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Title: Improving Safety on Construction Sites by Using Real Time Sensor Data to Monitor Worker Field-of-View and Proximity to Hazards and Reduce the Generation of False Positive Alarms

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Dr. Joseph Louis

The construction industry is infamously recognized for having jobsites identified as hazardous working environments due to workers-on-foot commonly functioning at dangerous heights and in close proximity to other construction entities, among other reasons. These hazardous operations result in an increased risk of worker injuries and fatalities caused by fall hazards and struck-by object or equipment incidents. Construction workers are involved in these incidents due to proximity and visibility issues caused by the congested, continuously changing, and dynamic nature of the worksite. Previous research studies concentrated on developing various resource localization systems to prevent these hazardous interactions on site based on proximity of workers to hazards on site. However, these previously established systems typically generate false positive alarms that produce the false-alarm effect for workers and contributes to the risks present on jobsites. This thesis develops a system to minimize the occurrence of false proximity alarms on construction worksites for proximity and visibility related hazards.

Information was collected from contractor interactions and literature reviews to create a safety rules-based system to monitor the interactions on site pertaining to falls and struck-by equipment incidents. Along with the developed rules-based system, an enhanced proximity detection system that uses real-time sensor data was devised to track worker-on-foot's field-of-view and proximity to other construction entities. A virtual model was also added to the study to enable spatial analysis of the system and entities in the real-world. This model contributed to monitoring and observing

hazardous construction interactions without liability issues brought forth by real-world experiments. Ultimately, the developed framework issued safety warnings to workers when they had their backs facing the other entities on site, which created restricted visibility conditions for hazards in their close proximity. This focus reduced the emission of false positive alarms while still successfully alerting workers of fall and struck-by hazards. The developed detection system and virtual model has great potential to enhance construction safety by monitoring field-of-view to reduce false positive alarms and mitigate the occurrence of visibility and proximity related incidents on worksites.

Improving Safety on Construction Sites by Using Real Time Sensor Data to Monitor Worker Field-of-View and Proximity to Hazards and Reduce the Generation of False Positive Alarms

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Kelsey Chan, Author

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For my Mom and Dad

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CHAPTER 1. INTRODUCTION

Construction sites are notorious for being hazardous environments due to their dynamic nature, continuous movement of resources onsite, and the uniqueness of each worksite. In 2016, the Bureau of Labor Statistics (BLS) recorded 991 fatalities in the construction industry, which was approximately 21.1% of the 4,693 fatalities that occurred in the private industry (OSHA 2016). The preeminent causes of private sector worker deaths in the construction industry, in order from highest number of fatalities to the lowest, were falls, struck-by object or equipment, electrocution, and lastly, caught-in/between. The Occupational Safety and Health Administration (OSHA) has classified this distinct group as the Fatal Four, which was responsible for approximately 63.7% of the construction worker deaths in 2016.

In the U.S. construction industry, fall accidents are the main source of the observed injuries and fatalities (Hinze and Gambatese 2003; Bobick 2004; Hu et al. 2011; Kang et al. 2017). The majority of construction sites involve laborers working at dangerous heights and in intricate work environments, resulting in these accidents (NIOSH 2004; Kang et al. 2017). Despite the enforced and strengthened workplace guidelines and work practice improvements implemented on construction sites, the risk related to fall accidents has not decreased. The number of fatal falls to lower levels increased from 447 in 2007 to 553 in 2011 (BLS 2011; Jebelli et al. 2015). Fall incidents are caused by falls from elevation or ground level to lower levels, falls through existing floor or roof openings, falls through the floor or roof surface, falls on same level where the point of contact was the same level supporting the individual, scaffolding collapsing under the weight of the workers, and jumps from structures and equipment (OSHA 2011). The lack and misuse of fall protection are the leading contributing factors to falls that occurred in the structural steel erection line of work causing many fatalities and injuries due to this type of accident (Beavers et al. 2009; Kang et al. 2017). In 2016, fall hazard situations were responsible for 384 fatalities or 38.7% of the industry's total (OSHA 2016). More than 80% of fall accidents occurred from a height of less than 9 meters or approximately 30 feet (Kang et al. 2017). The amount of fall incidents still occurring, raises concerns for the effectiveness of safety programs used and the type of precautions such as technological advancements being implemented to prevent these types of accidents from occurring.

The dynamic status of construction sites also results in close-proximity interactions between various entities, such as workers-on-foot and heavy equipment that can lead to struck-by equipment incidents. Unsafe proximity of workers-on-foot to construction equipment and equipment to equipment interactions have been identified as another one of the distinct safety issues on construction jobsites (Pradhananga and Teizer 2013; Wang and Razavi 2016). Based on statistics published by OSHA, from 1995-2008 struck-by equipment hazards accounted for 58% of the total struck-by accidents (Wu et al. 2013). There are many different cases caused by human factors that result in struck-by equipment incidents such as improperly positioning equipment for the operation, removing or using inoperative safety devices, causing distractions on site, and incorporating insufficient or a lack of external protective measures such as spotters and the use of Personal Protective Equipment (PPE) (Hinze et al. 2005). In 2016, struck-by object and equipment incidents were responsible for 93 fatalities, which equates to 9.4% of the overall fatality total for the industry (OSHA 2016). A report from the Center for Construction Research and Training (CPWR) conducted in 2015 shows that 162 out of 985 fatalities were caused by struck-by incidents (Wang et al. 2017). The number of deaths due to being struck-by an object or equipment observed an increase of 20% from 2011 to 2015, which is alarming due to the escalated amount of research completed in attempting to prevent these incidents from occurring (Wang et al. 2017).

These issues have been considered in previous studies that aimed to implement different technological advancements such as sensors to improve worksite activities. The dynamic nature of a construction site, and the hazards and difficulties presented by the on-site work, also necessitate the use of intelligent ways to support on-site construction staff and personnel. (Behzadan et al. 2008). Wang and Razavi (2016) note that a large number of proximity avoidance systems have been developed utilizing various technologies such as radio frequency identification (RFID), laser scanning to identify blind spots, radar-based proximity warning systems, ultra wideband (UWB), global positioning system (GPS) to monitor and observe proximity issues to prevent contact collisions involving struck-by equipment incidents (Chae and Yoshida 2010;

Marks et al. 2013; Ruff 2006; Cheng et al. 2013; Lee et al. 2009; Choe et al. 2014). Likewise, tools for identifying fall risks around the construction site have been introduced such as using inertial measurement units (IMU) sensors, automated models to monitor fall hazards, Building Information Modeling (BIM), and Prevention through Design (PtD) tools to prevent fall hazards from frequently occurring on site (Navon and Kolton 2006; Zhang et al. 2014; Qi et al. 2014; Yang et al. 2015; Jebelli et al. 2015). Even with the above-mentioned technological tools developed previously, there are limitations on the implementation in the industry.

Unlike previous research, this study focuses on using real-time sensor data and virtual modeling to reduce the generation of false positive alarms sent to workers by current proximity detection systems and mitigate proximity and visibility issues observed in fall hazards and struck-by equipment incidents. For example, workers-on-foot are typically assigned to various close-proximity tasks such as being a spotter for an operation. As a spotter, workers have the construction entities involved with the operation approaching them and in their field-of-view. Therefore, they are aware of the close-proximity hazard nearing them even if it may seem dangerous. An alarm, generated from previously developed proximity detection systems, in this scenario is not required to alert the worker and is classified as a false positive alarm because the worker has the entity in their field-of-view and is not threatened. This false positive alarm results in creating the false-alarm effect, which leads to the worker potentially ignoring valid alarms.

The main objective of this research is to generate effective and accurate warnings specifically when a hazard is within close proximity to workers-on-foot and out of their field-of-view by using real-time sensor data and virtual modeling to ultimately minimize false positive alarms from being sent to workers. To do so, the researcher focused on primarily sending a warning to the worker-on-foot when there is a hazard that is within close proximity to them and they are unaware of. The researcher assumed that when a worker has their back towards other construction entities, they are unable to see those entities due to humans having limited visibility behind them. Sending a signal every time a worker is within close proximity to other entities results in the workers becoming used to these unnecessary alarms and ignoring valid alerts, which leads to fatalities. The researcher sent warnings to the worker when they 1) had their backs towards the hazardous and approaching entities on site, which limited their field-of-view, and 2) were in close proximity to the entities.

This enables the generation of effective warnings to ultimately reduce the emission of false positive alarms to preserve the validity of the warnings being sent to the workers in hazardous situations.

Physically, fall and struck-by incidents are not similar. However, they are caused by similar factors such as visibility issues, deficiency of sensor implementations for workers on site, worker behavior, lack of training, and complacency. The research presented in this thesis develops an enhanced proximity detection system that will monitor the worker-on-foot's position along with their orientation/heading to limit the generation of false positive alarms. The methodology presented utilizes a virtual model, which receives the transmitted and collected data to identify areas that are deemed unsafe for the workers-on-foot in regards to their interactions with other entities on site. This methodology will allow workers to become more aware of their surroundings and facilitate management teams to create fitting solutions for fall and struck-by equipment incidents and enforce these solutions appropriately. Chapter 2 focuses on describing research that has been previously conducted on fall hazard risk assessments, proximity detection systems, and the research gap that was identified by the author. Chapter 3 introduces the methodology for the research presented in this study that focuses on improving proximity and orientation of the workers-on-foot. Following this, the performance of the system created by the researcher is demonstrated through various case studies, simulations, and field experiments. Finally, the results are discussed, which include limitations, contributions, and future work.

CHAPTER 2. LITERATURE REVIEW

Incorporating technological advances into construction practices to mitigate proximity and visibility issues caused by fall hazards and struck-by equipment incidents can reduce the high injury and fatality rate observed by the construction industry due to these incidents. This research focuses on developing a framework to detect hazardous situations that arise due to visibility and proximity issues resulting in fall hazards and struck-by incidents and delivering effective warnings when these incidents occur. Currently, different technological implementations have been tested in the field to observe and track the positions of workers and equipment to identify and monitor imminently hazardous situations and deliver the imperative safety warnings to the affected personnel on site. However, these existing systems generate false positive alarms, which creates the false-alarm effect for warnings sent to workers (Wang and Razavi 2016). The generation of false positive alarms also leads to unsafe situations arising due to the workers potentially ignoring accurate warnings and not being aware of their surroundings. Along with this, these systems do not provide visualization tools that enable spatial analysis to send warnings to workers on site. This chapter provides a review of previous research studies that have been conducted to prevent fall hazards and remove proximity issues on site while providing the context for the focus of this research.

First, fall-hazard detection and assessment practices are examined to evaluate the impact these tools have on mitigating fall risks. Second, a section dedicated to reviewing the distinct types of worker behavior and physical demand monitoring systems available in construction is provided to display the effects of how worker awareness and physiological distractions contribute to hazardous struck-by equipment incidents. Insight on how using various systems and advancements can improve worker performance quality to reduce the amount of struck-by equipment accidents is also provided. Third, state tracking implementations is considered to observe the impact these studies have on improving the close proximity and visibility issues between various entities by concentrating on the location and functionality of equipment on site. Next, a summary of the various proximity detection related studies is considered. Finally, a section dedicated to identifying the gap in literature and defining the objectives of this research is presented.

2.1 Current Fall Hazard Safety Implementations

Fall hazards are the leading cause of the construction industry's fatalities due to construction work involving working at heights and the complacent enforcement of fall-hazard protection (Kang et al. 2017; NIOSH 2004). Navon and Kolton (2006) note that adequate fall detection and prevention measures can reduce and even eliminate fatalities due to falls on the worksite. It is critical to first identify and assess the fall risk associated with the diverse factors impacting construction workers to effectively implement fall-prevention efforts (Soursa et al. 2014; Jebelli et al. 2015). To understand the risks involved with these incidents, a variety of studies utilizing different technologies, tools, and techniques have been developed. First, fall hazard identification studies implemented into the design phase of the project are introduced. Second, the fall hazard identification tools developed and later implemented into the construction phase is presented.

2.1.1 Fall Hazard Identification in the Design Phase

The design phase of any project is crucial for risk analysis to identify potential hazards on site especially for fall incidents. A study conducted by Qi et al. (2014) explored how BIM could be used to enhance worker safety. This study also utilized PtD tools to mitigate construction site hazards in the design phase. The research reported that by developing these application tools, fall hazards can be checked automatically in building information models and provide design alternatives to users to prevent future fall scenarios from occurring. The combination of BIM and PtD can be used by architects and engineers during the design phase to check for compliance with specific fall safety requirements, which results in enhanced construction site safety for fall hazards (Qi et al. 2014). Similarly, Zhang et al. (2014) conducted a study to investigate how potential fall hazards that are unknowingly built into the construction schedule can be eliminated through developing an algorithm to detect the location of potential fall hazards and provide installation guidelines of corresponding fall protection equipment that solves the identified hazards virtually in BIM. The results from this study show the effectiveness of using tools like BIM to detect and visualize probable fall hazards during the design and planning phases. Additionally, the automatically generated fall prevention plan must be checked by a safety specialist, which enables the proper adjustments to be made if other safety guidelines or best practices need to be followed (Zhang et al. 2014).

A fall hazard prevention model was developed by Navon and Kolton (2006) to automate fall prevention procedures and identify dangerous fall activities in the project's schedule. This automated model defined areas in the building where fall hazards appeared, proposed protective guardrail erection, integrated the guardrails into the schedule for the user, and continuously monitored the existing protective measures in real time. Due to the applicability of the model, this safety tool can be used during the design and construction phases of a project making it a useful managerial tool to prevent fall hazards (Navon and Kolton 2006). These studies contribute to removing fall hazards by aiding management teams primarily in the design phase. The technology and tools discussed next, focus on monitoring fall hazard situations in the construction phase using real-time data collection techniques.

2.1.2 Fall Hazard Identification in the Construction Phase

Jebelli et al. (2015) and Yang et al. (2015) used Inertial Measurement Units (IMUs) to collect kinematic data that can be used to assess the movements of workers and determine whether their behaviors and actions will lead to a fall incident. This data collection can be implemented into the construction phase of a project to aid management teams in preparing for potential changes being made to the plans formed in the design phase due to the unpredictable nature of construction sites. Even with a large amount of planning in the design phase, it is hard to project the various hazards that may occur in the construction phase. Therefore, different studies and advancements need to be researched for this specific phase. A comprehensive fall-risk assessment completed by Jebelli et al. (2015), developed an IMU and attached it to the right ankle of the participants' body to collect kinematic data for the calculation of maximum Lyapunov exponents (Max LE), which was used to assess construction workers' fall risk movements and behaviors. This research allows safety managers to gain a better understanding of how workers react to jobsite fall hazards and the diverse safety measures needed to mitigate fall risks in a more efficient and effective way. By using IMU sensors and Max LE, construction management teams have the ability to discern a project's built-in risk before the project begins in order to identify "invisible" fall hazards on site (Jebelli et al. 2015). The developed sensor allows construction worker movements, pertaining to falls, to be understandable, so if the risk does occur on site the management teams will be prepared to make adjustments. Yang et al.

(2015) used IMU to develop a method that can automatically detect and document near-miss fall incidents based on the worker's kinematic data. This near-miss fall detection approach provides the industry with quantitative information about near-misses and offers the foundations for using near-miss fall data to alert workers about their real-time fall risks. Unrecognized near-miss falls can be identified by using this sensor and the corresponding algorithm, which gives researchers and safety managers the opportunity to better understand individual workers' behavior concerning near-miss fall hazards and the conditions that contribute to these incidents (Yang et al. 2015).

Although these studies all contribute to removing fall hazard situations, there is a lack of using sensors and real-time tracking tools to better understand the behavior of workers, accurately monitor the position and field-of-view of the worker, and using visualization tools to observe worker interactions. With the implementation of these tools, fall hazards have a higher chance of being mitigated effectively. The next section of the literature review focuses on monitoring systems studied to mitigate hazardous interactions between workers-on-foot and heavy equipment to prevent struck-by equipment incidents.

2.2 Struck-by Equipment Incident Detection

This section is categorized into three subsections due to struck-by incidents comprising multiple entities including workers-on-foot and heavy equipment. To obtain a better understanding of the aspects involved in this type of incident, each subsection focuses on a single entity that contributes to these incidents and the current implementations previously studied to improve this onsite interaction. First, worker behavior and physical demand monitoring advancements are investigated to acquire insight on how the use of various systems and advancements can improve worker performance quality, how the effects of worker awareness and physiological distractions contribute to these incidents, and how to improve worker interactions with other entities to ultimately reduce the amount of struck-by equipment hazards. Next, state tracking implementations are considered to recognize the impact that monitoring equipment and occasionally workers, has on bettering struck-by incidents by observing the equipment's daily activities and interactions with other entities on site. These technologies do not directly relate to struck-by incidents, but they contribute to the research needed to mitigate these hazards by focusing on technological advancements that enhance the resources that constitute these incidents. Finally, current proximity and contact collision avoidance detection systems on construction sites are evaluated to observe the advancements used to improve the interactions between workers-on-foot and heavy equipment to remove proximity issues that contribute to struck-by incidents.

2.2.1 Worker Behavior and Physical Demand Monitoring Systems and Practices

Along with unsafe interactions between different entities on construction and work-zone projects, physiological practices and ergonomics have an impact on worker behavior and hazardous situations as well. Investigating these systems aids this research to better comprehend the areas of safety that need to be monitored using technological implementations and how monitoring worker awareness and behavior impacts unsafe interactions specifically fall-risk and struck-by equipment incidents. Construction workers are frequently exposed to excessive physical demands such as repetitive lifting and material handling while performing tasks on site due to the laborious nature of the industry (Seo et al. 2016). Previous research conducted by Rwamamara et al. (2010), Bouchard and Trudeau (2008), and Garet et al. (2005) suggests that excessive work physiological demands can negatively affect project safety and productivity. This negative side effect is caused by a decrease in workers' well-being, attentiveness, motivation, and capacity to perform muscular work, adding to the occurrence of dangerous fall and struck-by incidents (Gatti et al. 2014). To mitigate these issues, worker monitoring has been researched to observe hazardous motions performed on site that decrease worker awareness and to yield management teams with applicable alternatives to incorporate into their on-site safety programs.

Devices that are capable of performing assessments on worker’s physiological conditions can play an important role in supporting the development of these needed tools, methods, and techniques in hopes of enhancing worker awareness and construction workforce safety (Gatti et al. 2014). In a study conducted by Gatti et al. 2014, Physiological Status Monitors (PSM), which are capable of monitoring various physiological parameters in a non-invasive, autonomous, and wireless manner, were used to monitor the heart rate and breathing rate of workers in static and dynamic activities. The worker monitoring system successfully analyzed the relationship between physical strain and task level productivity (Gatti et al. 2013), performing automatic work sampling to facilitate real-time productivity assessment (Cheng et al. 2013b), and monitoring of ergonomically safe and unsafe behavior of construction workers (Cheng et al. 2013c; Gatti et al. 2014).

Previous research and applications in construction resource optimization have focused solely on tracking the location of material and equipment, which contributes to the lack of studies developed on remote monitoring for improving safety and health of the construction workforce (Cheng et al. 2013c). A study conducted by Cheng et al. (2013c) presented a new approach for monitoring ergonomically safe and unsafe behaviors of construction workers using non-intrusive real-time worker location sensing (RTLS) and PSMs. Using a set of experiments, the researchers demonstrated that UWB and PSMs data collected through monitoring and tracking workers can be fused to automatically identify and localize the ergonomic related hazardous working behaviors (Cheng et al. 2013c). Another example that incorporates monitoring systems into observing unsafe working behaviors is a study conducted by Seo et al. (2016) that uses a simulation-based framework to estimate physical demands and corresponding muscle fatigue. A quantitative evaluation was generated on the impact of muscle fatigue during construction operations. The study estimates physical workloads by combining discrete event simulation (DES) and biomechanical analysis, predicting the level of fatigue under estimated workloads using dynamic fatigue models, and finally evaluating the impact of muscle fatigue on the planned operation. This worker-monitoring system allows management teams to better understand workers' response to physical demands by adding workers' capabilities as changing variables into traditional DES approaches, enabling pro-active management of human resources (Seo et al. 2016).

The lack of tools for identifying potential ergonomic risks in a proposed workplace design has caused many difficulties in properly implementing safety and health precautions and programs into workplace design practice to better understand how worker awareness impacts hazardous site interactions between entities. Evaluating ergonomic considerations early in the project planning before workers are faced with these issues would be the most effective way of handling and reducing these issues. For example, a study conducted by Golbachi et al. (2015) addresses this issue by exploring a motion data-driven process in a virtual workplace. The researchers coupled the ergonomic analysis with three-dimensional virtual visualization of the working environment to provide designers with quantitative information regarding the risks involved in current and proposed workplace design. These studies show that developing worker monitoring systems that observe workers movements, behaviors, and awareness, regardless of the intensity of the situation or project, can improve safety on site and prevent further injury and fatalities.

2.2.2 State Tracking Implementations

The National Safety Council's "2016 Injury Facts" chart books showed that struck-by incidents due to backing vehicles and equipment still remains a serious occupational hazard (NSC 2017). Acknowledging that the number of struck-by incidents on construction sites is still high and the consequences due to these accidents are very severe, the states of construction entities, in this case, equipment, should be properly monitored and analyzed so that potential collisions and hazards can be prevented and reduced (Wang and Razavi 2016). Monitoring the movements, location, and activities being worked on by heavy equipment through state tracking has improved construction management techniques by allowing the teams to create solutions such as new logistics plans and different trainings, for issues that have occurred or have the potential of occurring. The ability to automatically detect the locations of items can improve the performance of material distribution and monitoring to ultimately improve the overall project performance (Razavi and Haas 2010). When considering the state of a construction entity, there are various components that 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 of the entity such as idle time, and other safety-related information (Wang and Razavi 2016). The research conducted on state tracking and monitoring of the distinct entities on site contributes to improving the safety of the construction industry by allowing management teams to have access to information including the communication and information tools required for efficient identification, locating, tracking of materials as well as the reporting and control of their transport to shops and job sites, (Razavi and Haas 2010) and identifying areas on site that are hazardous and unsafe for workers-on-foot.

The accurate collection of construction entity state information also contributes to impacting construction site safety by increasing situational awareness resulting in preventing struck-by equipment incidents present on site (Wang and Razavi 2016). For example, Park et al. (2017) used a combination of Bluetooth low-energy (BLE)-based location detection technology, 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 using BIM. A set of seven scenarios were 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 the construction site monitoring process and can potentially improve construction-site safety (Park et al. 2017). The RTLS developed by Lee et al. (2012) aimed to locate workers and equipment in dynamic and busy construction sites, to identify and prevent hazardous situations between workers-on-foot and heavy equipment present on site. The experiment conducted contributes by allowing management teams to have a system that is comprised of localization and tracking technology that can be utilized for monitoring workers and other objects to alert workers when they are in danger (Lee et al. 2012).

Razavi and Haas (2010) developed a modified functional data fusion model that was used 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 potential struck-by equipment incidents by allowing management teams to accurately observe the interactions between construction entities and prevent unsafe situations from occurring. In addition to this system, various methods have been researched such as a study that presents an enhanced boundary condition method that incorporates the tag-reader angle and reader geometric configuration factors to control and monitor the accuracy of al locating system that integrates RFID and real time kinematic (RTK) GPS (Su et al. 2014). This study shows that by incorporating proposed configuration factors into boundary condition–based methods in RFID locating could significantly increase the locating accuracy, and the corresponding quality control filters based on these two factors could ensure the achieved accuracy level to meet specific application needs such as identifying hazardous interactions (Su et al. 2014).

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). Additionally, Teizer et al. (2010) used real-time construction object location information to enable proximity analyses to aid management teams and research groups to prevent deadly and disastrous accidents such as workers struck-by equipment (Su et al. 2014). The next section of the literature review will look into the various proximity detection systems currently being researched or used in the construction industry to improve the interactions between workers-on-foot and heavy equipment and to prevent unsafe situations from occurring on site.

2.2.3 Current Proximity Detection and Contact Collision Avoidance Systems

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 with each other 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 incidents is a priority for project safety objectives, technology driven safety can assist existing safety best practices (Teizer et al. 2010). To reduce the high fatality rates due to close-proximity situations, advancements in sensing technologies and state tracking have been developed and have prompted the expansion to proximity detection systems (Wang and Razavi 2016). Proximity detection studies have been closely analyzed in the past decade to assist construction workers and management teams in reducing fatalities on site due to close-proximity and visibility issues. For example, Chae and Yoshida (2009) used RFID technology to prevent collision accidents between heavy equipment and workers-on-foot. Functions for the collision prevention system were defined and a final collision prevention system composed of working area estimation, collision risk analysis, and warning to persons concerned was designed. Additionally, the radio frequency remote sensing and actuating technology developed by Teizer et al. (2010) can improve construction safety by sending the appropriate warnings or alerts to workers-on-foot in a pro-active real-time module once the specific equipment get too close in proximity to other entities on site to prevent fatal struck-by incidents.

A study conducted by Marks and Teizer (2012) used similar technology, but different field testing conditions to remove close-proximity encounters between heavy equipment and workers-on-foot. The results of this study show the ability of the system to detect close proximity hazards and further record when a proximity alert is activated, which can later be used to analyze “near-misses” to prevent this type of situation from occurring in the future (Marks and Teizer 2012). A new safety approach that uses small GPS units attached to hardhats to collect continuous location dataVe the safety performance of workers near equipment or other hazards (Pradhananga and Teizer 2012). This system demonstrates how users can measure the safety performance of construction resources automatically to prevent hazardous interactions between entities and to use the information for safety education (Pradhanaga and Teizer 2012). Marks and Teizer (2013a) also contributed to the proximity detection studies by conducting a study that evaluated the capabilities and reliability of low-cost (semi-)passive RFID technology as the main component of a pro-active real-time personal protection unit (PPU). The results indicated that both position and orientation of the PPU impact the accuracy of the system's ability to activate the appropriate alerts during hazardous proximity encounters and that by implementing this system in the construction industry, workers-on-foot can be alerted during close-proximity situations and make adjustments (Marks and Teizer 2013a).

Furthermore, a framework for the implementation of a sensor-based proximity warning system used to minimize backing accidents was created and developed by Choe et al. (2013). In addition, a study was conducted by Luo et al. (2015) that focused on workers' response to a proximity warning of static safety hazards on construction sites using a location-based proximity warning system called Proactive Construction Management System. Park et al. (2016) created and evaluated a proximity detection and alert system using Bluetooth sensing technology to prevent and analyze hazardous proximity situations between pedestrian workers and construction equipment. These detection technologies 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 PPE fail (Teizer et al. 2010). UWB, an active RFID technology, was utilized in a study conducted by Cheng et al. (2012) to track resources such as equipment and workers in real-time to later transmit to a visualization tool that aided decision makers to make accurate adjustments. This tracking technology was developed to increase situational awareness for construction site stakeholders in dynamic construction site operations. By analyzing the location of construction resources and accurately identifying, monitoring, and measuring the status of work tasks this tool helped improve project safety performance in real-time. To contribute to the research challenge of real-time pro-active construction safety and site monitoring, this study used real-time UWB data and a virtual environment to visualize relevant safety and activity performance information to provide a decision maker with a better understanding of the safety issues on site based on quantitative and objective data collection (Cheng and Teizer 2012).

2.3 Identification of Gaps in Research

All of these studies have contributed to making the construction industry a safer working environment by proposing techniques to monitor worker awareness and reduce the number of fall and struck-by equipment incidents caused by proximity and visibility issues. However, there are still limitations in implementing these advancements in the worksite. Current fall-risk sensing technology focus on and is limited to workers' posture and behaviors. Adapting to sudden changes can be difficult for current fall risk practices due to the lack of research and preparation completed that uses real-time data to provide decision makers with a clearer understanding of projected hazards that exist on site. The research reported in this thesis uses real-time sensor technology to monitor the position and field-of-view of the worker involved in fall operations. The developed framework focuses on monitoring workers' physical motions rather than internal-body functions to identify and prevent hazardous fall scenarios and fatalities by emitting imperative warnings.

Despite all of the benefits previous unsafe-proximity detection research provides the construction industry, a common limitation to these studies is the high possibility of generating false positive alarms while using these techniques on site. Frequently generated false alarms can result in the workers disabling the alert system used to track the equipment to prevent distraction and/or ignoring the alarms whether they are helpful or not. The generation of false positive alarms in previous studies has put a constraint on the real-world implementation of the devices and methods developed (Ruff 2010, Teizer et al. 2010, Wang and Razavi 2016). The main reason for the frequent generation of false positive alarms is that distance is the only factor being considered in previous studies are (Teizer et al. 2010; Cheng and Teizer 2013) while other factors such as orientation of entities are being ignored or require calculations to obtain. Li et al. (2012) identified that simply sensing the proximity between entities is inadequate for safety control due to it limiting the information and study to one factor.

Based on the review of literature presented in this chapter and industry safety performance, this research seeks to bridge the following gaps in this research:

1. <u>Monitoring fall hazards without real-time data and primarily in the design phase</u>

Many of the developed worker and overall project monitoring systems for fall hazards are limited to implementation during the design phase, which restricts quick adjustments being made on site if an incident occurs. By using real-time data and testing the systems during a construction-phase fall hazard situation, this framework can be implemented to identify and prevent hazardous fall scenarios.

2. <u>Considering distance as the major factor in unsafe-proximity detection</u>

Frequently generated false positive alarms are produced on site due to the distance between entities being the major factor considered in previous unsafe-proximity detection systems. To prevent the future generation of false positive alarms on site, the field-of-view in addition to the proximity between workers-on-foot and other entities will be considered in this thesis.

3. <u>Conducting experiments with both entities facing each other and one entity stationary</u>

Since distance is the major factor considered in previous work and humans do not have 360-degree vision, visibility issues, ultimately the areas behind the worker, are still present on site. Previous studies test their proposed unsafe-proximity detection systems with both entities facing towards each other, which is not always the case on site (Marks and Teizer 2012). In addition, the experiments conducted had one entity static, which does not represent the dynamic nature of the construction industry. With the field-of-view monitoring aspect of the developed system focusing on the mitigating hazards approaching the worker-on-foot from behind, the visibility and safety of the worker can be improved. This research aims to mitigate visibility and proximity issues by integrating this enhanced proximity detection system on site, therefore reducing the fatality and injury rates observed by the industry.

4. <u>Limited virtual environment implementation</u>

Using real-time data to observe worker movements on site through a controlled environment has been limited. Using the virtual environment, the researcher has the ability to use spatial analysis to identify hazardous situations based on prior analysis of site conditions between workers-on-foot and other entities and monitor the actions of the workers without liability issues.

This thesis aims to minimize the generation of false positive alarms by developing an enhanced proximity detection system that uses real-time sensor data and a virtual model to monitor the position and orientation of the worker-on-foot during the construction phase. In order to achieve this goal, the researcher developed a framework to examine the interactions of entities on site and determine potential visibility related hazards and to answer the following research questions:

1. Can we increase the effectiveness of warnings for proximity and visibility related hazards?
2. How can we make use of real-time sensor and telematics data to improve safety?
3. Can we enforce safety practices in the construction phase?

These questions guided the researcher to develop a detection system that addresses the gaps identified in previous studies and visibility and proximity issues present in fall and struck-by equipment incidents while also reducing the generation of false positive alarms. The proposed methodology, introduced in the next section, will also aid decision makers by developing a tool that removes subjectivity and quantitatively monitors and analyzes results initially.

CHAPTER 3. RESEARCH METHODOLOGY

The main objective of this research is to reduce the generation of false positive warnings specifically for cases where a hazard is within close proximity to workers-on-foot and out of their field-of-view by developing an enhanced proximity detection system that uses real-time sensor data and virtual modeling. Along with this objective, the research aimed to address the following research objectives:

1. Develop a framework that generates effective and accurate warnings specifically for cases where a hazard is within close proximity to workers-on-foot and out of their field-of-view.

2. Potentially reduce the amount of fatalities and injuries observed in the construction industry caused by falls and struck-by equipment incidents

3. Mitigate visibility issues for workers-on-foot in the construction phase

This research will improve safety warnings and ultimately reduce the generation of false positive alarms and mitigate proximity and visibility issues observed in fall and struck-by equipment incidents on site. This detection system will enable management teams and decision makers with the ability to monitor the real-time status of equipment fleets and automate safety warnings through the pre-operation and construction phases of the project. This chapter describes the proposed methodology for delivering accurate warnings to construction sites through real-time sensor data collection and provides the experimental setup that will be used to validate the research conducted. Figure 3.1 provides an overview of the methodology developed in this research.

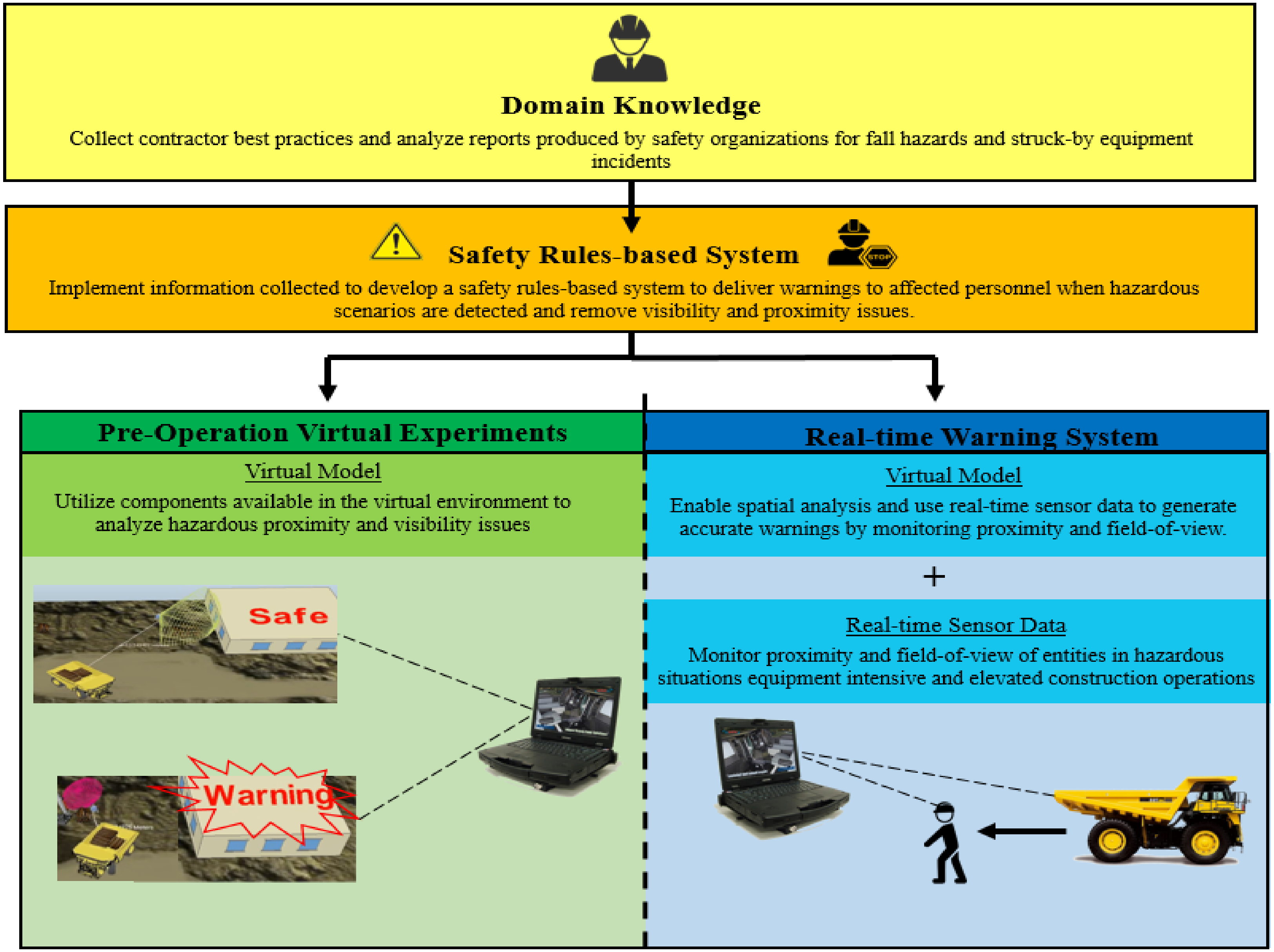

Figure 3.1: Overview of Research Methodology

This methodology is composed of four components that all contribute to monitoring the proximity and visibility of construction entities to reduce the generation of false positive alarms and enable accurate warnings to be sent to the entities on site involved in a hazardous interaction. Initially, reports developed by various organizations were investigated to obtain a better understanding on the types of incidents that cause a majority of the construction industry fatalities. Additionally, site visits were conducted to gain insight on contactor best practices used to promote safety on site and to obtain information about the frequency of fall hazards and struck-by equipment incidents. The literature review and site visits confirmed the need for improved safety tools for construction personnel involved with heights and heavy equipment operations. Based on these investigations, a safety rules-based system was developed to set parameters for the experiments and to analyze hazardous situations in typical construction operations under specific guidelines. Following this, a typical construction site was modeled in the virtual environment to observe hazardous scenarios without real-world factors such as liability issues. The pre-construction modeling was also used to observe the interactions between entities and to label situations as hazardous or not. Next, an enhanced detection system that focused on simultaneously monitoring the positions and field-of-view of workers was developed to mitigate visibility and proximity issues by sending warnings to affected personnel.

This system eliminates the emission of false positive alarms that occur on site from current proximity detection systems. The proposed detection system was then used in real-world cases involving a worker-on-foot, heavy equipment, and demonstrations where heights are involved to issue warnings when a hazard is identified as being within close proximity to the workers-on-foot and outside of their field-of-view. The goal of this research was to develop an enhanced proximity detection system that utilizes real-time sensor data and virtual modeling to reduce the generation of false positive alarms by emitting effective warnings specifically for cases where a hazard is within close proximity to workers-on-foot and out of their field-of-view.

3.1 Domain Knowledge

To obtain a better understanding of the types of incidents that cause fatalities in the construction industry an analysis of reports produced by various organizations and construction site visits were conducted. The reports provided by the National Institute for Occupational Safety and Health

(NIOSH) and the statistics provided by the OSHA gave valuable insight on the incidents that cause a majority of the injuries and fatalities in the industry (NIOSH 2017; OSHA 2016). Reports provided by NIOSH contained detailed summaries of what occurred during the incident, who the incident affected, and recommendations to prevent future scenarios. These reports included incidents that occurred from the early 1990s to the late 2010s, which shows that solutions have not been effectively implemented into the industry to prevent workers from being involved in hazardous situations on site. When going through the Fatality Assessment and Control Evaluation (FACE) reports, falls and struck-by equipment incidents had the majority of the reported injuries and fatalities on construction sites, which validates the need for a change in construction site safety regarding these types of hazards. Due to the frequency and severity of fall hazards and struck-by equipment incidents reported, these two fatal interactions were selected to base the case studies of this experiment on. Additionally, falls and struck-by incidents were ranked first and second in the Fatal Four by OSHA, verifying the need to remove these types of hazardous situations from the industry. After these incidents were filtered out, the researcher considered the capacity of the virtual environment to simulate these incidents and the ability of real-world testing to depict the hazards brought forth by this study to assure the accuracy of the detection system to emit warnings. The chosen reports are discussed further in the case study section of this paper.

Best practices were also obtained from site visits and contractor interactions. The researcher met with various construction engineers on jobs throughout Washington and Oregon and discussed these hazards and how they are currently being monitored. The findings obtained through these interactions helped the researcher to gain insight on the changes that need to be made to the construction industry in regards to improving safety and reducing the fatality rates observed on site. Contractor interactions discussing the types of technological advancements that they have either used on their sites or have observed on other sites and the most frequent causes of injury and fatality they have experienced in the industry were conducted. Along with this, the rules and regulations enforced on site pertaining to falls and heavy equipment interactions and how these hazardous interactions can be prevented in the future were also considered. The information obtained from the site visits justified the need for safety improvements and advancements in the industry to potentially eliminate future fatalities and injuries. Furthermore, a rules-based system was developed from the information gathered in this section to create a system that issues effective warnings to workers-on-foot in proximity and visibility related hazards to reduce fatality and injury rates as well as create a safe working environment.

3.2 Safety Rules-Based System

The rules-based system was used to integrate the best practices collected from site visits and information obtained from the reports created by various organizations to analyze hazardous situations on site. This system can be utilized by construction management teams and decision makers during the pre-construction phase to identify potential hazards that could put their workers in danger throughout the process of the project. Additionally, this system provides guidelines that focus on enabling imperative and precise warnings to alert workers-on-foot of a close proximity and limited visibility situation with construction entities. The rules-based system focused on two major concepts; distance and field-of-view. To evaluate these concepts, safety parameters for both proximity and visibility monitoring are set in the rules-based system to ensure that an adequate warning was sent to the workers-on-foot involved in a hazardous situation.

Distance is a key component in this system because construction workers are often required to function in close proximities to heavy equipment and building edges on construction jobsites (Marks and Teizer 2012). Due to workers being in close proximity to various entities on site, Marks and Teizer (2012) state that a real-time proximity detection and warning system capable of alerting construction personnel and equipment operators during hazardous proximity situations is needed to promote safety on construction jobsites. To determine the proximity parameters that would ensure a warning would be sent to the affected personnel and the appropriate amount of reaction time was available for the worker to remove themselves from the hazardous situation, two factors are considered.

First, the information obtained from site visits and the report analyses are considered. Based on these analyses and contractor interactions, a distance of approximately 20 feet between entities for struck-by equipment incidents and a range of 10-15 feet for fall incidents were deemed sufficient and safe proximities. Second, a hazard zone study done for multiple types of equipment was conducted by Awolusi et al. (2015) that concentrated on creating hazard zones for workers-on-foot around pieces of construction equipment. The study shows that dump trucks have the most visibility related fatalities and two hazard zones were also determined based on the function of two types of dump trucks commonly used. A range of 2 to 6.3 meters or 6.5 to 21 feet for the front and backs and a distance of 2 meters for the sides of the trucks was found to be hazardous for these dump trucks. From these reports and research, a range of 4 to 9 meters or approximately 13 to 30 feet was used for the rules-based system corresponding to fall hazards and the struck-by incidents in the virtual environment. This distance can be adjusted depending on the type of operation or hazard observed. In the design phase, these parameters were set for the virtual entity following the given path, explained later in this chapter, while working in close proximity to a dump truck operated by the researcher for preliminary tests. For the construction phase experiments, the system used the signal relayed from the GPS to the computer using UWB communication, explained later in this chapter, attached to the enhanced proximity detection system for the worker-on-foot, heavy equipment, and building ledge to measure the workers actual proximity between the entities. A factor of 111,000 was used in the rules-based system to convert the longitude and latitude values obtained from the system to provide coherent values for the virtual scene. This conversion resulted in the truck and worker virtual entities moving in the scene according to where their detection system moved in the real-world.

To reduce the amount of false positive alarms potentially sent by the system, field-of-view was incorporated into this system. Position and other information, such as orientation (roll, pitch, and yaw) combined can define a user's spatial context with much greater precision than with position alone (Behzadan et al. 2008; Wang and Razavi 2016). In addition, focusing solely on sensing the proximity between entities is inadequate for safety control (Li and Jobes 2012; Wang and Razavi 2016). Similar to the distance safety parameters set, the researcher inserted safety parameters for the detection system pertaining to field-of-view. Unsafe interactions between workers-on-foot, building edges, and heavy equipment occur when the worker's back is facing the entity. To monitor this, a proximity sensor is placed on the back of the virtual entity representing the worker-on-foot in the virtual environment, later discussed in the chapter. If the sensor established by the rules-based system is interfered with, it simulates the worker-on-foot not having the entity in their field-of-view and being in a hazardous proximity to the entity. The rules-based system generated an effective warning to the affected personnel if this situation occurs. Additionally, the system only emitted a warning if the worker was within the unsafe distance from the entity and had their back towards the entity to reduce the amount of false alarms emitted. By monitoring these two components, distance and orientation, the fatality rates that occur on site due to proximity and visibility issues and the generation of false positive alarms that are caused by previously studied proximity detection systems can be reduced.

Overall, this rules-based system was used to deliver a safety warning to the affected personnel when the worker-on-foot does not have the entity in their field-of-view and is in close hazardous proximity to the entity. This will reduce the amount of generated false positive alarms and will allow decision makes to implement adjustments in a timely manner. This safety rules-based system will allow management teams to make appropriate changes to safety regimens on site, provide workers with safety alternatives, and identify areas that need attention in regards to creating a safer environment by allowing decision makers to set safety parameters in this system specific to their site. Data collected from the enhanced proximity detection system was sent to the rules-based system in the virtual model to emit to accurate warnings when the worker-on-foot is not aware of approaching hazards. With this virtual model, the conditions are controlled allowing construction teams to observe hazardous scenarios without liability issues.

3.3 Pre-operation Virtual Model Experiments

The virtual model primarily enables spatial analysis in real-time to produce accurate warnings and reduce the generation of false positive alarms, but also provides decision makers with a visualization tool to observe fall hazards and struck-by equipment incidents. This virtual environment provides a precise simulation of the complex and dynamic construction operations without liability and proprietary issues that come with real-world testing. A virtual environment called Virtual Robotic Experimentation Platform (V-REP) was used to model the unsafe interactions observed from information gathered in previous components and through real-world testing. V-REP is a platform that uses the coding language Lua and 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 where diversity of sensors and actuators operate asynchronously with various rates and characteristics (Freese et al. 2010). The rules-based system, previously described, was implemented into the V-REP coding system to evaluate the proximity and visibility issues in fall hazards and struck-by equipment incidents. In the pre-operation phase, V-REP and the functions offered by the platform and the developed rules-based system are the main sources of contribution to the analysis. This component focuses on the virtual environment modeling implementation in the pre-operation phase and the contributions of this initial study. The safety parameters incorporated into the rules-based system are tested through these initial experiments by modeling typical construction site operations in the scene. Observing the selected construction entities interact in a controlled environment enables the researcher to determine if V-REP can track filed-of-view accurately and characterize interactions as safe or hazardous before using V-REP for real-world tests. Running these pre-operation experiments facilitates the researcher to validate and ensure that V-REP is capable of sensing proximity and visibility to justify its use for the real-world experiments introduced in the next component description.

During the pre-operation phase, the virtual environment utilized various components and functions provided by V-REP to monitor proximity and visibility issues without the use of sensors to establish an initial study for this model. This study solidified the effectiveness of this platform and its ability to precisely simulate the hazardous fall and struck-by equipment incidents by using the available tools and the rules-based system. Virtual entities such as trucks and various shapes were used in the scene to simulate a typical construction operation to observe the proximity and visibility issues without liability and proprietary constraints. For this initial modeling study, a struck-by equipment incident was modeled instead of a falls incidents due to the various components involved in this type of incident. The researcher assumed that if the virtual environment was capable of monitoring visibility and proximity issues for this type of incident, then it would have the means to model fall hazards as well. A typical loading and unloading material operation was modeled in the scene shown in Figure 3.2.

Figure 3.2: Typical Construction Equipment Operation Modeled in V-REP

To represent the truck performing the unloading task of the scene, a truck was imported into the scene and controlled by the researcher. A virtual entity modeled after a human was used as the worker-on-foot and a cube colored brown was modeled to represent wood being unloaded from the dump truck operation. A proximity sensor was used to represent the worker-on-foot's field-of-view. When the worker was idly moving into position to transport a piece of wood to the safe area of the operation, the sensor was displayed as wider and orange due to the worker's awareness being increased, shown in Figures 3.3 and 3.4.

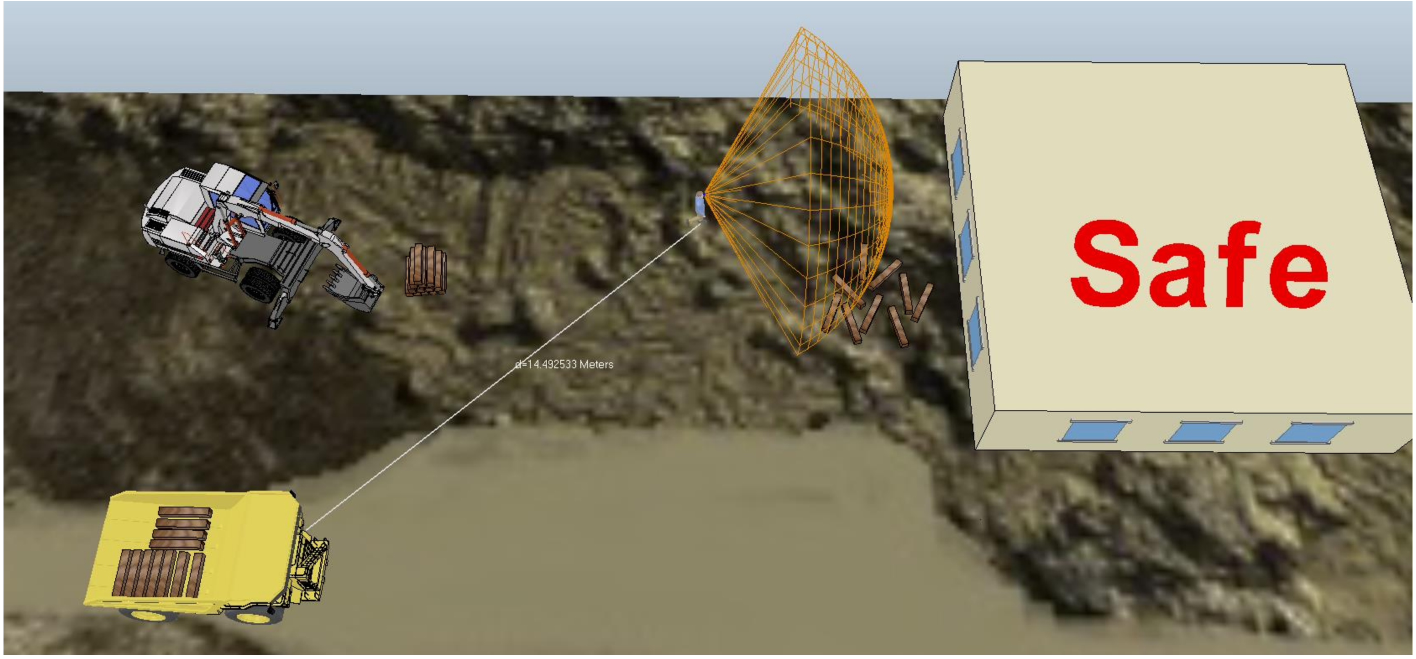

Figure 3.3: Worker Moving into Position to Transport Materials with Wider Field-of-View

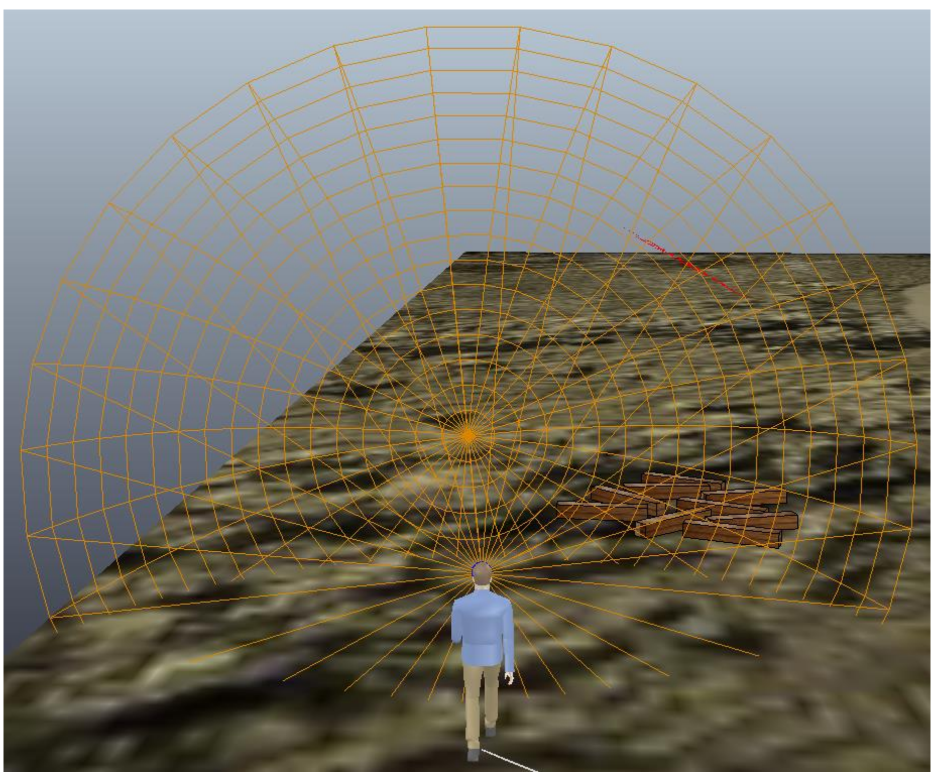

Figure 3.4: Worker with Wider Field-of-View

The worker’s awareness is higher in this situation because they do not have to focus on a task and the worker is moving towards the unloading zone with the truck in their field-of-view. When the worker moves into the blind spot of the truck to pick up a piece of wood to move to the area away from the operation, the sensor was displayed as narrower than the first sensor due to the worker’s awareness being decreased, shown in Figures 3.5 and 3.6.

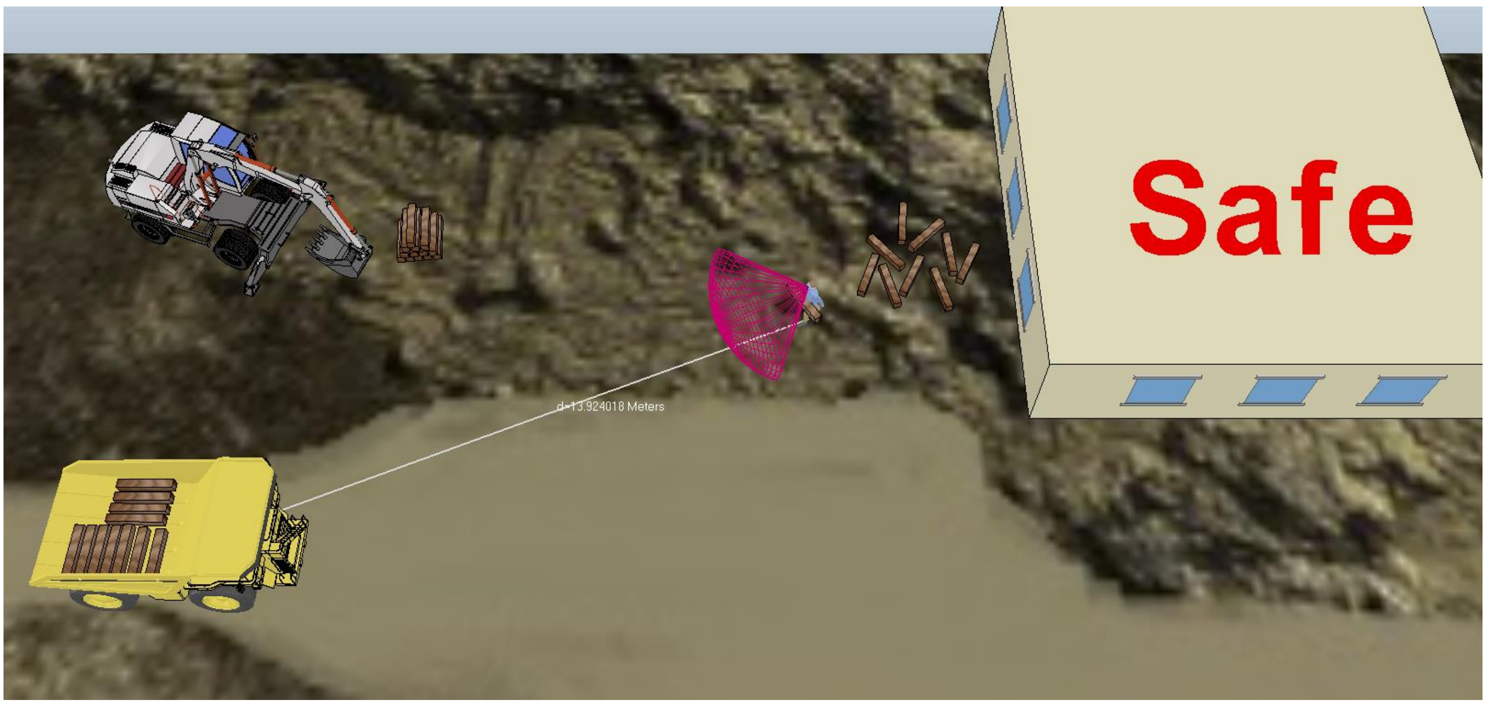

Figure 3.5: Worker Transporting Materials with Narrower Field-of-View

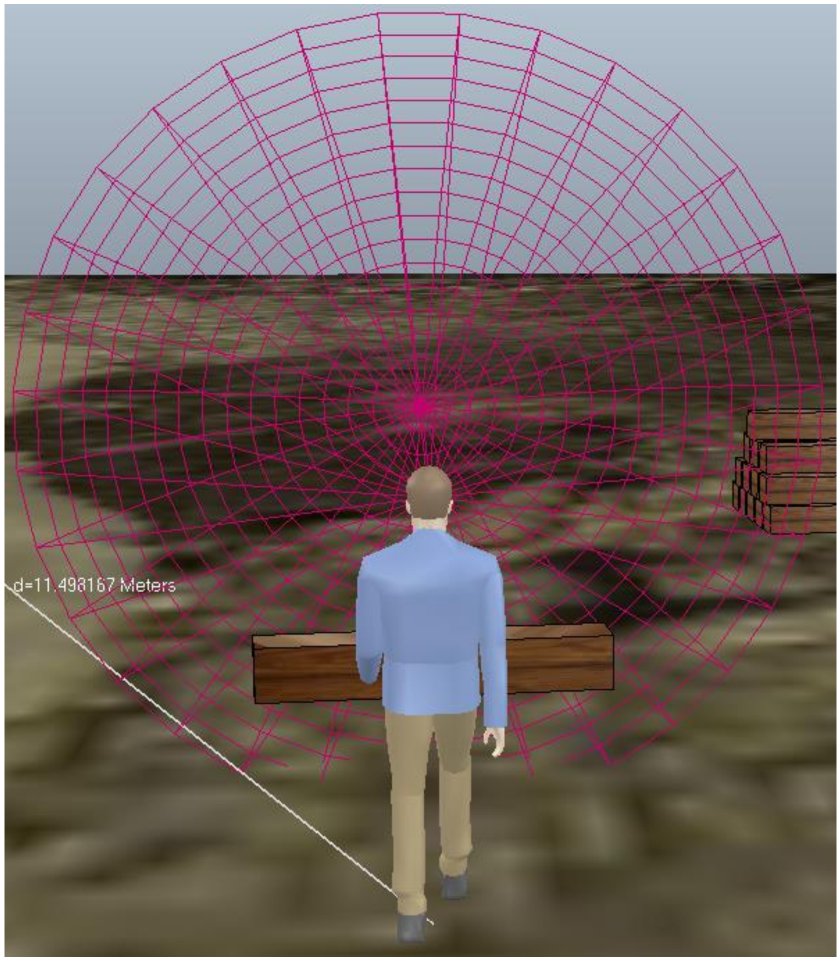

Figure 3.6: Worker with Narrower Field-of-View

The worker's awareness is lower due to the worker moving into the truck's blind spot area and focusing on transporting the wood rather than the surrounding operation zone, which results in the truck moving out of the worker's field-of-view. This interaction results in an unsafe situation where the worker could be involved in a struck-by equipment incident that could lead to fatality. The dump truck, controlled by the researcher, reversed into the worker to determine if a warning would be emitted accurately. Since the truck was in close proximity to the worker-on-foot and interfered with the cone-shaped proximity sensor, a warning was sent and the operation stopped until the truck was a safe proximity away from the worker shown in Figure 3.7.

Figure 3.7: Warning Projected for Identified Hazardous On-Site Interaction

Along with a warning text displayed to notify the user of a hazardous situation, the cone-shaped proximity sensor attached to the worker changes from red to a dark green to signify a warning. This monitored test verified that this platform is capable of accurately representing real-world hazards caused by struck-by equipment incidents and is capable of simulating other construction hazards such as falls. Furthermore, the use of this virtual environment during the pre-operation phase is important for the researcher to observe proximity and visibility issues in simulated construction operations to analyze imminent hazardous situations that could arise during the construction phase. With these tests, the researcher is also capable of classifying interactions between construction entities as hazardous or not and ultimately justify the experimentation platform’s use for real-world tests.

3.4 Real-time Warning System

In the construction phase, the virtual environment was used to enable the spatial analysis in real-time to generate warnings for the affected personnel on site by using a detection system that utilized sensor data from real-world experiments. The enhanced proximity detection system shown in Figure 3.8, composed of sensors, was developed to monitor proximity and visibility issues present in typical construction operations and to generate effective warnings to reduce the emission of false positive alarms.

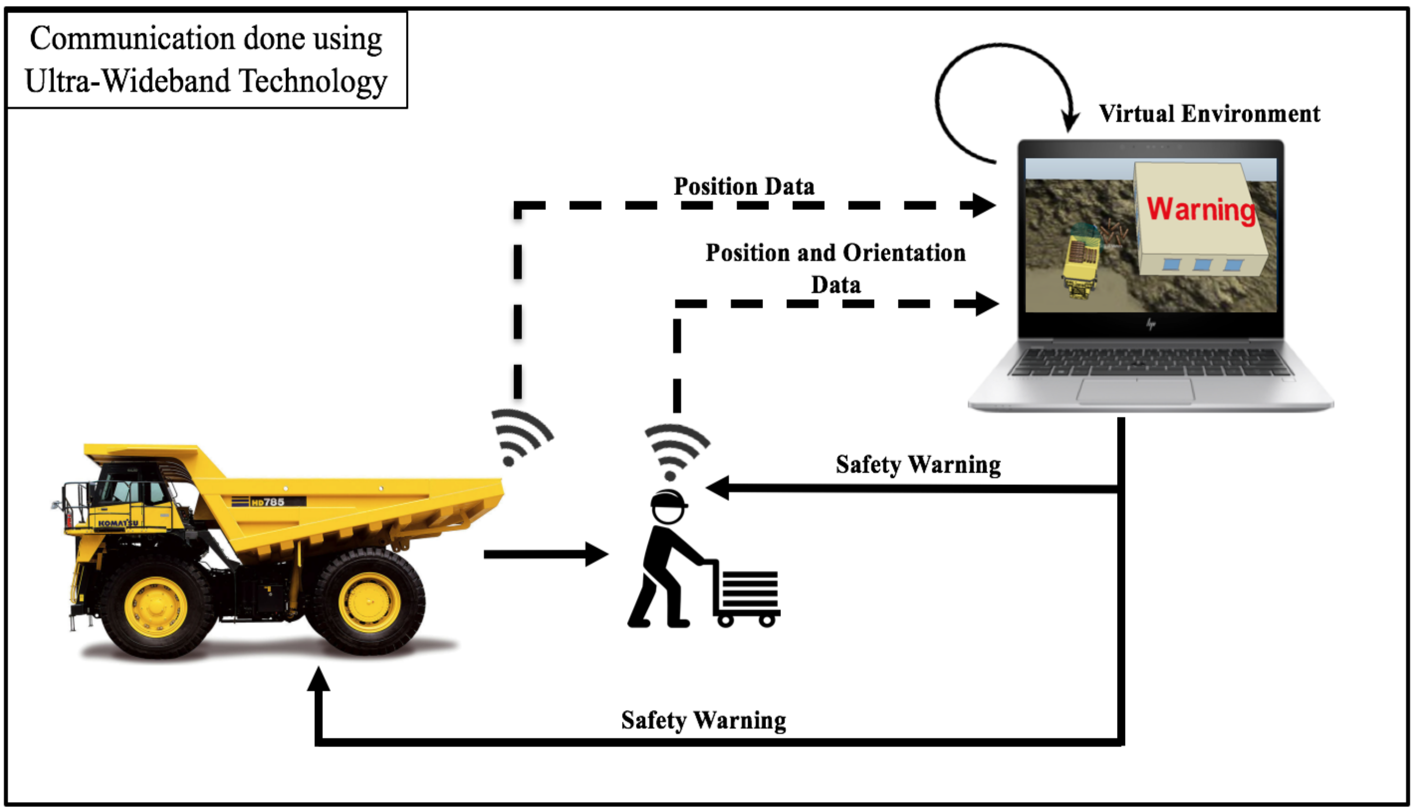

Figure 3.8 Enhanced Proximity Detection System Process

The first component discussed in this chapter is the hardware system that is made of three different real-time sensor boards that monitor the proximity and field-of-view of the construction entities selected and are attached to each entity involved. The signal relayed from the hardware systems attached to the entities will be sent to the V-REP simulation using UWB communication to identify when a safety warning should be returned to the affected personnel or equipment on site. The virtual environment will use the signal to identify hazardous situations and generate effective warnings to reduce the emission of false positive alerts. Second, the field-of-view aspect of this research included in the hardware system is discussed. Third, the location aspect of this study also a part of the hardware system, is discussed. The field-of-view and position monitoring are discussed to show the importance of these aspects being observed to reduce false positive alarms and the fatality rate caused by proximity and visibility issues. Next, the real-world experiments conducted to monitor the interactions of the various entities are discussed. Demonstrations based on fall and struck-by equipment incidents are performed in the real-world tests. Finally, the real-time sensor application in the virtual model used the sensor data collected from the hardware system and the real-world experiments to observe hazardous interactions and mitigate proximity and visibility issues. From here, the generation of accurate warnings was emitted to the affected personnel to eliminate the emission of false positive alarms that result from running current proximity detection systems.

3.4.1 Hardware System

The hardware system is composed of an Arduino microcontroller board, a Pozyx board, and a Global Positioning System (GPS) board shown in Figure 3.9. To collect useful and applicable sensor data, a code was developed for each sensor board to download the specific parameters pertaining to each entity's action. The three boards that make up the hardware system have different functions and characteristics that enable the system to collect data in real-time.

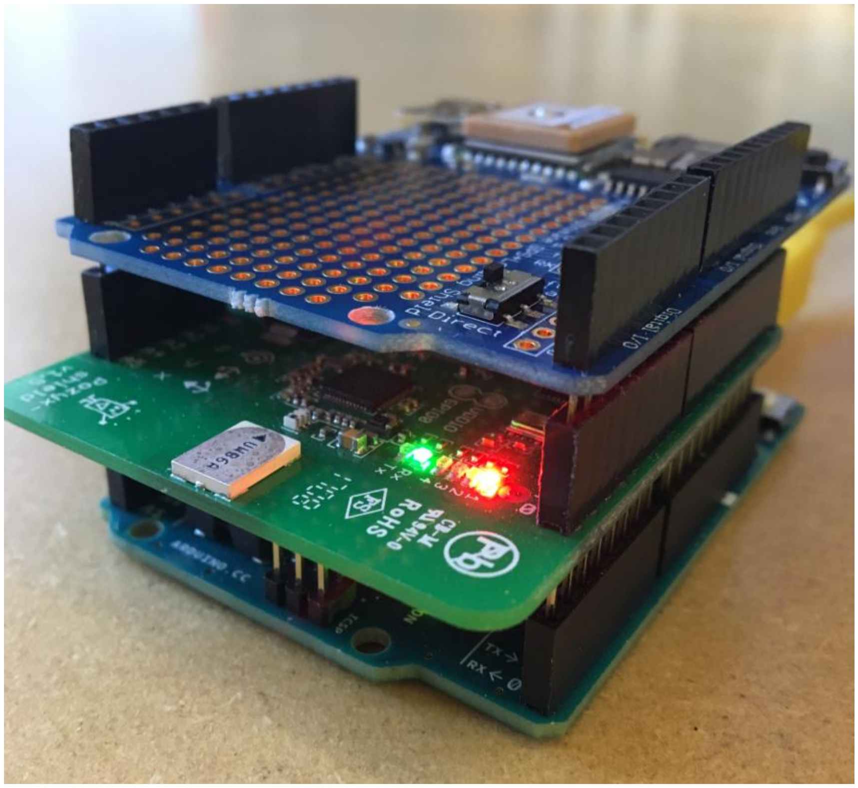

Figure 3.9: Hardware System: Arduino (bottom), Pozyx (middle), and GPS (top) boards

The Arduino 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 can affect its surroundings by controlling lights, motors, and other actuators. Arduino works with a written code in the Processing programming language. Arduino was implemented into this study because of its easy-to-use code and its ability to communicate with other boards and their functions. The Arduino code controls the orientation features of the Pozyx board (introduced later in this step), the GPS value accuracy, and the formatting of the values printed.

3.4.1.1 Field-of-View Aspect of Enhanced Proximity Detection System

To monitor worker field-of-view, a hardware solution that provides accurate communication between systems and localization called Pozyx was used. In order to achieve accurate data collection, the Pozyx system relies on UWB that enables communication for Arduino projects.

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. Applications of UWB include high-speed communication networks and data links, collision and obstacle avoidance, precision systems for personnel location, asset tracking, inventory control, and intelligent transportation systems (Teizer and Castro-Lacouture 2007). The accelerometer and gyroscope in this system was used to monitor the orientation of the workers-on-foot to observe if the workers have the equipment in their field-of-view and to prevent visibility issues on site. Unlike previous research (Cheng and Teizer 2012), the researcher did not use equations to calculate the heading of the workers due to the Pozyx board monitoring this aspect on its own. With this implementation, human error is reduced.

3.4.1.2 Positioning Aspect of Enhanced Proximity Detection System

To monitor the position of the construction entities involved in each case, a GPS board was used to obtain real-time position sensor tracking data. The GPS board attached to the system provided the virtual environment with an accurate location monitoring system. This system allowed the virtual entities to move in the virtual environment based on the real-world sensor data collection. Due to the different case studies being tested in various locations, the latitude and longitude coordinates set as the base for obtaining these values changed during each experiment. As previously mentioned, in order to convert the obtained latitude and longitude values into values that V-REP could interpret, a factor of 111,000 was multiplied to the values received from the GPS. By using this conversion, the virtual entity was better represented in V-REP. The signal from the GPS board to the corresponding satellite was the strongest when there were no obstructions such as trees or buildings interfering with the signal. Therefore, this combined GPS board and hardware system is most effective for construction projects outdoors. This data enabled the detection system to monitor the movements of the entities involved to identify hazardous situations and determine when to emit a warning to the affected personnel. This hardware was used in real-world studies by attaching the three boards to a worker’s hardhat shown in Figure 3.10 so that the field-of-view can be analyzed based on data collected when the worker moves or rotates their head throughout their daily tasks.

Figure 3.10: Hardware System Attached to Worker-on-Foot Hardhat

3.4.2 Conducted Real-world Demonstrations

When conducting the real-world demonstrations, each board was attached to the other with the Arduino board on the bottom, the Pozyx board in the middle, and the GPS board on the top as shown in Figure 3.10. To obtain accurate real-time sensor data from construction equipment and labor-intensive operations along with fall hazard situations, the hardware system consisting of the Arduino, Pozyx, and GPS boards was attached to each entity of focus. The detection system attached to the worker-on-foot was utilized to monitor the field-of-view and position of the worker in relation to the specific entity being detected for each case. A sensor was also attached to the 5-ton truck and passenger vehicle to monitor the position of the truck in relation to the worker in the virtual environment. To begin each real-world test and ensure the accurate virtual environment simulation based on the sensor data, the code associated with each detection system was downloaded prior to attaching it to the entity.

During the experiments, a UWB communication system, explained in Figure 3.8, was attached to the computer monitoring the virtual scene and was used to send information between the detection systems for each entity and the virtual model shown in Figure 3.11. This communication system made it possible for the sensor information obtained from each entity to be converted into data that V-REP could interpret and accurately display in the environment. To obtain accurate data, the UWB system must be in range of each sensor attached to the various entities or a nil value will be presented resulting in the virtual entities in the scene not portraying the real-world interactions accurately. Holding the UWB system on the outside of the computer guaranteed the best signal collected from both entity's sensors. When the sensors were working properly, field data was accurately obtained to display the potential struck-by equipment and fall incidents in V-REP.

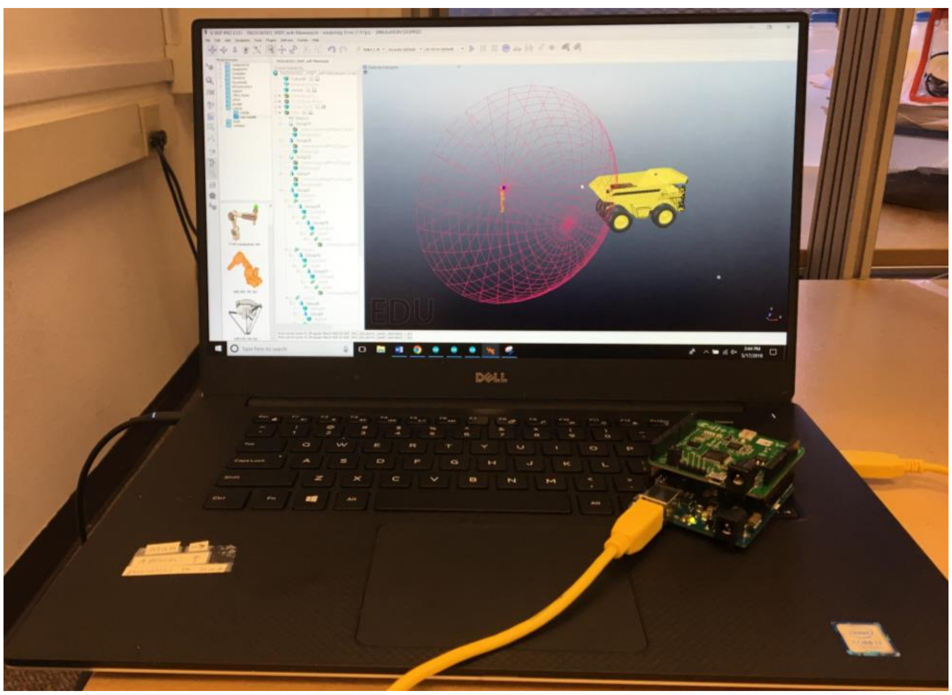

Figure 3.11: Data Analysis of Received Signal from UWB Communication System in Virtual Environment

3.4.3 Using Real-time Sensor in Virtual Model to Visualize and Track Entity Locations and Field-of-View

To observe real-world interactions between entities in V-REP, the combined hardware system was then attached to a power source and fastened to the worker-on-foot's hardhat, shown in Figure

3.10, the passenger vehicle, and/or the 5-ton truck specific to each case. Figure 3.12 shows the passenger vehicle with the enhanced proximity detection system attached above one of the back-seat windows of the vehicle. This location provided the best signal to the other systems being used for this experiment.

Figure 3.12: Hardware System Attached to Passenger Vehicle for Real-World Experiment

Figure 3.13 shows the 5-ton truck used in this study for one of the experiments conducted. By using the dump truck provided by Oregon State University, the experiments are relatable to real-world construction sites due to dump trucks being used frequently on many construction projects.

Figure 3.13: 5-Ton Dump Truck Used for Real-World Experiments

Figure 3.14 shows the truck's detection system attached to the gate of the truck to provide the highest accuracy in signal communication between the systems. The researcher chose to connect the hardware system to the top of the worker's hardhat to receive the best GPS signal for precise use in V-REP. The worker performed the tasks associated with potential fall and struck-by incidents to collect real-time data to be modeled in V-REP. From here, the field-of-view was analyzed based on sensor data collected and sent to V-REP to track when the worker moved or rotated their head. The location and orientation of the worker were both monitored through the safety rules-based system and movements of the associated virtual entity in V-REP. The location of the truck was monitored with the associated virtual entity in V-REP as well.

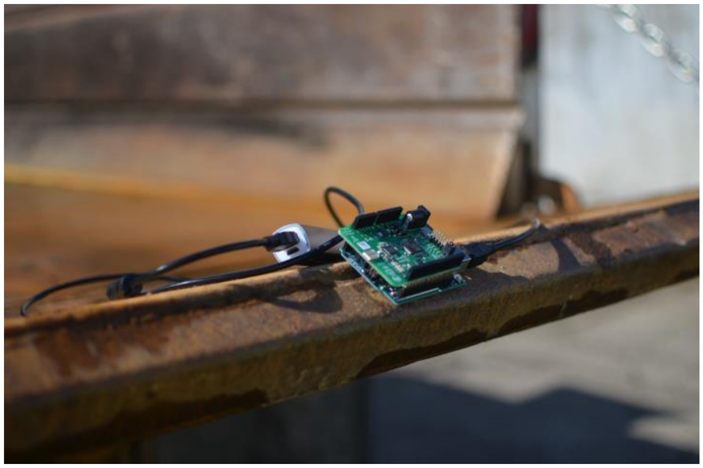

Figure 3.14: Hardware System Attached to Dump Truck for Real-World Experiments

In the V-REP scene, there are various virtual entities such as a mannequin, truck, text, sensors, and measurement tools that symbolized the different construction entities on site to simulate the dynamic nature of construction sites. The mannequin represents a worker-on-foot and the multiple movements that the laborers complete throughout the cases performed. The sensor in the real-world is attached to the top of the worker's helmet to obtain an optimal signal for the GPS. However, the V-REP sensor was placed on the back of the mannequin's head symbolizing the area behind the worker they do not have a clear view of. Placing the cone-shaped proximity sensor on the back of the worker's head, the researcher aimed to reduce the generation of false positive alarms by focusing on the scenarios where the worker was unaware of unsafe situations due to their back being directed towards the equipment or ledge. The researcher assumed that when a worker has their back towards other construction entities, they are unable to see those entities due to humans being restricted of 360-degree visibility. Sending a signal every time a worker is within close proximity to other entities is unnecessary and results in workers ignoring valid alarms to prevent unsafe situations. The researcher focused on only sending warnings to the workers when they 1) had their backs towards the other entities on site, which limited their field-of-view, and 2) were in close proximity to the entities. This enables the generation of accurate warnings to reduce the emission of false positive alarms rather than having workers ignore alarms whether they are effective or not. A measurement tool between the worker-on-foot and the truck was implemented into the scene to determine the distance between the two entities based off of the GPS locations provided through the signal of the detection system attached to the worker and vehicle shown in Figure 3.15.

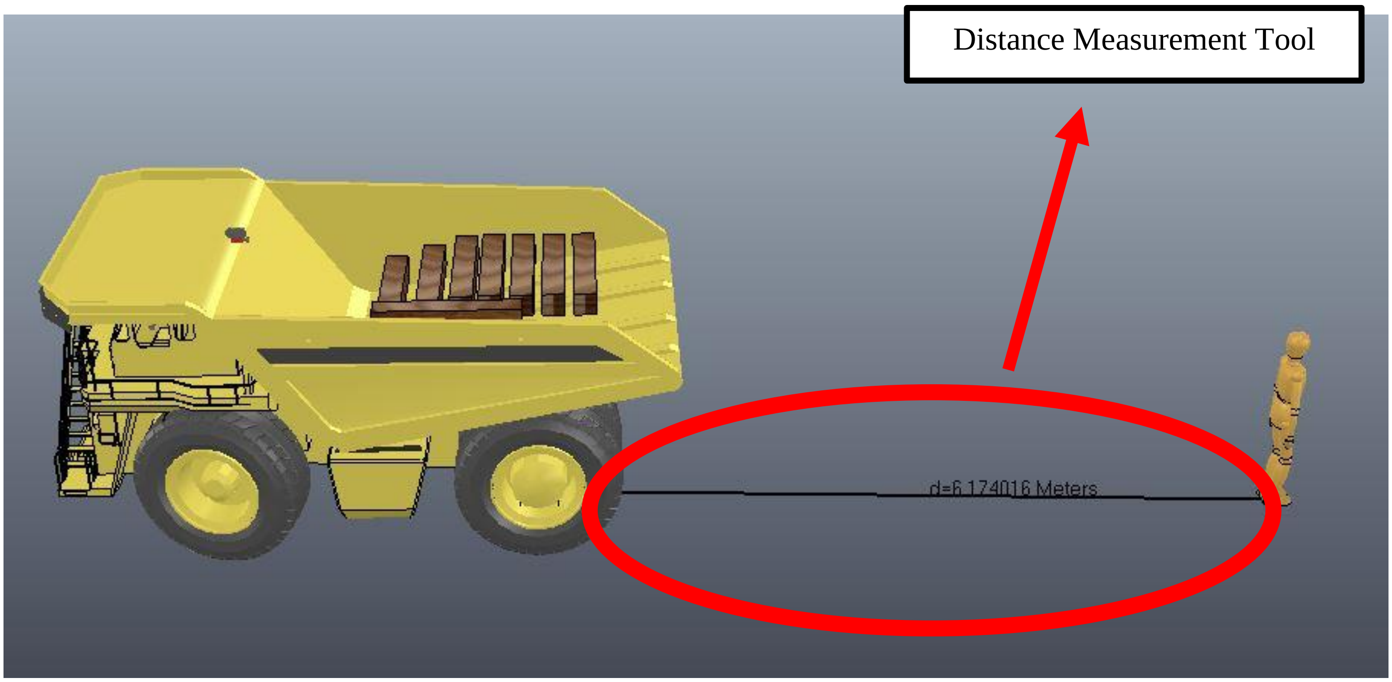

Figure 3.15: Distance Measurement Tool in V-REP

In V-REP, if the cone-shaped proximity sensor attached to the mannequin symbolizing the field-of-view of the worker was intersected based on the real-world movement of the detection system, then a hazardous situation that can potentially result in fatality has been recognized and V-REP will print a “Warning” text to alert the affected personnel of a hazardous situation.

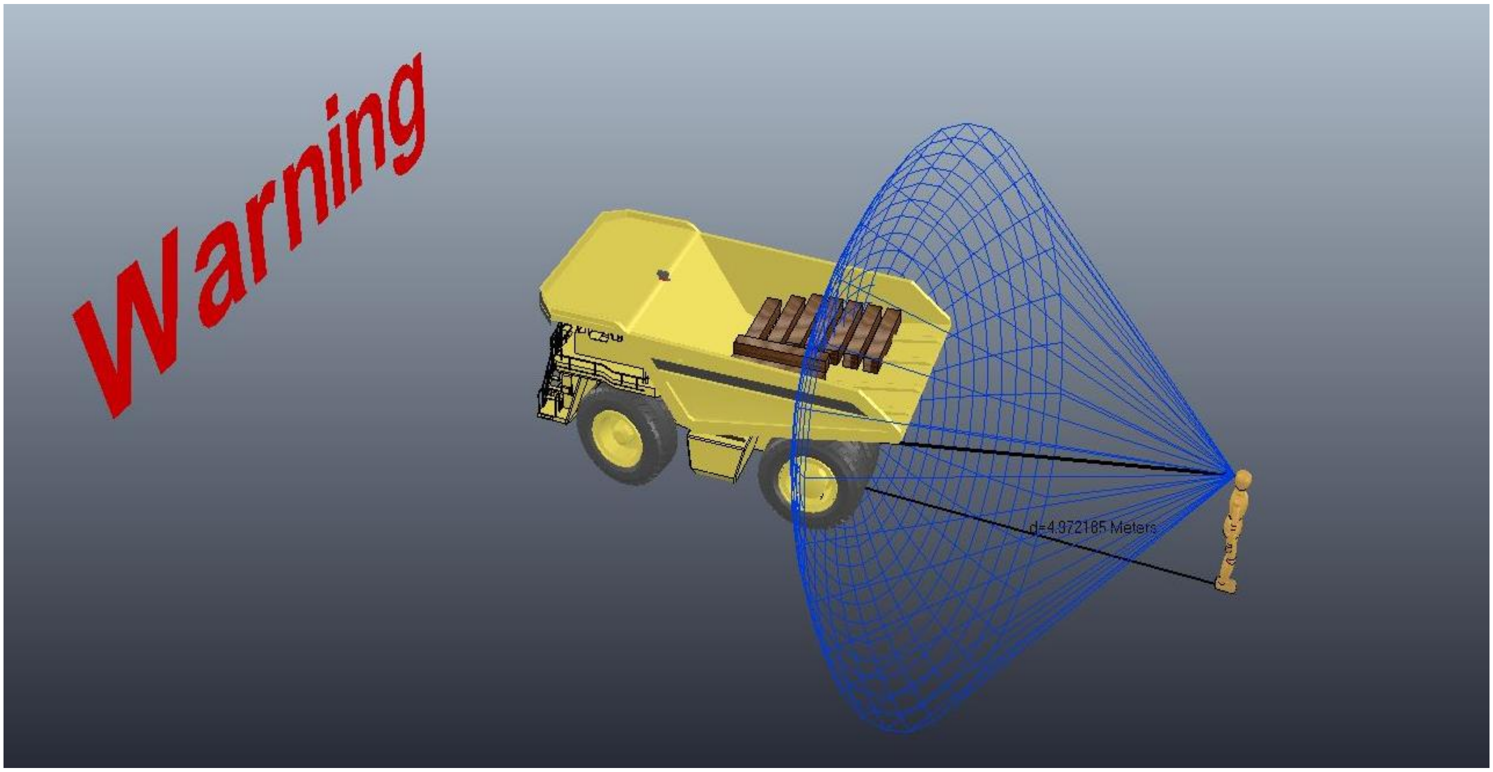

Figure 3.16: Warning Text Printed in V-REP to Alert Worker

Figure 3.16 shows the warning text projected in the virtual environment when a hazardous situation is detected and the cone-shaped proximity senor is disturbed. If a warning is detected in V-REP, a warning is emitted through sending a signal to an attached LED light from the virtual environment, to the UWB communication system, and then to the affected personnel on site. Figures 3.17 and 3.18 show the illuminated LED red lights attached to the hardware system for both the UWB communication and the worker-on-foot to signify the detection of a hazardous interaction.

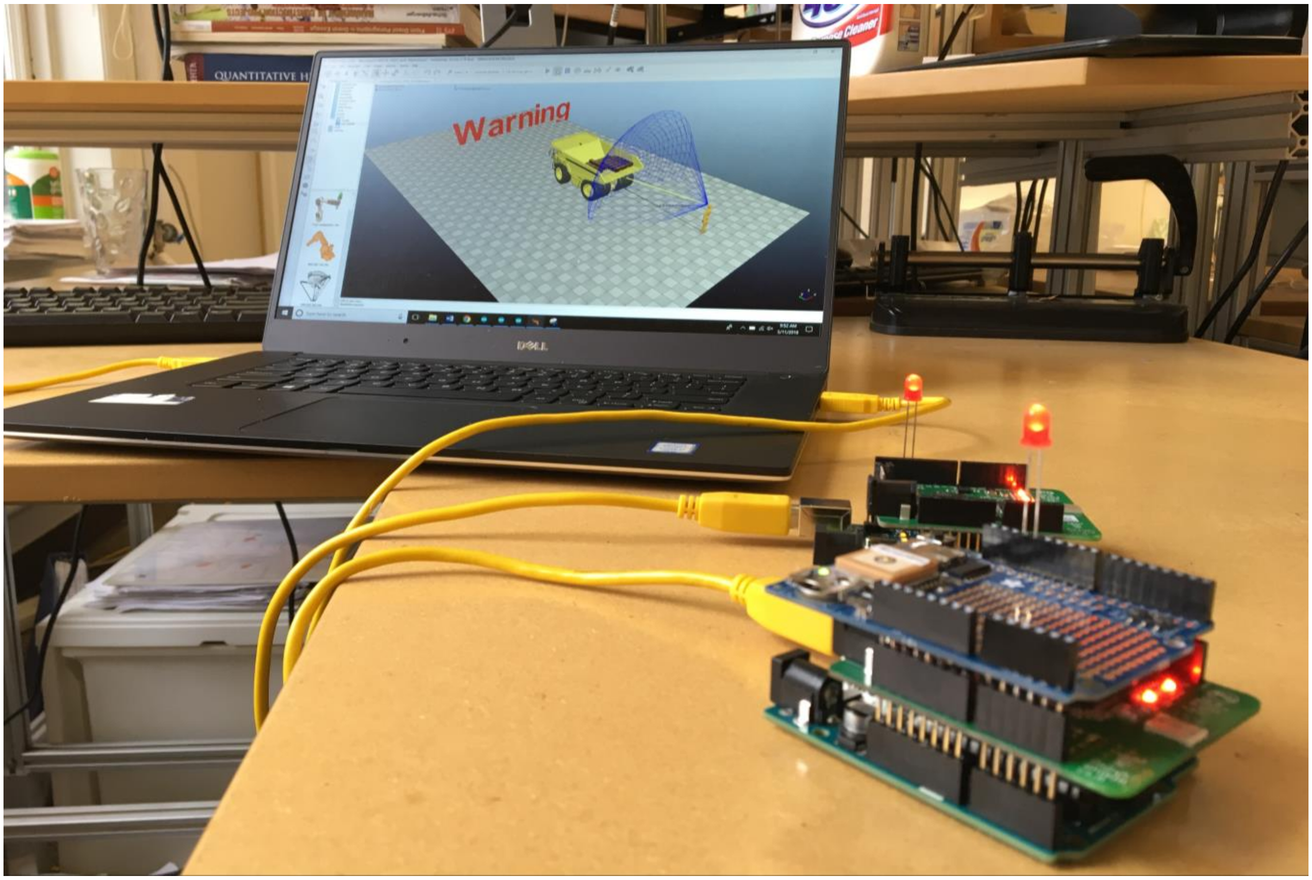

Figure 3.17: Physical LED Light Illumination Warning

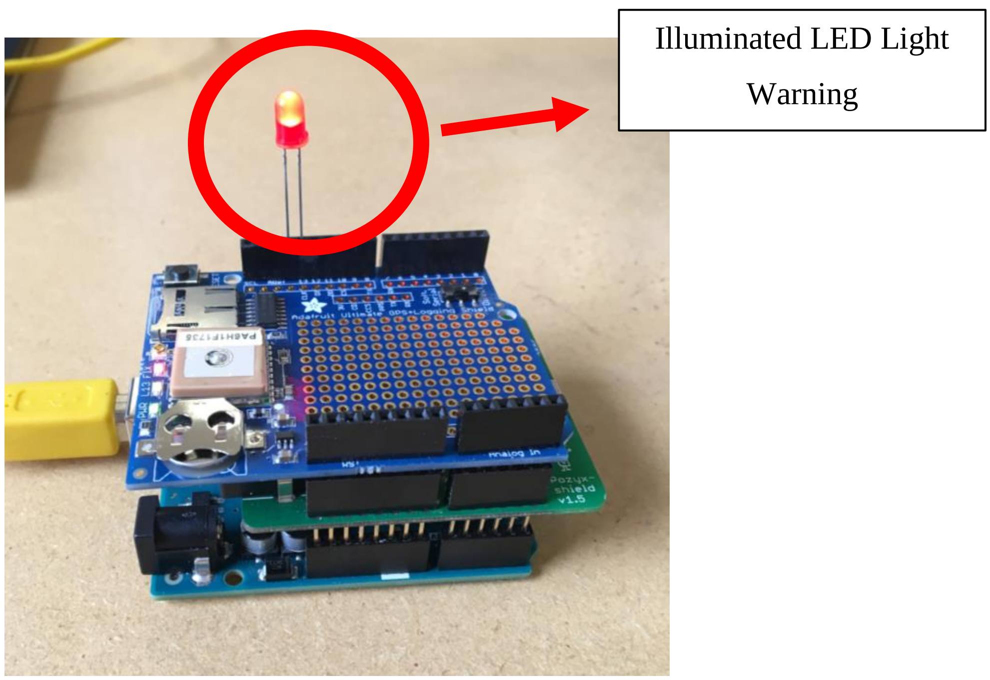

Figure 3.18: Close-Up of the Illuminated Warning LED Light

Due to poor lighting when conducting the real-world experiments, the LED warning tests were conducted indoors to show the functioning warning system. If the worker-on-foot is at a distance away from the equipment or edge that is greater than or equal to 13 to 30 feet and the cone-shaped proximity sensor is not intersected, then V-REP will print the text "Safe" shown in Figure 3.19.

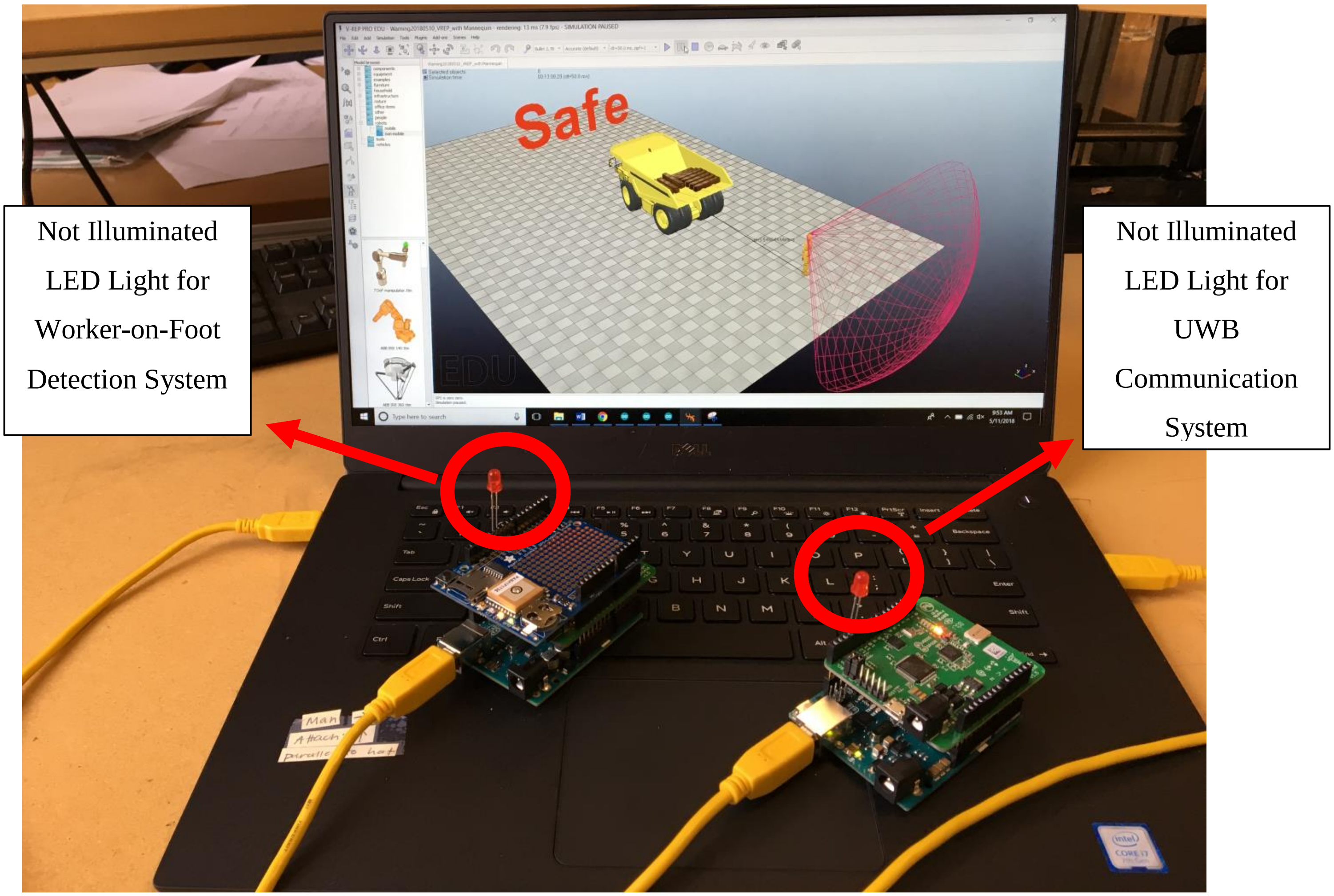

Figure 3.19: Worker is Safe and LED Warning is Not Illuminated

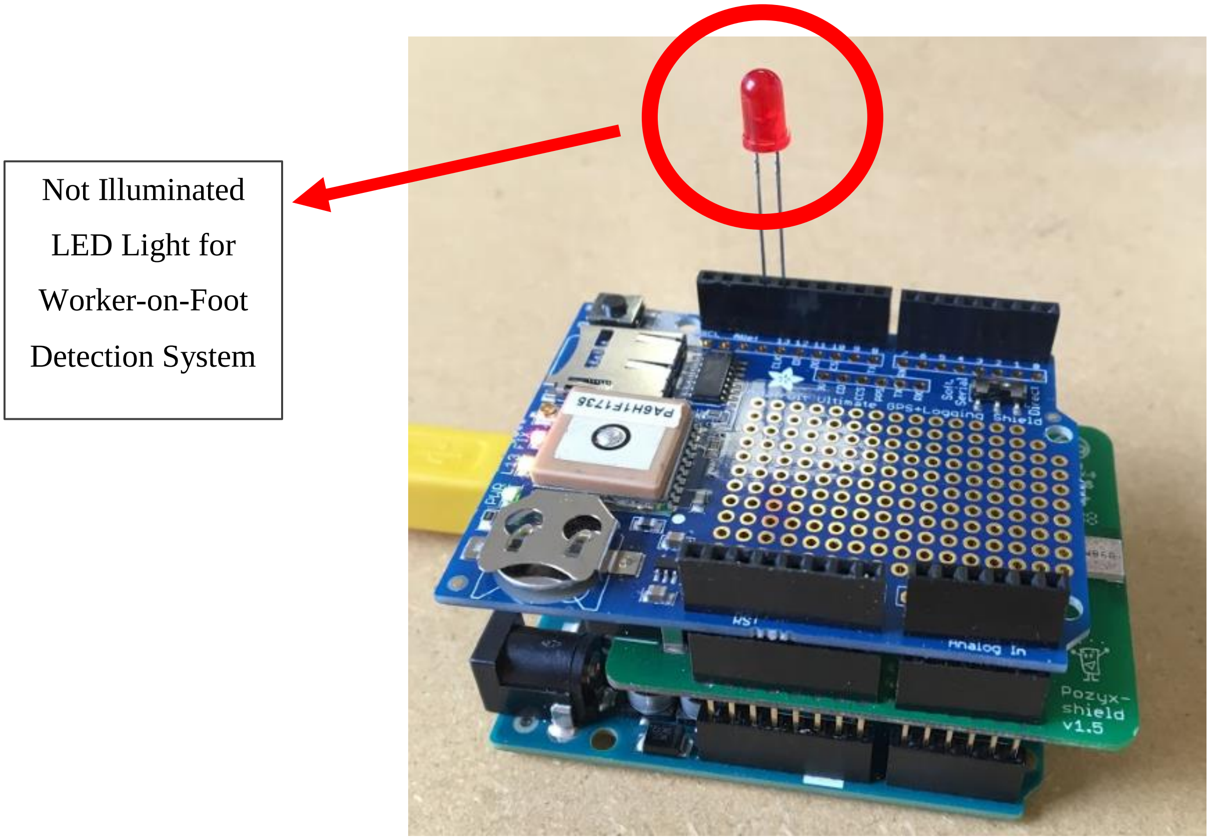

Figure 3.20: Close Up of the Safe LED Light

The device shown in Figure 3.20 was attached to the worker-on-foot's hardhat. The researcher decided to run the tests indoors to provide a clearer visual of the warning being sent. With these warnings being produced, the false-alarm effect will be limited on site and hazardous interactions between workers-on-foot and other construction entities will be reduced.

3.5 Methodology Chapter Summary

Using a virtual environment such as V-REP is ideal for this type of study due to it enabling the use of spatial analysis in real-time to accurately emit warnings when a proximity or visibility issue is detected and ultimately reduce the generation of false positive alerts. This visualization tool is beneficial to this study due to liability issues when running the real-world experiments, which made the methodology for this research difficult to validate with only real-world tests. Potentially hazardous situations in the real-world cannot be investigated on an actual construction site due to lives being put at risk, therefore virtual environments were used to present the unsafe scenarios (Chan and Louis 2017). Additionally, the use of the sensor based detection system mitigates visibility and proximity issues by sending a warning to personnel that are within close proximity to hazards and do not have the hazard in their field-of-view. The gathered data aided the researcher to determine proximities that were unsafe and verify that field-of-view positively contributes to improving worker related construction operations and effective warnings are emitted to reduce the generation of false positive alarms. By using these technological advancements in the controlled real-world testing, the researcher was capable of developing a field-of-view tool for workers-on-foot to use in order to enable decision makers and management teams to analyze and observe areas in these interactions that need improvement to reduce the fatality and injury rates of the industry.

CHAPTER 4. Experiments and Results

The developed methodology was validated through applying the system to various case study scenarios to identify and observe areas in an equipment intensive construction operation and fall risk scenarios that could create unsafe conditions. Each case study was designed to evaluate the effectiveness of the proposed proximity and field-of-view detection technology in a typical construction environment. The experiments attempted to simulate a construction environment for testing the enhanced proximity detection system while ensuring the safety of subjects during the process. To determine hazardous areas in these interactions, field-of-view of workers-on-foot was observed by using the developed hardware system to monitor the position and orientation of worker. The proximity and field-of-view detection system involved in these experiments used a wireless communication line consisting of UWB radio technology. The signal received from the communication system was used in a virtual environment, V-REP, to enable spatial analysis in real-time that resulted in the generation of accurate warnings to the affected personnel. This approach focused on improving the safety of workers-on-foot in the vicinity of fall hazards and heavy equipment in a typical construction work site. The results show the importance of monitoring field-of-view to limit the amount of false positive alarms generated and sent to workers. Each experiment is described and the results are reported for each case study. The first study focuses on fall hazard scenarios and the three case studies presented after, focus on improving and observing struck-by incidents.

4.1 Fall Hazard Case Study

Construction work usually involves working at heights and in complex work environments, which constitutes the industry as being riskier in terms of worker health and safety (NIOSH 2004). Due to fall accidents being the main cause of injuries and fatalities in the U.S. construction industry, the researcher decided to include a case study involving a fall scenario (Hinze and Gambatese 2003; Bobick 2004; Hu et al. 2011). Fall incidents occur at different heights due to the uniqueness and complexity of each construction site project. According to a study conducted by Kang et al. (2017), more than 80% of fall accidents occurred from a height of less than 9.1 meters. This statistical evidence serves to alert safety regulators and agencies of the need to change the current fall safety programs implemented on site. To reduce these incidents from occurring and to improve the current safety programs for these hazards, the developed proximity and field-of-view detection system monitors the orientation and position of the worker. The first subsection discusses the applicable fall hazard scenarios that this case, where the worker-on-foot is working close to a ledge, was based on. Second, the experiment conducted for this case study is explained and the results obtained are reported.

4.1.1 Applicable Fall Hazard Scenarios on Construction Sites

There are many different scenarios where workers are exposed to various fall hazards. The case study simulated a fall hazard scenario that focused on the worker moving towards an unsafe ledge or area on site. These incidents can be seen when workers are moving large materials that obstruct their vision due to the characteristics of the item they are transporting. The workers may not have the opportunity in a situation like this to be completely aware of their surroundings and can unsafely approach a ledge or a hole in the building. This could result in a worker falling into the hole or off of the ledge and injuring themselves or others around them. Fall hazards are also observed if there are limited implementations of guardrails on site. If the worker-on-foot is expecting a guardrail to be on a ledge and there is not one provided, then a fall hazard can result from this assumption due to the worker's complacent attitude.

4.1.2 Fall Hazard Real-World Experiments and Results

To simulate this type of situation, an area on the ground in the real-world was labeled as the unsafe area and a sensor was placed in that zone shown in Figure 4.1. This study used the enhanced proximity detection system to mainly focus on the system attached to the worker-on-foot's hardhat due to heavy equipment not being involved in many fall incidents from projects dealing with heights. To begin the case study, the code for each system, the ledge, worker-on-foot, and the UWB communication system used to communicate signals between these two detection systems, was downloaded to the appropriate detection system board. From here, the boards were calibrated and tested in

V-REP to ensure that the GPS location system and the Pozyx orientation monitoring system were both operative. The functioning systems were connected to the affiliated entities. To receive optimal GPS coordinates for the system, the detection system was attached to the top of the hardhat on the worker-on-foot and on the ledge shown in Figures 3.10 and Figure 4.1 marked by the hatched area.

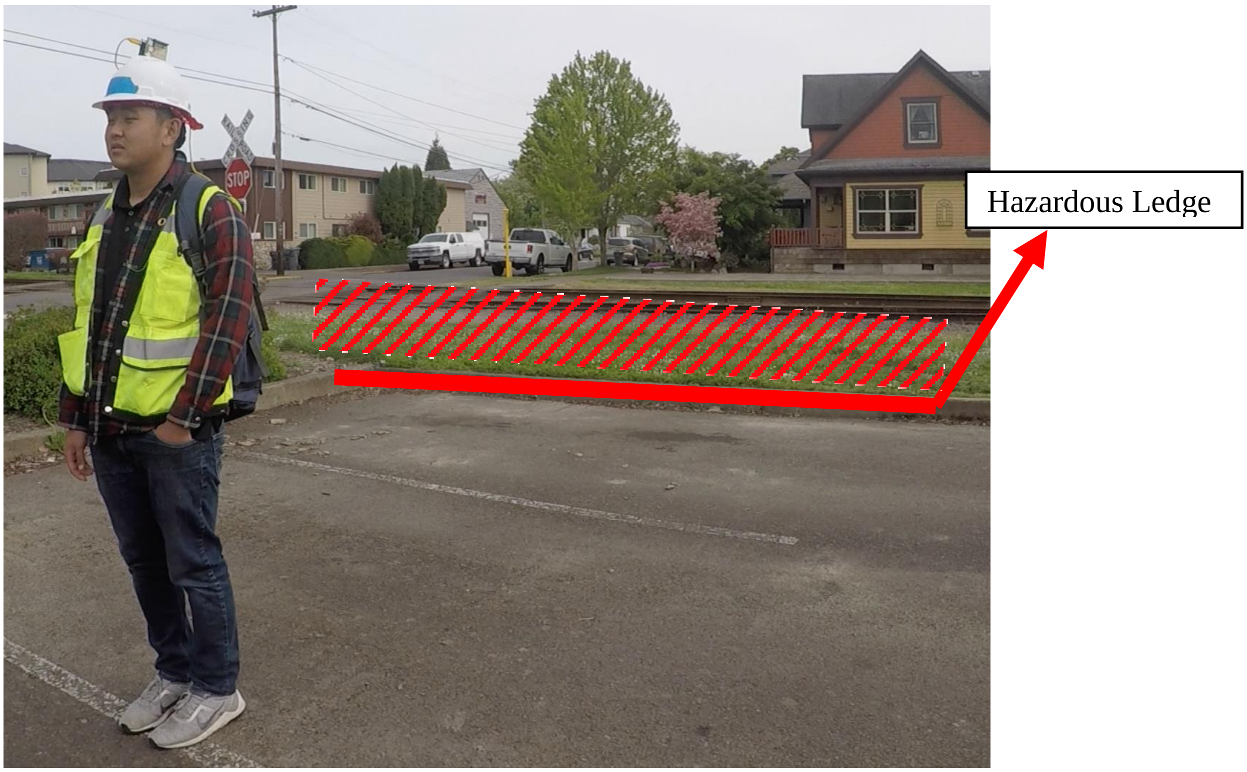

Figure 4.1: Hardware System Location for Fall Hazard Ledge Experiment

To monitor the movement of the worker throughout this study, the GPS location of where the worker would begin and end were obtained first. The hardware systems attached to the ledge and the hardhat had to both be in range with the UWB communication system connected to the computer to provide ideal results in the virtual scene. A parking lot and raised sidewalk on Oregon State University's campus were used to simulate the worker approaching an unsafe ledge during a high-rise construction project shown in Figure 4.1. The worker moved with their back facing the raised sidewalk to simulate an unsafe situation where a worker is not aware of a ledge in a building construction project. In the virtual environment, the worker with the attached cone-shaped proximity sensor are placed on top of a building modeled in V-REP shown in Figure 4.2.

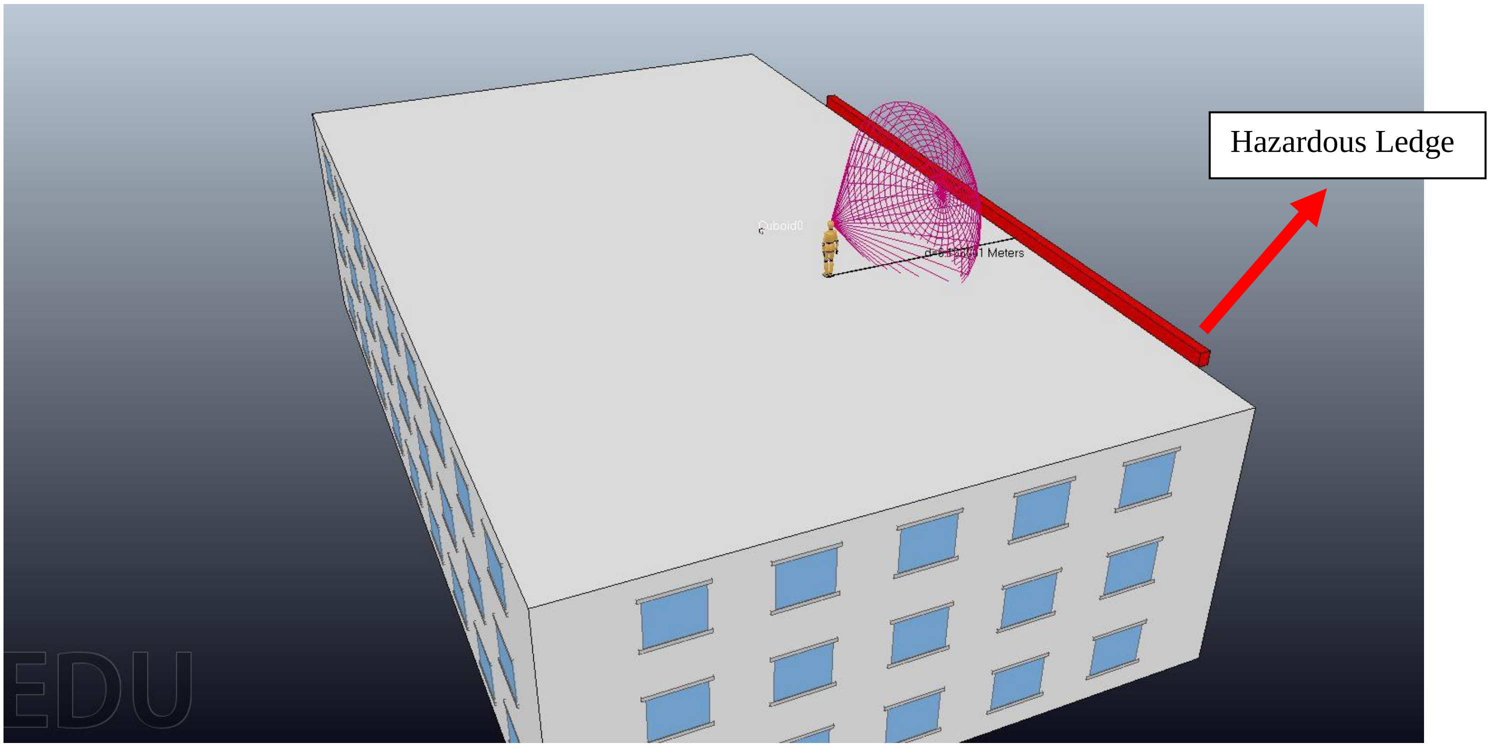

Figure 4.2: Fall Hazard Scenario Modeled in V-REP Worker is Safe (Red Cone-shaped proximity sensor)

A red rectangle was created in the scene to symbolize the hazardous ledge and was assigned to be detected by the mannequin and the cone-shaped proximity sensor to emit an accurate warning. If the worker was within 4 meters or approximately 13 feet away from the ledge and did not have the cuboid in their field-of-view, then a warning was sent through the virtual scene by alternating the colors of the sensor from red (Figure 4.2) to blue shown in Figure 4.3.

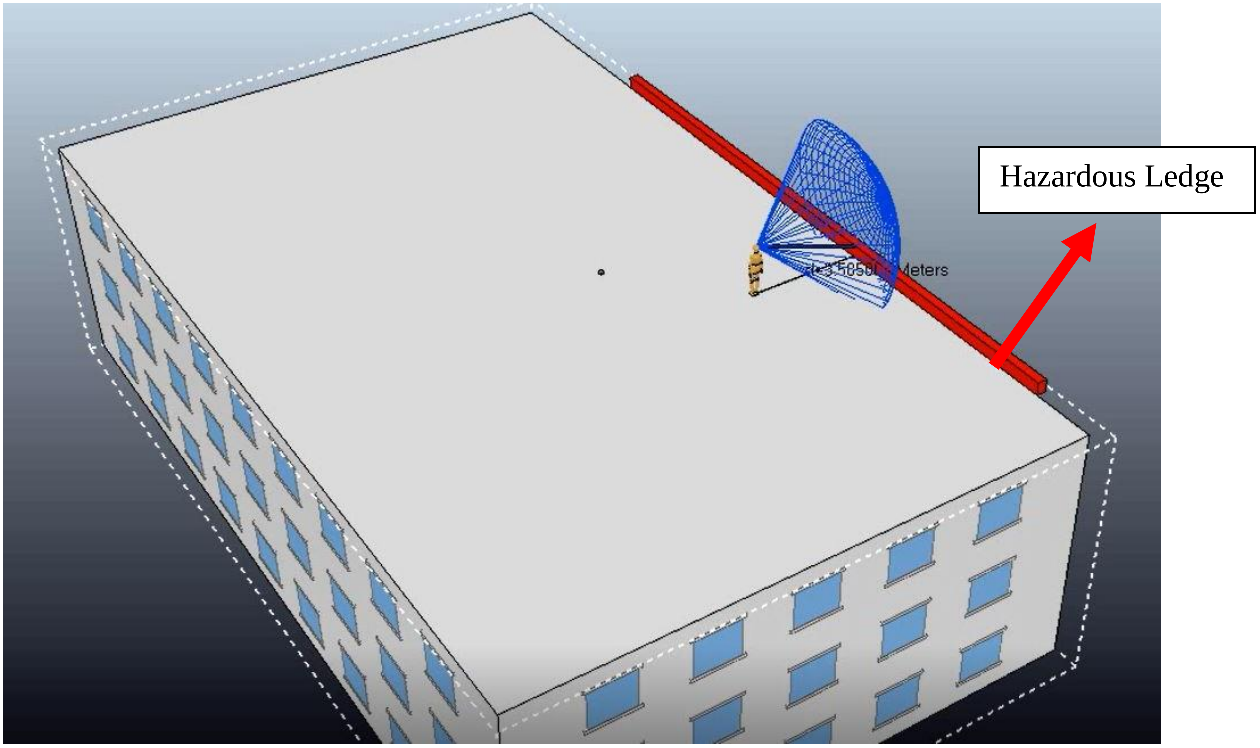

Figure 4.3: Fall Hazard Scenario Modeled in V-REP Warning Sent (Blue Cone-shaped proximity sensor)

A warning was sent every time the worker was near the rectangle representing the ledge proving the enhanced proximity detection system valid. Four tests were completed to allow the GPS signal to make the appropriate adjustments to ensure that the movement from the worker in the real-world was mimicked by the mannequin in the virtual scene.

4.2 Struck-by Equipment Incident Initial Case Study

Based on the safety needs of the construction industry pertaining to struck-by equipment incidents, a proximity and field-of-view detection system was developed in this research. The developed detection system was evaluated in various settings due to the hazards focused on in the study varying in classification of tasks performed. The cases developed evaluated the different capabilities of the system for each incident under simulated construction environments. The first case involved the worker-on-foot moving back towards a stationary piece of equipment. This test was used to simulate a worker moving into the heavy equipment's blind spot or moving into the path of the heavy equipment without being aware of the operation taking place. The first subsection discusses the applicable struck-by equipment construction site scenarios that this case, where the worker-on-foot is moving on site and the equipment is static, are based on. Second, the experiment conducted for this initial case study is explained and the results obtained are reported.

4.2.1 Applicable Struck-by Equipment Scenarios on Construction Sites: Worker-on-foot Dynamic and Equipment Stationary

There are multiple construction operations that may involve situations where the worker is moving towards a stationary piece of equipment. For example, a raking or screeding job where a worker is using tools to smooth out materials laid down by dump trucks. Although the worker may not be fatally injured in these scenarios, this initial study aided the researcher in developing the case studies and verifying that the system is capable of detecting worker field-of-view and proximity to other entities on site. Workers involved in these tasks typically have their heads down to move and smooth the materials dropped off by the equipment, resulting in their field-of-view narrowing and their awareness possibly decreasing when focusing on the task at hand. Similarly, most construction sites need to lay out zones for different workers to complete various tasks specific to that location or surveyors need to lay out certain working zones as well. This puts the worker in a situation where they are also completing their tasks with their heads down and moving around with the potential of not checking their surroundings before completing their tasks, which puts them in danger when working around heavy equipment and in congested job sites. Another task involves a spotter directing an operator from one side of a construction site to the other. The spotter may forget to check their surroundings when directing the equipment to another location on site and may cross into the path of another operating piece of heavy equipment causing them to be involved in struck-by incident due to the worker being unaware of the working conditions around them.

4.2.2 Initial Struck-by Equipment Experiment and Results

To simulate these construction operations, a student wore the hardhat with the field-of-view and proximity detection system attached and performed tasks similar to the cases mentioned above. The steps taken to conduct this study were completed by utilizing three researchers/students to perform each required task. Similar to the setup for the first case study, the code for each detection system, the truck, worker-on-foot, and the UWB system used to communicate signals between these two systems, were downloaded to the appropriate detection system board. From here, the boards were calibrated and tested in V-REP to ensure that the GPS and Pozyx orientation and location monitoring systems were accurately operative. To enable observers to obtain a clear understanding of the hazardous situation being displayed, the researcher rotated the truck in the virtual scene prior to running the simulation. The functioning hardware systems were connected to the affiliated entities. To receive optimal GPS coordinates for the system, the system was attached to the top of hardhat on the worker-on-foot and on the gate of the dump truck shown in Figure 3.10 and Figure 4.4.

Figure 4.4: Detection System Attached to Gate of Dump Truck

The detection system attached to the truck and the hardhat had to both be in range of the UWB communication system connected to the computer to provide ideal results in the virtual scene. When the systems were set up and running properly, the worker-on-foot was instructed to move towards the stationary truck with their back facing the rear of the truck. Once the worker was in a certain range set by the researcher (approximately 20 to

30 feet away from the truck) and had their back towards the truck, the entity assigned to be detected by the mannequin for struck-by equipment hazard cases, simulating a hazardous interaction such as those mentioned above, a warning was sent. The warning was emitted based on the received sensor data and real-time spatial analysis performed in V-REP shown in Figure 4.5. When the worker moved forward, away from the truck, the text in the virtual model displayed “Safe”.

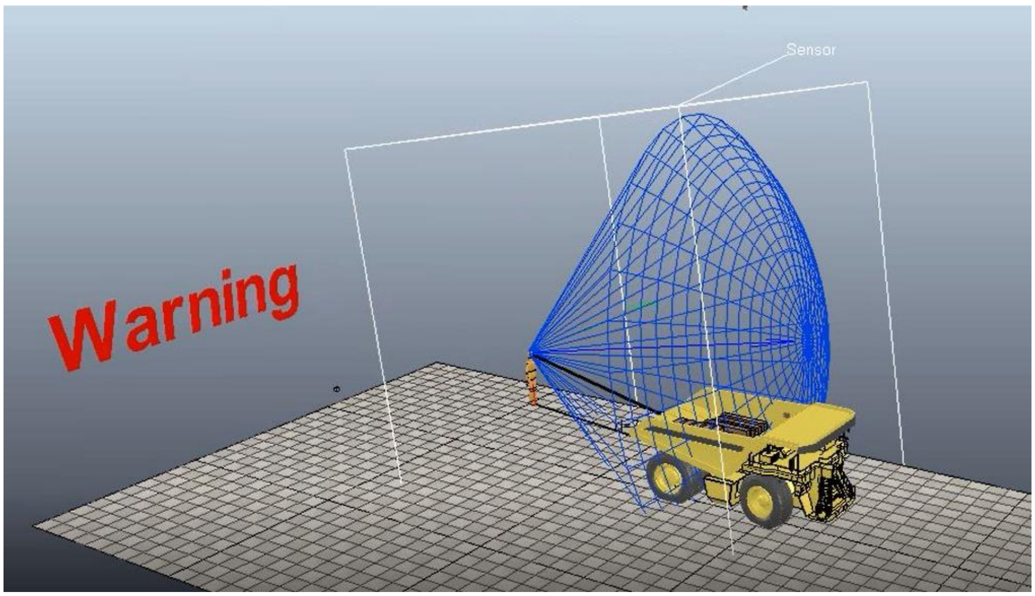

Figure 4.5: Warning Text Displayed for Real-World 1 Experiment

This warning will provide management teams with the ability to stop the operation before workers are fatally injured or implement the appropriate solutions to prevent this type of incident from occurring in future interactions. Additionally, this system will effectively minimize the amount of false positive alarms emitted to provide workers-on-foot with valid warnings and reduces proximity and visibility issues.

This case study was conducted at the facility management services office on Oregon State University’s campus. The weather during this study was approximately 40-50 degrees Fahrenheit with a light wind. Site conditions consisted of a gravel ground with some vegetation in certain parts of the study area. A research team member equipped with the detection system and the proper PPE approached the 5-ton dump truck provided by the facility management department shown in Figure 4.6.

Figure 4.6: Enhanced Proximity Detection System Tested in Real-World Struck-By Equipment Case 1

As the researcher approached the stationary dump truck in reverse, the mannequin representing the worker-on-foot in the virtual model also moved in the scene towards the modeled truck. During these movements, the cone-shaped proximity sensor was red symbolizing that the worker is not in a hazardous situation. For this initial study, the parameters for the sensor were set to send a warning when the worker-on-foot was 9 meters or approximately 30 feet away from the truck. When the worker-on-foot and the mannequin virtual entity in the virtual environment were in close proximity and oriented away from the truck, the proper warnings were successfully sent through the virtual environment identified in Figure 4.5. A blue sensor is displayed when there is a hazard detected. When the worker-on-foot in the real-world and the mannequin in the virtual environment approached the truck, and were oriented towards the truck, the worker was deemed as safe. A text projecting “Safe” was visible in the visualization when the worker was in this position and orientation shown in Figure 4.7. This method was repeated four times, to ensure the accuracy of the system and to give the GPS signal time to adjust. Three out of the four runs were successful, with the worker-on-foot virtual entity receiving a warning in the virtual environment.

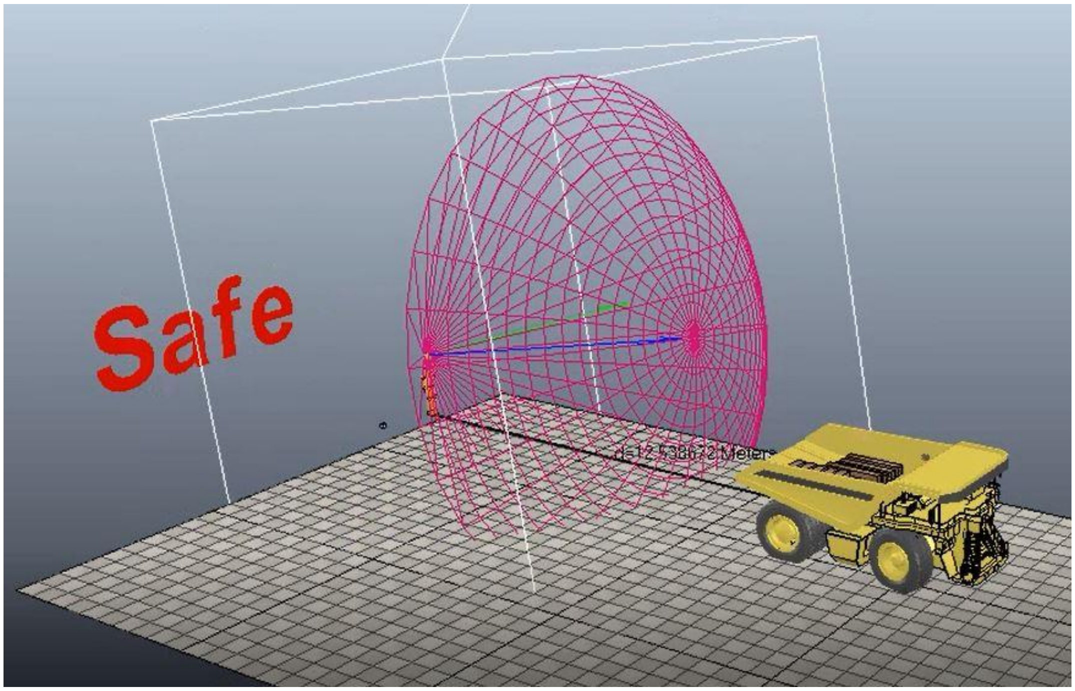

Figure 4.7: Safe Text Displayed for Real-World Case 1 Worker Experiment

4.3 Struck-by Equipment Incident Case Study 2

The second case focused on situations where equipment moves through construction sites and the worker-on-foot remains static. This case was used as an additional initial study to ensure the detection system functioned properly when other entities on site were also dynamic. The first subsection discusses the applicable struck-by equipment construction site scenarios that this case is based on. Second, the experiment conducted for this case is explained and the results obtained are reported.

4.3.1 Applicable Struck-by Equipment Scenarios on Construction Sites: Worker-on-foot Stationary and Equipment Dynamic

Situations where workers on site are static occur often, which cause many injuries and fatalities. For example, construction projects require a lot of team work and communication, which results in workers using cellphones throughout their daily tasks.

When workers use their cellphones, they become distracted and lose awareness of their surroundings, leading to potential fatal incidents between other moving entities on site. In addition to this scenario, a worker bending down to drop an item off and pick a different item or tool up contributes to this type of incident due to the worker possibly dropping into the blind spots of the equipment by reducing the amount of visibility points of their body when they move down towards the ground to retrieve and unload an item. Another construction scenario similar to this, involves the utilization of spotters for equipment operations. Although the equipment operator should be checking their blind spots and not solely relying on the direction of the spotter, an operator inspecting their blind spots is not always guaranteed. Spotters are put at high risk when static due to many factors such as focusing on the equipment operation they are assigned to and not being aware of other operations occurring around them or not having the proper communication tools to direct the operators, which is important because most sites have excess noise in other locations on site. Whether the workers are assigned to be a spotter or not, by directing traffic and equipment operations could lose track of other operations occurring on site due to the workers focusing on their current task of directing one operation. This can result in the worker moving into the path of another equipment operation occurring on site causing an unsafe scenario on site. The enhanced proximity detection system developed in this research relied on monitoring the field-of-view of each worker and the proximities between equipment and workers-on-foot and visualizing these scenarios in a protected virtual environment to reduce these situations from occurring.

4.3.2 Struck-by Equipment Case 2 Experiment and Results

To simulate these situations, the student stood in an open parking lot while the equipment, a passenger vehicle, approached the student in reverse. A passenger vehicle was used to simulate a piece of construction equipment due to liability issues and proprietary issues of obtaining equipment to perform these tasks without potentially placing both the operator and researcher in danger shown in Figure 4.8.

Figure 4.8: Detection System Tested in Real-World Struck-By Equipment Case 2

The researcher stood with their back towards the reversing equipment to represent situations where both entities do not have the ability to see one another on site. The steps taken to conduct the second case study were similar to those used in the first case study to a certain degree. Setting this study in the real-world and virtual environment were identical to the first case study, but the interaction between the truck and the worker differed. First, a passenger vehicle was used to replace the truck used in the first case study due to liability issues for the student. Instead of having the worker approach the equipment, the passenger vehicle approached the worker in reverse. Once the vehicle was within the specified range both in distance and orientation deeming the interaction as hazardous, the virtual environment projected a warning in the scene. An accurate warning was sent to the worker-on-foot through an LED light illuminating on the UWB communication system connected to the compute and the worker-on-foot detection system presented by Figure 3.18. These case studies were used to ensure that the systems were operating precisely to use for the third study where both entities were traversing.

The case study was performed in a parking lot on Oregon State University's campus, which provided a smooth path for the researcher to work on. During this study, the weather was approximately 50-60 degrees Fahrenheit with winds up to 12 mph. A range of 6 meters or approximately 20 feet was set for the sensor on the mannequin. When the vehicle was within the specified range of the worker, the virtual environment emitted a warning through the scene shown in Figure 4.9.

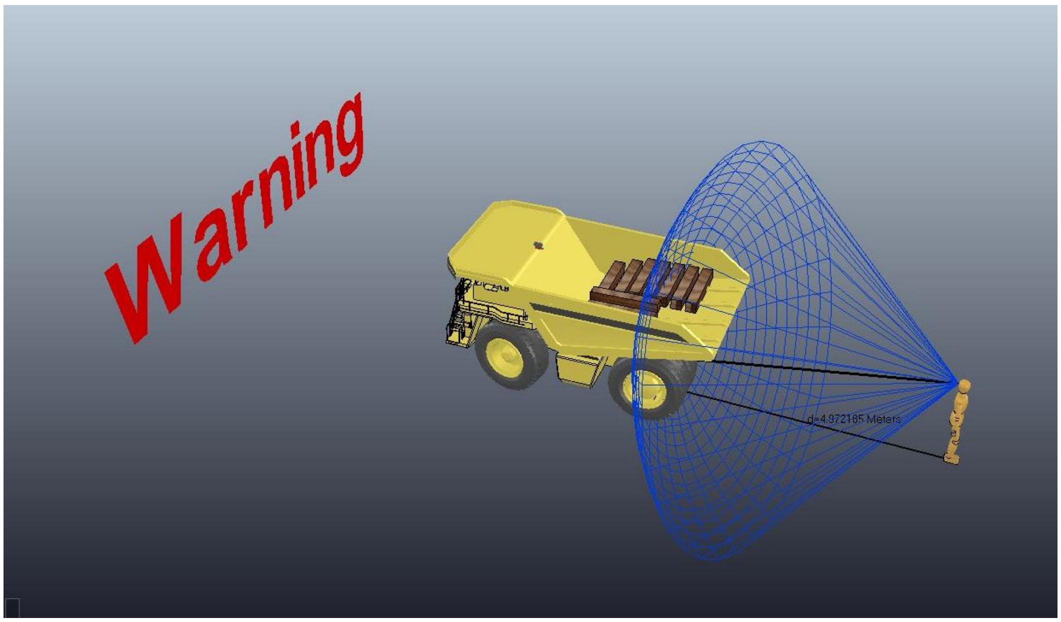

Figure 4.9: Warning Text Displayed for Real-World Case 2 Experiment

The operation was then stopped. To show the effectiveness of the enhanced proximity detection system, the worker faced the vehicle and the text in the virtual scene projected “Safe”, due to the worker having the vehicle in their field-of-view shown in Figure 4.10, and mentioned previously, by having the cone-shaped proximity sensor component not directed towards the truck.

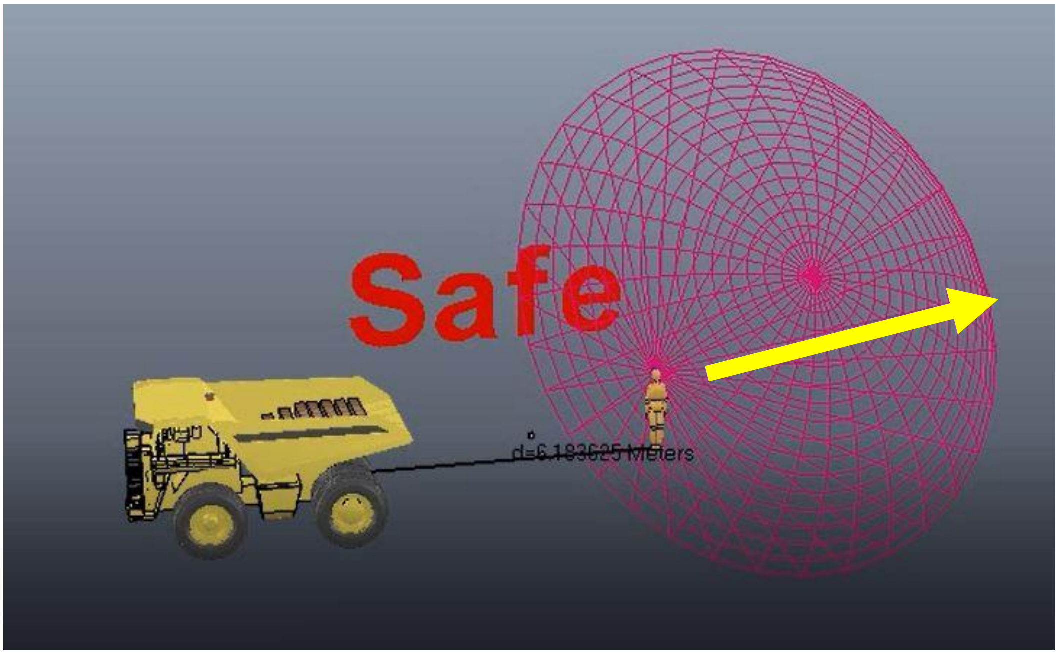

Figure 4.10: Worker has the Truck in Field-of-View

The worker then oriented their back to the vehicle and the "Warning" text was projected again presented in Figure 4.11. Five tests were completed for this case study to ensure that the GPS signal was functioning properly and to identify accurate warnings needed to be sent to the worker.

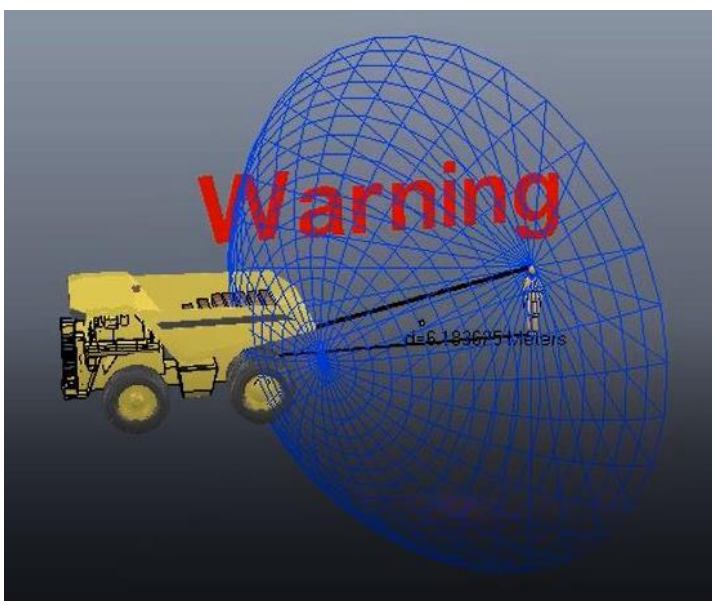

Figure 4.11: Worker Does Not Have the Truck in Field-of-View

4.4 Struck-by Equipment Incident Case Study 3

The final case for this study concentrates on situations where both entities are dynamic, which represents a majority of the construction activities present on site. As mentioned before, there have been multiple studies conducted that have developed proximity detection systems. However, most of these experiments limit field tests to always having one entity in the study stationary. This does not depict the dynamic nature of real-world construction sites and limits the studies. By conducting an experiment where both entities are dynamic, this research aimed to accurately use real-time sensor data and virtual modeling to generate effective and accurate warnings specifically when a hazard is within close proximity to the workers-on-foot and out of their field-of-view to limit the generation of false positive alarms. The first subsection discusses the applicable struck-by equipment construction site scenarios that this case, where both construction entities are moving, was based on. Second, the experiment conducted for this innovative case is explained and the results obtained are reported.

4.4.1 Applicable Struck-by Equipment Scenarios on Construction Sites: Both Worker-on-foot and Equipment Dynamic

There are many scenarios on construction sites where workers-on-foot and equipment operations cross paths, leading to many hazardous interactions. For example, loading and unloading material operations require a large amount of movement from workers-on-foot and heavy equipment. In a congested area, these interactions become hazardous for both entities due to the workers frequently moving behind the equipment to transport materials from the drop-off spot to a different location. This puts the workers in danger due to most of the workers becoming complacent with their work and do not think of this simple task as being harmful to them. If the proper precautions are not implemented then the workers have a higher chance of getting injured if they do not communicate with or notify another worker on site of what they are doing. Complacent and comfortable workers are at a high risk to be injured in these situations due to their attitude towards their jobs. This outlook can lead these workers to wandering into the blind spot of a piece of equipment on site. In result of this viewpoint, injury and fatalities have a higher possibility of occurring. Workers that are not aware of their surroundings because they are distracted such as walking and talking to a colleague on site can also lead to these struck-by incidents. The workers could potentially travel into an equipment operation path, which would lead to a high chance of injury. Another scenario where distractions could lead to equipment-related injury and fatality is caused by a worker-on-foot using tools to transport materials or manually transporting the materials to a different location. If the worker accidentally drops a piece of material or the tool being used such as a wheel barrow breaking down during the transporting process, and the worker suddenly stops, the worker is put in a hazardous situation due to other entities assuming the worker is still moving towards the location and do not see the worker stopped moving.

4.4.2 Struck-by Equipment Case 3 Experiment and Results

To simulate these situations, the researcher moved along a path while a passenger vehicle approached them in reverse. A passenger vehicle was utilized instead of equipment due to liability issues to reduce risk to the researcher involved. This test is important to the study due to the real-world aspect of the test. Workers and equipment are forced to work dynamically with one another in congested zones on typical construction sites. This case better represents these interactions between workers-on-foot and equipment on site. Other studies such as a study conducted by Marks and Teizer (2012) evaluated a proximity detection system, but limited their field trials to having one entity static and the other dynamic, which does not accurately represent the real-world interactions that occur on construction sites. The test was conducted in the same parking lot as the previous case study and the weather was approximately 70 degrees Fahrenheit with winds of 13 mph. A similar process to the previous two case studies was conducted for this final struck-by incident case. The initial process was identical to the previous studies, but unlike the first two studies where one entity was stationary, both the worker-on-foot and the passenger vehicle were dynamic. This type of interaction was studied to simulate real-world interactions on construction sites where there are various entities traversing throughout the job site at every moment. A typical construction interaction was simulated where the worker transported materials from one location to the next as a piece of heavy equipment reversed into the same location as the worker to possibly unload or load the material the worker was moving. The researcher moved forward to allow the GPS signal to adjust and to simulate the worker-on-foot picking an item up to transport to a different location. Next, the worker proceeded backwards towards the vehicle that was also moving backwards in the direction of the worker.

Making observations on a test where both the worker and equipment or vehicle are dynamic can be unsafe. However, these tests are required to understand the real-world interactions between workers-on-foot and heavy equipment utilizing the systems. To ensure the safety of the researcher, the vehicle operated in the parking lot while the worker maneuvered on a raised sidewalk. This raised sidewalk acted as a barrier to protect the worker if the researcher in charge of the computer and monitoring the experiment was not paying attention leading to the vehicle possibly colliding with the researcher shown in Figure 4.12.

Figure 4.12: Detection System Tested in Real-World Struck-By Equipment Case 3

When the vehicle was within 6 meters or approximately 20 feet, a warning was sent, which symbolized a hazardous encounter between the worker-on-foot and equipment. A notification from the virtual scene was given through the sensor alternating colors when a hazardous interaction occurred. The safe sensor was a dark red color and when a warning was emitted the sensor turned to a dark blue presented in Figures 4.13 and 4.14. After the warning was sent, the researcher instructed the worker to turn to face the equipment to show that the worker would be safe and no warning would be sent because they are now aware that the equipment is within a close proximity to them and they have the equipment in their field-of-view. This test proves that the amount of false-alarms can be reduced with this detection system by exclusively sending a warning when the equipment is not in the worker's field-of-view or paying attention and in close proximity to them. Five tests were run to ensure the accuracy of the system.

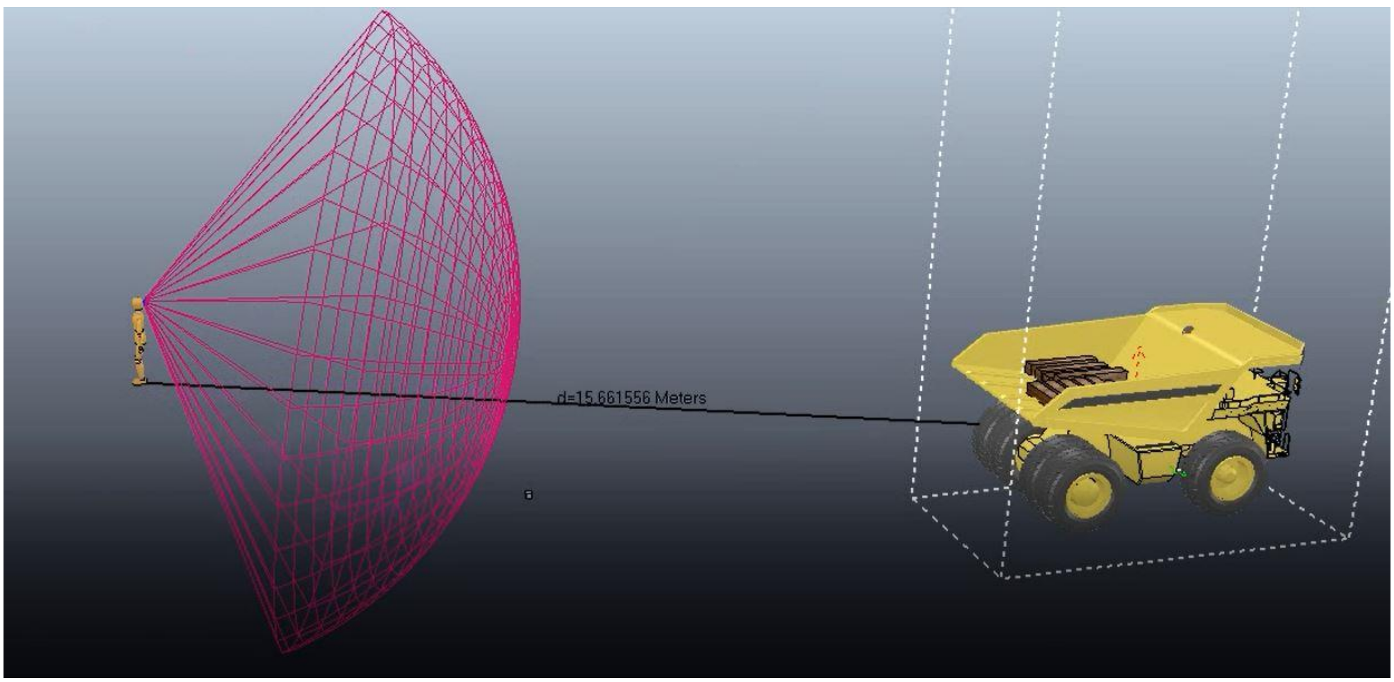

Figure 4.13: Worker-on-Foot is Safe (Red Cone-Shaped Proximity Sensor) for Real-World Case 3 Experiment

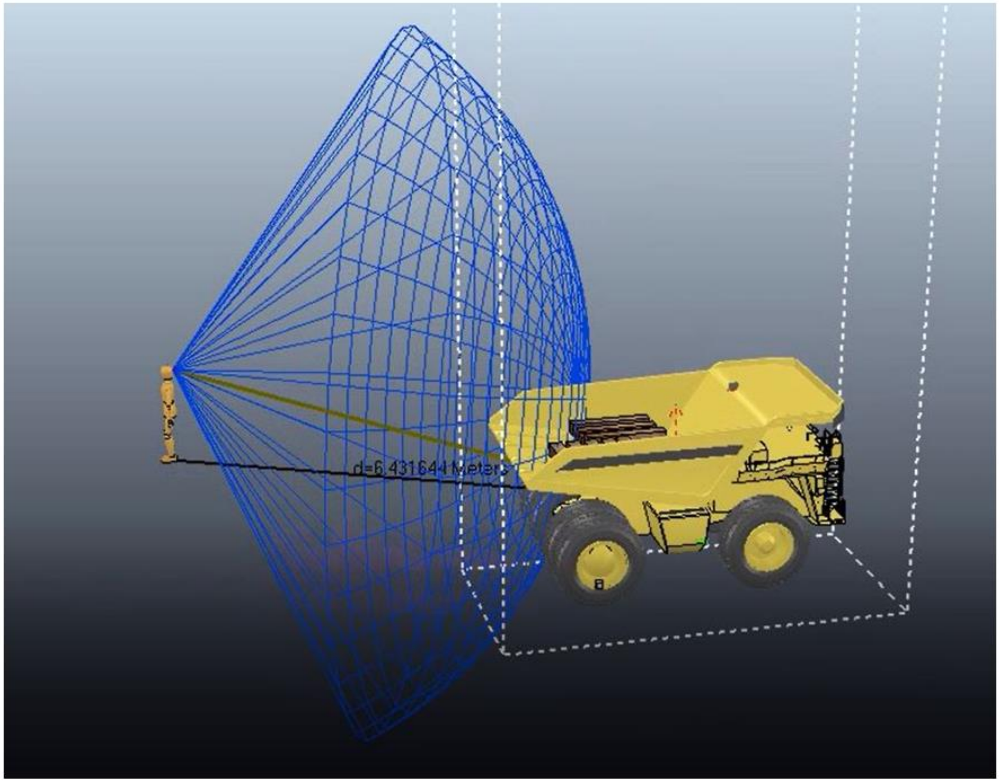

Figure 4.14: Warning (Blue Cone-Shaped Proximity Sensor) Sent to Worker-on-Foot for Real-World Case 3 Experiment

4.5 Physical Warning Sent to Affected Personnel

Protecting and alerting workers of hazardous situations caused by struck-by equipment incidents and falls is one of the objectives of this research. Through the case studies and virtual environment, it is shown that the developed orientation and position detection system is capable of cautioning workers-on-foot of imminent hazards on site such as heavy equipment and approaching ledges. To make this detection system an effective tool, a warning needs to be sent to the worker directly on site so that the worker can react to the hazardous situation. The researcher expanded the functions of the system to send a small-scale physical warning system to the UWB communication system that communicates between the boards and the worker-on-foot from the virtual environment. Controlled environment tests were completed for this section of the research due to the difficulty in capturing the LED light illumination in the real-world. Applying this system to the construction phase is still valid.

When the worker is safe, the LED on both the worker's hardhat and the UWB communication system attached to the computer remains off presented by Figure 4.15.

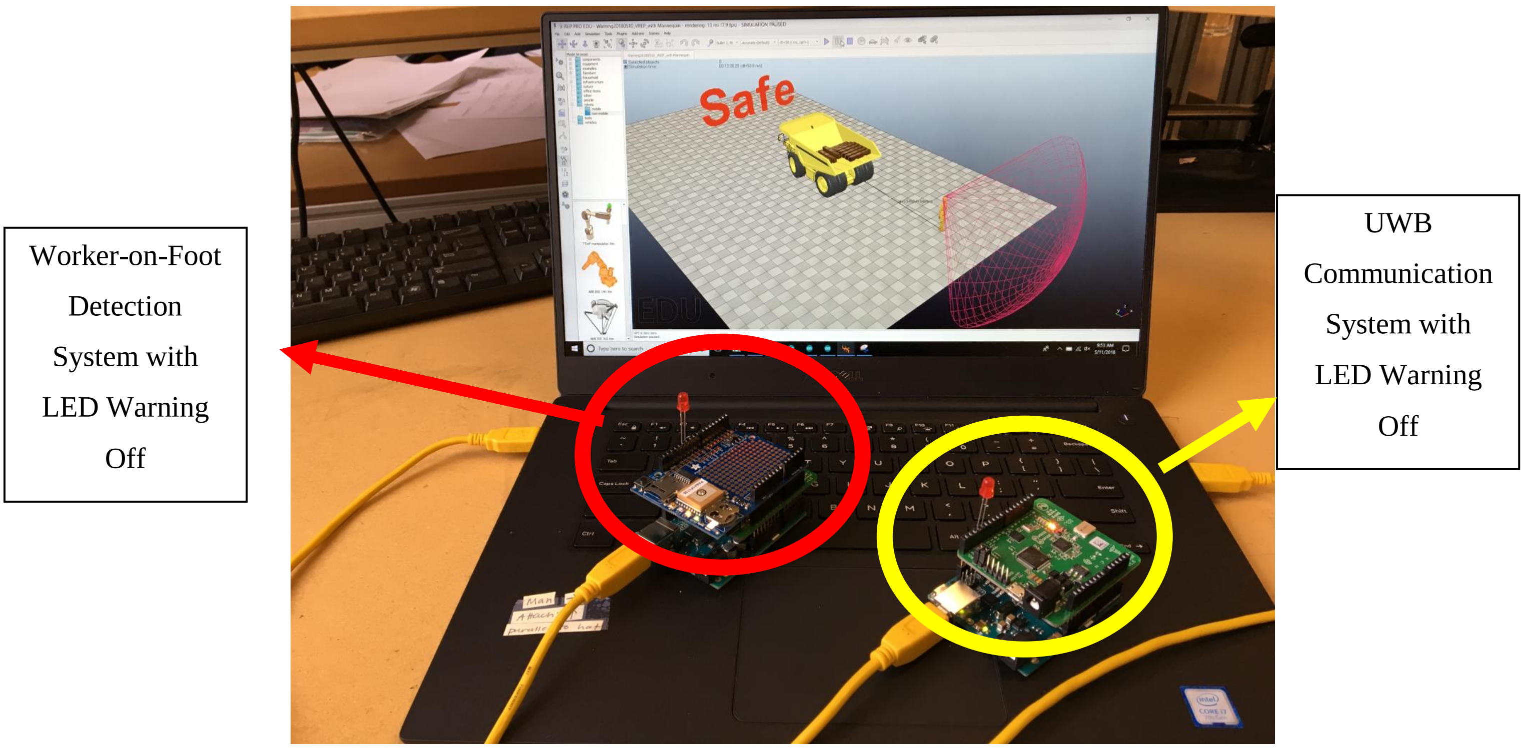

Figure 4.15: LED Warning is Off Due to Worker-on-Foot Safe

If a warning is identified by the virtual scene due to the parameters being interfered with, then the LED on both systems will illuminate shown by Figure 4.16. Due to determining the most sufficient warning type whether it be visual, audible, or a vibration, being out of the scope of this research, a future study will need to be organized to advance this warning model. The LED light was used specifically to validate the enhanced proximity detection system. Proof that this warning was sent to the worker through observing if the LED illuminates or not was difficult to determine when running the real-world tests. Therefore, the researcher conducted experiments to provide evidence of the detection system's ability to send a warning directly and precisely to the worker-on-foot. Any warning could have been sent to the worker-on-foot such as an audible or vibration warning. The LED light was chosen to validate the detection system due to researching the most effective warning method being out of the scope for this research.

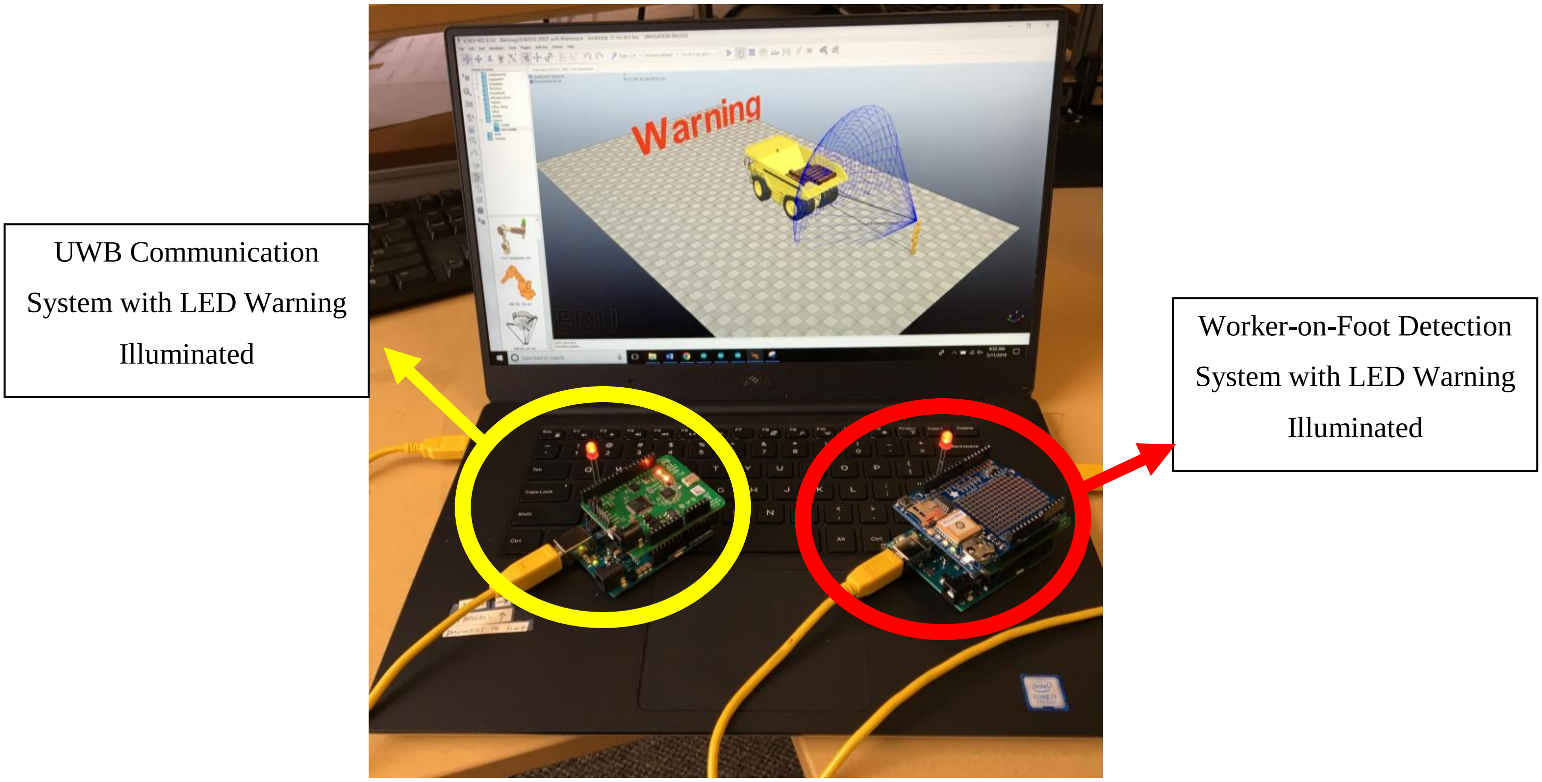

Figure 4.16: LED Warning is On Due to Worker-on-Foot in Hazardous Scenario

4.6 Experiment and Results Chapter Summary

With this orientation and position detection system, management teams will have the ability to provide their workers with a safer working environment that contains limited amounts of distractions from false positive alarms that current proximity detection systems emit. Due to the worker's limited visibility when their back is facing other entities, focusing the case studies on instances where the worker does not have construction equipment in their field-of-view enables accurate warnings to be sent. The real-time spatial analysis enabled by the virtual environment contributed to the accuracy of the warnings emitted to the workers-on-foot in hazardous situations mentioned above.

CHAPTER 5. DISCUSSION

The enhanced proximity detection system provided valuable insights on how the construction industry safety programs and tools need to be improved. Due to 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. In addition to these interactions, there are many construction projects that consist of high-rise jobs resulting in laborers working at dangerous heights and hazardous situations (Jebelli et al. 2015). This research uses an enhanced proximity detection system and virtual experimentation platform to determine how visibility issues affect the workers on site by using a sensor-based detection system, which will limit the generation of false positive alerts. The researcher assumed that when a worker has their back towards other construction entities, they are incapable of seeing those entities due to humans being restricted of 360-degree visibility. Sending a signal every time a worker is within close proximity to other entities results in the workers becoming used to these unnecessary alarms and ignoring valid alerts, which leads to unsafe interactions. The researcher focused on only sending warnings to the workers when they had their backs facing the other entities on site, which limited their field-of-view, and were in close proximity to the entities. This enables the generation of accurate warnings to reduce the emission of false positive alarms that cause distractions for workers.

By using this system and platform, the researcher was able to monitor actual worker movement and orientation to observe hazardous interactions, how field-of-view obstructions add to fatality rates, and how worker awareness to the hazard plays a role in these events. The virtual platform allows the researcher to make observations of visibility and proximity issues without the added constraints of liability and putting workers at risk when testing to verify the need of conducting real-world tests. This research proposed a framework that provides a solution to monitoring fields-of-view for workers-on-foot involved in equipment intensive operations and fall hazard situations to potentially reduce the amount of fatalities due to struck-by equipment incidents and falls and the generation of false positive alarms.

5.1 Research Summary

From the results, the proximity and field-of-view detection system successfully emitted a warning in each hazardous scenario. Therefore, this system can potentially reduce fatal injuries caused by workers operating near ledges and struck-by incidents by eliminating current proximity detection system's emission of false-alarms and providing a visualization tool. A warning was sent to the worker when a proximity or visibility hazard was detected by the virtual entities in the virtual environment based on the interactions in the real-world, which augments other systems found in literature that solely consider proximity. This research adds an important consideration to extant capabilities of current proximity detection systems by also evaluating the impact of monitoring visibility as well.

On detecting a hazardous proximity interaction while the worker did not have it in their field-of-view, the cone-shaped proximity sensor virtual entity monitoring both the proximity and orientation in the virtual scene changed from red to blue. The red cone-shaped proximity sensor displayed in the virtual scene indicated that the worker was safe and a blue cone-shaped proximity sensor indicated a warning from a hazardous situation. Accurate distances customized by the researcher for the proximity sensors in the virtual environment measured both proximity from entities and orientation of the worker successfully. Each enhanced proximity detection system for the two types of incidents, falls and struck-by equipment, were set to detect different objects from specified distances that ranged from 4 to 9 meters or approximately 13-30 feet depending on the modeled scenario. These distances were assigned in the virtual environment based on information gathered from contractor best practices from site visits and reports produced by various organizations, mentioned in the second chapter of this thesis. The distance values can be altered in the virtual environment program depending on the type of operation or hazard specific to each construction site this system is applied to. This feature of the virtual environment allows the management teams and decision makers to customize the scene to match the construction site they are currently working on. The worker on the building was assigned to detect the red cuboid set at the edge of the building and the ground-worker was assigned to detect the truck. Both cases were successful in detecting the objects they were assigned to that interfered with the sensor boundaries.

5.1.1 Warning System

Based on the alert received from the virtual environment and the real-time sensor detection system through the UWB communication system, a physical warning was sent to the worker through an LED illuminating on the detection system that would be attached to the worker. For this study, the LED was tested in an indoor and controlled environment due to capturing whether the light was illuminated or not being difficult in the real-world testing phase. If this warning is further developed, the appropriate warning varying from a visual, vibration, audible, or a combination of these warnings can be implemented into the construction site effectively. To emit the warning to illuminate the LED, there were multiple factors involved.

By using Pozyx and GPS systems, the mannequin and truck virtual entities both moved respective to the enhanced proximity detection system in the real-world allowing the warning to be emitted accurately and only when the worker had their back towards a hazardous entity. Through using the virtual environment, the researcher was able to customize the scene to parameters to those they desired, as mentioned above. Additionally, parameters such as alternating the cone-shaped proximity sensor component color when a warning was produced, programming the cone-shaped proximity sensor component to detect a specific object, and controlling the range of field-of-view for the cone-shaped proximity sensor were implemented by the researcher to generate successfully accurate warnings and further reduce the emission of false positive alarms. These tools authorize management teams to customize and accurately represent their construction sites to allow the detection system to precisely collect results based on the conditions presented on site. Utilizing the virtual scene spatial analysis, the enhanced proximity detection system can be appealingly introduced to the conservative industry by presenting and collecting research data that is relatable and understandable. Providing contractors with videos and re-enactments through the virtual scene will enable real-world hazard observations to potentially persuade the industry to consider the technological adjustments and solutions needed to create a safer working environment. The re-enactments and LED light warning system can be used for training new employees to prevent future injury and fatality caused by falling off of ledges and struck-by equipment incidents by sending accurate warnings.

5.1.2 Improving Worker Field-of-View

The results successfully show that the enhanced proximity detection system tracks the areas that the worker is not aware of. This is important for workers in congested and highly dynamic working environments to provide them with the highest amount of protection. By tracking areas where the worker may not be apprehensive to, the detection system can be implemented to mitigate visibility and proximity issues on site. In addition, the system successfully eliminates false positive alarms that are created by current proximity detection systems by tracking entities and objects that the worker does not have in their field-of-view and is within close proximity to. The researcher assumed that when a worker has their back facing other construction entities, they are unable to see those entities due to humans being restricted of 360-degree visibility. Sending a signal every time a worker is within close proximity to other entities results in the worker disregarding all future warnings including those that may be valid, leading to hazardous situations. The researcher focused on only sending warnings to the workers when they 1) had their backs towards the other entities on site, which limited their field-of-view, and 2) were in close proximity to the entities. This enables the generation of accurate warnings to reduce the emission of false positive alarms that distract workers. If a worker has the object in their field-of-view and is in close proximity to them, a warning is not required because the worker is aware and can make adjustments if needed. It is only when the worker is unaware and the object is within an uncomfortable distance to them that a warning should be emitted, which this research received successful results in.

5.1.3 Innovative Study Incorporating Dynamic Nature of Construction Entities

Contrary to most previous research completed on proximity detection systems, the researcher in this study conducted a case study where both research entities were dynamic. This allowed the researcher to test the system in a realistic construction interaction. Most studies test the detection systems with one entity stationary due to liability issues, but this does not accurately represent the dynamic nature of a construction site. The concept of monitoring both entities moving with the detection system is needed for an accurate representation of the stresses that workers are under while on site. To precisely display both entities moving, multiple tests were conducted for each case to calibrate the GPS coordinate signal. The researcher received a signal by ensuring that the GPS had direct access to the satellites and clearing interference between the worker, truck, and UWB communication system. Overall, the proximity and orientation detection system monitoring a dynamic interaction successfully detected hazardous situations, reduced false-alarms, and can provide a safer working environment by reducing visibility and proximity issues on site.

5.2 Limitaions

As with the majority of experimental research and studies, the proximity and field-of-view detection system experienced limitations in the experiments and scope. Future studies could attempt to overcome these limitations which are described below:

- Controlled experiments:

The results obtained were limited due to the case studies being tested under controlled conditions. Construction sites expose the workers to multiple factors such as noise, dust, and harsh weather conditions, which were not duplicated through this study.

- Liability issues with using heavy equipment in experiments:

When testing the system with both entities in a dynamic state, a passenger car was utilized to eliminate larger liability issues. This may have an effect on how the detection system operates when put under the stressful conditions and construction circumstances.

- Unpredictable worker behavior:

Even with the implementation of this detection system, it is difficult to predict what workers will do when on the job, even if warned. Workers could completely disregard the warnings, not agree to wear the hardhat systems, and be fatigued and/or distracted regardless of the amount of times they have completed the task. Due to worker behavior not being the scope, the researcher was unable to gather data on this type of safety improvement to test the detection system. A future study should be done to determine the most effective warning type to integrate with the detection system produced in this study.

- Restricted GPS signal:

The GPS signal requires a few seconds to update resulting in the worker and vehicle moving at speeds that are slower compared to the movements observed on sites. To position the virtual entities properly based off of the GPS readings, the longitude and latitude values have to be input manually to provide a relative initial location to base the movement of the virtual entities on. Future work needs to be done to eliminate this manual input.

- Experiments focused only on workers-on-foot:

In this initial study, field-of-view monitoring was limited to the worker-on-foot, which eliminates the consideration of other workers that are involved in these situations such as operators. The researcher decided to focus solely on the worker-on-foot's field-of-view because the worker-on-foot is the entity in these interactions that has the highest risk. No protection is provided for the worker, other than PPE, during these operations. This results in their lives being exposed to a higher possibility in being fatally injured as opposed to operators who have the cab of the equipment absorb impacts.

To reduce the limitations observed in this research, future studies are needed to improve the effects this system has on workers and on the worksite.

CHAPTER 6. CONCLUSIONS

One of the top priorities for each construction project is to have an accident and injury free jobsite. Unfortunately, fall hazard safety tools are limited to monitoring worker behavior, physical demands and focus on creating solutions in the design phase. This limited research causes hazardous situations due to the unprepared nature and complexity of the construction phase Additionally, statistics specific to proximity issues in the construction industry and the high frequency of contact collisions on construction sites demonstrate that current safety practices are insufficient (Marks and Teizer 2012; Wang and Razavi 2016). Current proximity detection systems are limited to monitoring only the proximity between entities and do not take other factors into account. This generates many false positive alarms that result in distracting workers on site. Additionally, the experiments conducted in previous studies have one entity, either the worker-on-foot or the equipment, static, which does not represent the dynamic nature of construction sites accurately.

The main objective of this research is to reduce the generation of false positive alarms by developing an enhanced proximity detection system that is based on proximity and visibility to emit accurate warnings specifically when a hazard is within close proximity to workers-on-foot and out of their field-of-view by using real-time sensor data and virtual modeling. The researcher assumed that when a worker has their back towards other construction entities, they are incapable of seeing those entities due to humans being restricted of 360-degree visibility. To complete tasks on site, workers-on-foot and other entities work in close proximity to each other either based on the tasks they are assigned or the congested work sites. Sending a signal when a worker is within close proximity to other entities is unnecessary due to the workers-on-foot being aware of the hazardous situation regardless of being near them and leads to workers ignoring valid warnings. To eliminate these added false alarm distractions, the researcher focused on only sending warnings to the workers when they had their backs facing the other entities on site, which limited their field-of-view, and were in close proximity to the entities. This enables the generation of accurate warnings to reduce the emission of false positive alarms that cause distractions for workers.

6.1 Summary of Research Process

The data collection process consisted of developing a proximity and field-of-view detection system using real-time sensors to relay a signal to a rules-based system. The rules-based system was designed based on contractor best practices from site visits and literature reviews on reports from organizations. From the rules-based system, the virtual environment was capable of enabling spatial analysis to generate precise alerts and reduce the amount of false positive alarms. Combined, this enhanced proximity detection system and virtual model accurately generated warnings for the worker-on-foot construction entity. A physical warning was also sent to the worker-on-foot by illuminating an LED light on the worker's hardhat detection system. Four case studies were conducted to test the effectiveness of the enhanced proximity detection system to emit accurate warnings during fall hazard situations and struck-by equipment incidents. This detection system was tested on an experiment that focused on having both entities in a dynamic state to simulate real-world construction projects for both workers-on-foot and the equipment monitoring. Through the conducted case studies, the detection system successfully emitted effective warnings for both fall hazard scenarios and struck-by equipment incidents by focusing on both orientation and location of the worker-on-foot to other construction entities, therefore reducing the generation of false positive alarms.

6.2 Contributions of the Research

The research studied the effects of monitoring both proximity and visibility of construction entities to reduce the generation of false positive alarms and the amount of fatalities caused by fall hazards and struck-by equipment incidents. This thesis augments other systems found in literature that solely consider proximity and adds an important consideration to extant capabilities of current proximity detection systems by also evaluating the impact of monitoring visibility as well. This section specifies the contributions to the body of knowledge presented in this research. The following list enumerates the contributions of this thesis.

- Accurate warnings to reduce false positive alarms:

The virtual experimentation platform enabled spatial analysis to provide construction entities with the generation of accurate warnings and to identify hazardous situations presented on site. By using this virtual model, liability and proprietary issues are removed from solely running real-world experiments.

- Mitigate visibility and proximity issues

The developed enhanced proximity detection system will reduce the amount of visibility and proximity issues on site by monitoring the areas in regards to field-of-view and distance between entities that the worker-on-foot may not have access to. Due to this system concentrating on hazardous situations that workers are not aware of because they are behind them, accurate warnings are provided to remove the worker from these interactions. By including the field-of-view factor in this research, the industry can potentially observe a reduction in the amount of fatalities and injuries caused on site by fall hazards and struck-by incidents.

- Alter system to fit the needs of various worksites:

The literature review and contractor interactions used to create a safety rules-based system allows management teams of various projects to monitor proximity and field-of-view specific to their sites. The values for distance and field-of-view in the rules-based system can both be adjusted depending on the type of operation or hazard for each individual construction project. From here, the interaction between the components in the virtual scene will monitor these aspects according to the guidelines set by the user to send a warning to the affected entities.

- Both entities simultaneously tested in dynamic state:

The developed detection system was tested on an experiment that had both the worker-on-foot and equipment dynamic. This experiment demonstrates that this system is effective for monitoring real-world construction interactions between entities due to it simulating similar construction interactions. By having both entities dynamic while testing the detection system, the interaction between the two can be observed, which will provide decision makers with the ability to create the appropriate solutions and mitigate potential hazardous situations between them can be identified and implemented.

- Remove subjectivity from research:

This research provides an analytical approach to objectively examine construction safety by using real-time sensors and a virtual model to generate alarms and identify hazards on site.

- Use technological advancements to monitor fall hazards:

The developed enhanced proximity detection system is an innovative technology that can be used to monitor fall hazards. Unlike previous fall hazard safety tools, this detection system can be implemented into the construction phase to prevent workers from fall incidents that can occur due to the complexity of working at heights and the complacent views of workers.

6.3 Future Work

Subsequent to the evaluation of the feasibility of the proximity and field-of-view detection system in the controlled study environment, other parameters and potential factors on the system should be analyzed and observed through future studies. The following list contains the future work to further this research.

- Use of different types of heavy equipment:

A wider variety of construction hazardous situations should be monitored and analyzed with the developed system such as crane and excavator operations. The swing of the boom and counterweight of both cranes and excavators create many caught between incidents, which could be prevented with this system monitoring field-of-view. A sensor could be attached to the boom or counterweight of the equipment and if they are in a dangerous proximity of the workers who become complacent with the construction site then a warning can be sent back to the workers on site and the virtual entities in the virtual environment to produce new implementations into safety programs.

- Investigate previous incidents using detection system:

This research could also be used to model previous accidents from safety organization's reports to observe if field-of-view contributed to the incident. From here, management teams can reduce the generation of false positive alarms and emit accurate safety warnings to eliminate future visibility issues.

- Develop detection system to function indoors:

Advancements to the position-detection aspect of this research to open this system up to phases of the construction project that deal with indoor construction such as demolitions or finishing touch work should also be studied. The types of equipment used during this phase of the research are not necessarily large yet they have a lot of blind spots. When they work in congested environments, poorly-lit spaces, and at high speeds, workers-on-foot are still at risk to struck-by incidents.

- Test enhanced proximity detection system under real-world construction site conditions:

Modifying this study to being tested outdoors under real-world site conditions is recommended due to the various influences that actual construction sites bring such as noise, dust, or distractions from construction tasks causes workers to be at higher risk to dangerous interactions. The detection system is large in size so testing if it can function in real-world conditions presented on site is recommended. This step will help the implementation process of the technology into the industry by providing decision makers with a real-world experience to observe the impact that the detection system and virtual environment can have on projects in reducing proximity and visibility issues.

- Include study on the effects of worker behavior on the detection system:

Incorporating worker behavior studies would be beneficial to this study to evaluate the effectiveness of different warnings to provide the best results in reducing injury and fatality caused by falls and struck-by incidents on site. Monitoring how the workers react to the implementation of the system and various warnings emitted will help management teams determine how to incorporate the system into their safety programs and the type of warning system that will provide the workers with the safest working environment.

- Identify most effective GPS system for monitoring worker position:

Determining the best GPS system for detecting location would be ideal as well. There were some areas in the videos obtained from the scene that would glitch causing the sensor to fall out of line and not be represented well. Eliminating the manual input of the zeroed longitude and latitude points would also contribute to developing a precise detection system.

- Include an experiment that observes other personnel's field-of-view on site:

Opening a study that also monitors the orientation or field-of-view of the equipment operator along with the worker-on-foot would be most effective. This will allow management teams to monitor blind spots and how aware the equipment operators are of their surroundings to make adjustments to the training for operators. Additionally, the generation of false positive alerts will be reduced and proximity and visibility issues on site caused by fall hazards and struck-by equipment incidents will be mitigated.

6.4 Chapter Summary

Ultimately, this detection system and virtual model combination allows accurate and effective warnings to be emitted to entities on site by focusing on mitigating and monitoring situations where the worker-on-foot is in close proximity to the hazard and does not have the hazard in their field-of-view. The generation of false positive alarms will be eliminated with the use of this system because of the visibility monitoring aspect incorporated into previous research proximity detection systems. Humans do not have access to 360-degree visibility, but with this detection system the current visibility issues observed can be mitigated by having the system monitor the area behind the worker. Implementing this enhanced proximity detection system can further reduce injury and fatality rates caused by fall hazard situations and struck-by equipment incidents by eliminating the generation of false positive alarms and incorporating a system that detects the field-of-view of workers as well.

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