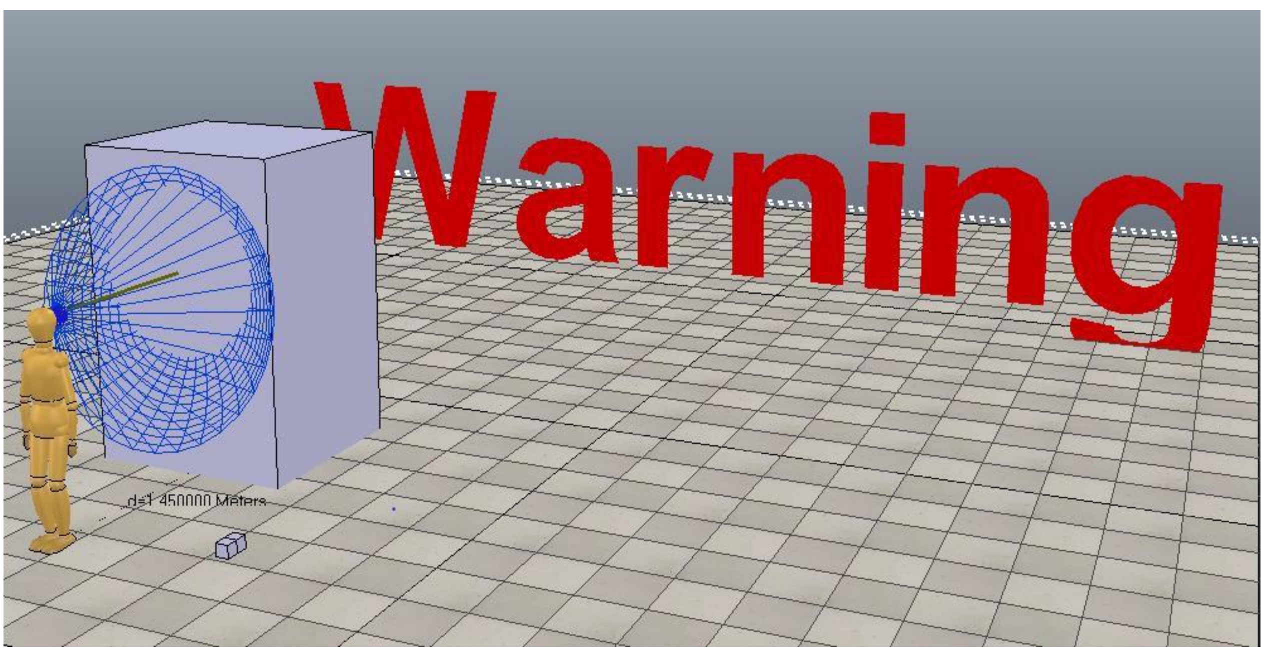

Figure 5.4 A warning is emitted when the equipment is in dangerous proximity to the worker-on-foot and in an unsafe line of sight

The signals received from the system are sent to the proximity sensor set on the mannequin's head. The sensor on the mannequin moves when the worker-on-foot moves his/her head in the real world, and the mannequin moves when the worker moves from one location to the next. When an object is detected behind the worker-on-foot, the sensor in the virtual environment turns blue, and the safe text changes to warning that a hazardous interaction has occurred.

Chapter 6 Conclusions

Because of the dynamic nature of construction sites, workers-on-foot and heavy equipment are forced to work within close proximity of one another, which causes many hazardous situations and visibility constraints. This research developed a hardware system and virtual experimentation platform to determine how visibility issues affect workers on site. By using this device and platform, researchers can monitor actual worker movement and orientation to observe reactions to hazardous interactions, how line of sight obstructions add to fatality rates, and how worker awareness to the hazard plays a role in these events.

The virtual platform allows researchers to make observations of visibility and proximity issues without the added constraints of liability and putting workers at risk. This research proposes a framework that provides a way to monitor the fields of view for workers-on-foot and equipment operators to potentially reduce the number of fatalities due to struck-by object incidents in work zones.

This chapter presents the conclusions of this study by discussing the contributions of this research to the body of knowledge and state of practice, the limitations of the research, and a plan for future work.

6.1 Contributions of the Research

The close proximity of workers on the ground to heavy construction equipment creates many visibility-related issues for operators that further create unsafe conditions and situations that could result in injuries or fatalities (Marks et al. 2013). This research proposes a way to monitor the fields of view of these two entities in work zones to observe their safety relationship and improve visibility issues on site. The main contribution of the research is to allow management teams to use a technological device to easily monitor the safety relationships and fields of view for workers-on-foot and equipment operators to reduce the fatality rates between these two entities in a work zone.

This research provides an analytical approach to objectively examine safety conditions, which contradicts the normal perception that safety is a subjective topic and difficult to quantify. With this research being analytically based, safe worker conditions and line-of-sight can be monitored and developed to determine the field of view relationship between workers-on-foot and equipment operators. This research is also based on a more technological approach, which is a modern step that is not common in the traditional construction industry.

With the incorporation of telematics and sensor data from this study, the safety relationships between various entities on site can be improved through monitoring of lines of sight. The data collected will help management teams generate appropriate warnings to reduce hazardous situations on site and to implement appropriate safety regulations to enhance safety guidelines in work zones. The results could potentially be used to create a safety model for real-time on-site alarms to improve safety in a timely manner, to eliminate hazards before they occur, and to be applied to a range of operations.

6.2 Limitations of Research

Limitations to the research include the fact that the safety model requires a rules-based system to be researched manually, which could potentially delay the amount of time spent on this area of the research. In addition, making observations of proximity and visibility issues between workers-on-foot and equipment operators is difficult because such studies require workers to be in close range of heavy equipment.

In addition, it is difficult to predict what workers will do when on the job, even if they are warned. Workers may completely disregard the warnings, not agree to wear the hard hat device, or be fatigued and/or distracted. Enforcement of the warnings and proper usage of the devices introduced in this research will also be difficult to monitor, as the construction industry may be resistant to change. In addition, gaining support and cooperation from a large number of construction companies may be difficult. Equipment usage will also be difficult to monitor because of proprietary issues. When the virtual model and safety model are applied to other case studies, more limitations will be discovered.

6.3 Future Work

This research can be applied to generic operations in work zones, but the case studies used in this test were limited to one type of incident, struck-by object. To further this research, evaluating a wider variety and larger number of case studies would be beneficial to validate the safety model and virtual model for other construction zones.

This research can also be used to model previous accidents from safety organizations' reports to observe whether line of sight issues created the incident. From there, management teams can decide whether worker field of view is affecting injury or fatality rates in their work zone and create appropriate safety warnings to eliminate future visibility issues.

In addition, the research can be advanced to provide automated processes to improve safety and other project controls within a project and to use different tracking devices to improve the system to perform at a higher level. The research can also be used to obtain telematics information for OEM's to implement into rules-based systems and test state identification.

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