Personal Protective Unit Position and Orientation of Proximity Detection and Alert Technology for Heavy Construction Equipment Operation

Eric D. Marks[1] and Jochen Teizer[2]

Abstract

The nature of construction sites often promotes hazardous conditions requiring workers and heavy construction equipment to operate in close proximity resulting in many interactions between ground workers and heavy construction equipment. Approximately one fourth of fatalities experienced by the construction industry in 2010 resulted from workers being struck-by an object or piece of construction equipment. The primary objective is to evaluate the capability of radio frequency (RF) remote detection technology to reliably provide alerts when the position and orientation of the personal protection unit (PPU) component of the system are varied. Field experiments designed to emulate typical interactions between ground workers and heavy construction equipment are completed. Various positions and orientations of the proximity detection and alert system's PPU component were created and evaluated based on typical worker movements based on construction tasks. Experimental results indicate that both the position and orientation of the proximity detection and alert system's PPU component impact the reliability of the system's ability to provide alerts during hazardous proximity conditions. Specific positions and orientations were deemed reliable and effective when deployed in the construction environment. The purpose is to generate data and knowledge of proximity detection and alert systems for eventual implementation of proximity detection and alert systems on construction sites.

Keywords: Heavy construction equipment, pro-active safety, proximity alert technology, workers-on-foot.

1. Introduction

Construction sites are characterized as dynamic environments each having a unique size and working conditions. Interactions between multiple construction resources including construction personnel, heavy equipment and materials are characteristic of construction sites. Hazardous proximity conditions are present when heavy construction equipment is operating in close proximity to ground workers. These conditions result in an increased risk

---

[1] Ph.D. Candidate, School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr. N.W., Atlanta, GA, 30332-0355, E-Mail: ericmarks@gatech.edu.

[2] Ph.D., Associate Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr. N.W., Atlanta, GA, 30332-0355, E-mail: teizer@gatech.edu.

of injuries and fatalities for ground workers through contact collisions between workers and heavy equipment.

Interactions between heavy equipment and ground workers on construction sites have been investigated in previous research efforts. A majority of this work focused on injury and fatality statistics of contact collisions between ground workers and heavy equipment. Pratt et al. (2001) found the repetitive nature of construction tasks can cause workers to experience a decrease or absence of awareness. Other research has cited limited operator visibility as a factor in creating hazardous proximity conditions on construction sites (Teizer et al. 2010).

In the past, the construction industry, including private companies and governmental agencies, have been slow in adapting and implementing automated technologies when compared to other industries (Pratt et al. 2001). The freight industry, transportation, ship building, mining, railroad operations, and manufacturing have been testing and implementing various prototype safety technologies including proximity detection and alert systems. Completed case studies from these industries and others have shown emerging safety technologies including proximity detection and alert systems can be used to provide ground workers another layer of protection through technology.

A lack of scientific evaluation data and results through experimental trials currently exists for construction safety technologies including proximity detection and alert systems. Evaluation through experiments designed to emulate the construction environment are needed for these safety technologies. Specifically, experiments that simulate ground worker movement and the resulting performance of the proximity detection and alert system is required for eventual deployment of these systems on construction sites.

2. Literature Review

Construction sites have a unique scope and set of working conditions. These sites are characterized by dynamic interactions between various resources including ground workers, heavy equipment and materials. Workspace on construction sites is often limited due to the unstructured and seemingly random movement of resources. Construction resources often function in close proximity to one another resulting in dangerous proximity situations for ground workers. Incidents in which construction equipment strikes a ground worker can result in an injury or fatality. As injury and fatality statistics indicate, hazardous proximity situations on construction sites remain a key problem in the safety of construction workers.

The following review covers injury and fatality incidents associated with hazardous proximity situations in the construction industry. The review also discusses current safety best practices in construction, real-time proximity detection and alert systems, and reviews methods for testing these systems. A research needs statement is derived and presented at the end of the review.

2.1 Construction Heavy Equipment-Human Interaction Statistics

The construction industry continues to experience one of the highest workplace fatality records per year when compared to other industries in the US. The construction industry experienced 721 fatalities in 2011, 17% of which resulted from workers colliding with objects or equipment on construction sites (CFOI 2011). These 123 construction fatalities resulting from workers colliding with objects or equipment accounted for 2.6% of the nation’s workplace fatalities experienced in 2011. Since 2003, the construction industry averaged 197 fatalities per year resulting from workers being struck-by construction equipment or other objects (CFOI 2009).

Heavy equipment-ground worker interaction also result in worker injuries which negatively impact the success of a project through decreased worker productivity, increased company medical costs, etc. In 2010, the construction industry recorded 24,710 injuries caused by workers colliding with equipment and other objects which accounted for 12% of all construction worker injuries in that year. Since 2003, the construction industry averaged 45,746 injuries resulting from workers colliding with equipment and objects on construction sites (CFOI 2011).

2.2 Causes of Heavy Equipment-Human Interaction

Research efforts in hazardous proximity situations between construction workers and equipment have resulted in many root causes of the current problem. Characteristics such as the harsh outdoor environment and the often repetitive nature of construction tasks can cause workers to decrease their awareness of surroundings (Pratt et al. 2001). Three general problems that result in hazardous proximity situations between construction equipment and ground workers: 1) Outdated or never implemented policies including a lack of knowledge of existing risk factors, 2) all incident causation data is collected after-the-fact resulting in limited real-time incident information if any is available, and 3) no real-time information is gathered during the incident.

Another study found that most heavy equipment-human accidents result from missing safety features on heavy equipment (OSHA 1990). The missing devices included components required to alert workers of their close proximity to the equipment. Other preventative measures including maintenance checklists for construction equipment and internal traffic control plans (ITC) were also investigated as possible causes of heavy equipment-human interaction problem on construction sites.

2.3 Safety Best Practices

Previous research efforts in construction safety have mainly focused on training and education. Much of previous research focuses on construction safety best practices in design, education, and training for safety. These safety best practices do not generate feedback during performance of the work task and are unable to provide alerts in real-time to construction personnel.

The Occupational Safety and Health Administration (OSHA) has developed and implemented several passive safety regulations requiring devices such as hard hats, reflective safety vests and other personal protective equipment (PPE). These regulations are passive attempts to improve safety in construction, but are incapable of providing real-time alerts for workers during hazardous proximity situations. Other regulations including incident recording and worker safety training can increase the awareness of equipment operators and ground workers in dangerous working conditions.

2.4 Real-Time Pro-Active Proximity Detection and Alert Technology

Automation has been found to simplify and improve some important construction engineering and management problems (Navon and Sacks 2006). Technology implemented on construction sites for safety can be categorized as reactive and proactive. Reactive technologies require data collection and analysis processing effort after an event occurs. Proactive technology collects and analyses data in real-time in order to alert construction personnel of potentially dangerous situations instantaneously. Real-time safety technologies implemented on construction sites have been proven reliable to provide alerts to workers and equipment operators in real-time when a hazardous proximity situation exists (Teizer et al. 2010). Construction safety technologies provide ground workers with an additional layer of protection when other safety best practices are not followed (Teizer et al. 2008).

Many technologies thought to be capable of alerting workers in real-time during hazardous proximity conditions such as RADAR (Radio Detection and Ranging), sonar, Global Positioning System (GPS), radio transceiver tags, vision, etc. have unique limitations when deployed on construction sites such as availability and strength of signal, weight, size, and power source (Ruff 2001). Other studies investigated several of the previously mentioned technologies as potential proximity detection and alert systems in the construction environment. Parameters such as read range, alert method, precision, reliability, and capability of performing in an outdoor environment were used to assess each proximity detection technology (Teizer et al. 2007). Radio frequency technology demonstrated potential to satisfy many of the tested constraints.

2.5 Test Methods for Proximity Detection and Alert Systems

Testing methods have been developed to evaluate the capabilities and reliability of proximity detection and alert systems. Manual methods of measuring and marking proximity alert distances for a camera and radar system were used for construction sites (Ruff 2005). These methods have been used for measuring proximity detection and alert systems (GPS units) on large capacity haul trucks during a surface mining operation (Steel et al. 2003). Three mobile vehicles and six stationary objects were fitted with the proximity detection and alert system. The system’s reliability was evaluated through field trials of interactions between large capacity haul trucks and ground workers.

A lack of scientific evaluation data exists for new and existing automated safety technology for implementations on construction sites. Proximity detection and alert systems using radio frequency technology need to be thoroughly evaluated through current or newly developed experimental methods, case studies, and resulting data analysis. A need exists to evaluate various mounting positions and orientations of proximity detection and alert system components.

3. Objective and Scope

The objective is to evaluate the effectiveness of various positions and orientations of proximity detection and alert system components to provide alerts in real-time to construction personnel when deployed in a simulated construction environment. The different positions and orientations of the system's components are designed to simulate ground worker movements. When heavy construction equipment and ground workers are in too close proximity, components of the proximity detection and alert system should be positioned such that the hazardous proximity conditions are detected and a real-time alert is activated. The scope includes hazardous proximity situations between heavy construction equipment and ground workers on outdoor construction sites.

4. Methodology and Results

Each set of experimental trials was designed to investigate the effectiveness of various component positions and orientations of the proximity detection and alert system in an outdoor environment. The experiments were designed to test various mounting locations of proximity detection and alert system components on existing Personal Protective Equipment (PPE) for ground construction workers. Typical movements and static positions of ground workers were also used to design the experimental trials.

4.1 Technology Tested

The real-time proximity detection and alert system utilizes active Ultra-High radio frequency (UFH) technology to detect proximity breaches of construction equipment and ground workers. If two or more construction resources are in too close proximity to one another, the sensing technology will activate alarms to warn construction personnel through devices called Equipment and Personal Protection Units (EPU and PPU respectfully). These two components are further described:

1. An in-cabin construction equipment protection unit (EPU) equipped with a reader, alert mechanism, and single directional antenna that serves as a transceiver device by transmitting and receiving tag information including the timestamp, tag identification and magnitude of the reflected radio frequency signal and

2. A personal protective unit (PPU) equipped with an alert mechanism, chip and battery in a small rectangular tag (8.5 cm by 5.5 cm). This tag can be installed on a hard hat or safety vest of a construction worker. Both the EPU and PPU components can be viewed in figure 1.

The EPU component of the proximity detection device can be powered by the existing battery on the piece of equipment. A signal broadcasted by the EPU is intercepted by the

PPU and reflected back to the EPU which activates an alert instantaneously in real-time when the devices are in close proximity to one another. The EPU provides an audible alert which creates ample noise so that the equipment operator is able to hear the alert above normal construction sounds. The alert is only provided to the equipment operator because he/she ultimately has control to stop or correct the hazard. Figure 1 shows the PPU mounted on a worker safety vest (left) and the EPU installed on a tripod and cart (right).

Figure 1: Proximity Detection and Alert System PPU (left) and EPU (right)

The EPU’s signal is broadcasted in a radial manner and loses signal strength as it moves farther from the EPU location. During the experimental trials, the strength of the signal emitted by the EPU remained consistent. The EPU’s antenna should be installed in locations such that the line-of-sight to objects is not obstructed. The proximity detection and alert system evaluated also possesses data logging capabilities. The accompanying data logging function of the system records the tag identification number, EPU identification number, time stamp of the proximity breach and the Received Signal Strength Indication (RSSI).

4.2 Experiments

Several experimental trials were designed and executed to evaluate various PPU positions and orientations on ground workers. The objective of these experiments was to identify the best position and orientation among multiple variations for the proximity detection and alert system tested. Each experiment was conducted in an outdoor environment designed to emulate conditions of an actual construction site. For each set of experimental trials, the weather conditions were mostly clear, mostly sunny, and the temperature was 75 degrees Fahrenheit. The test bed for these trials was a clear, flat, grass ground surface with no obstructions. A Robotic Total Station (RTS) was used to place markers along a straight path perpendicular to the face plane of the EPU antenna. Markers placed at consistent 3 meter intervals outlined the walking path for the test person. The test bed for these trials is shown in figure 2.

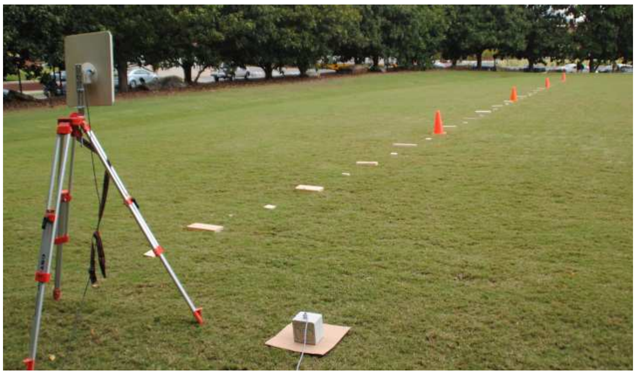

Figure 2: PPU Position and Orientation Test Bed

The EPU's antenna was attached to a tripod in order to exclude any objects from obstructing the line-of-sight between the EPU and PPU. The EPU antenna is directional meaning it is only capable of reading 60 degrees in both directions parallel to the face plane of the antenna. The centroid of the square antenna face was positioned 1.15 meters vertically from the ground surface which was the average elevation between the top of hard hat and center of the safety vest of the test person. The face plane of the EPU's antenna was perpendicular from the ground surface.

The test person started outside of the proximity detection and alert system's detection range (approximately 40 meters from the antenna) along the path outlined by the markers. The test person equipped with a PPU approached the EPU antenna on the straight marked path at a constant walking pace (4 meters per second). Once the alert was activated, the test person stopped and measured the distance from the stopped position to the EPU's antenna using a commercially available laser distance meter. This procedure was repeated ten times for each combination of tag position and orientation.

Eight combinations of tag positions and orientations were tested during the experimental trials. For the purposes of this experiment, the term "position" was defined as the location of the face plane of the device in relation to the ground surface. For example, a horizontal position is represented by the face place of the device being parallel to the ground surface and perpendicular to the EPU antenna face. Likewise, a vertically positioned device has the face plane perpendicular to the ground surface and parallel to the EPU antenna face. Both of these tag positions can be viewed in figure 3 where the tag is mounted on a hard hat in the vertical position (left) and horizontal position (right).

Four different tag orientations were used in combination with the tag positions. The orientations were based on the location of the tag in relation to the EPU antenna or the sky. Each of the four tag orientations was given a number (1, 2, 3, or 4) depending on the location of tag components such that each of the four possible orthogonal tag orientations was tested. Each subsequent orientation after the first initial orientation (orientation 1) was achieved by rotating the tag counter clockwise 90 degrees. The diagram in figure 4 shows how the tags were oriented in relationship to the EPU's antenna or the sky and ground reference. The experimental trials were conducted on three PPU tags.

Figure 3: PPU mounted on a hard hat in the vertical position (left) and the horizontal position (right)

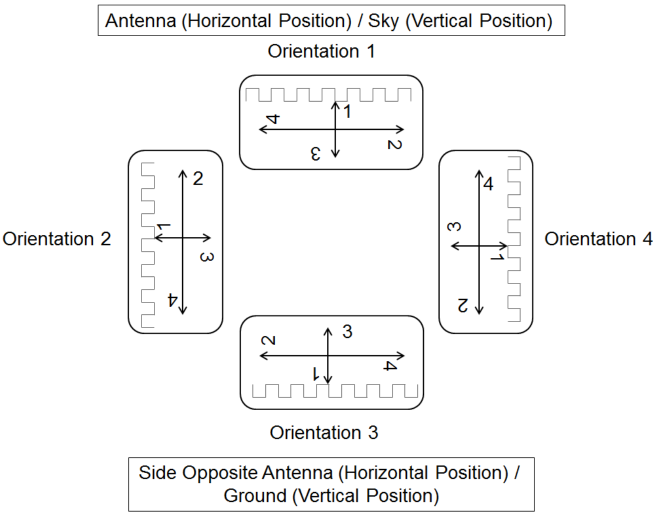

Figure 4: PPU Orientation in Relation to the EPU Antenna and Ground Surface

A statistical analysis was performed on the data gathered for the three tags during the experimental trials. Table 1 shows the statistical analysis of the alert distance results from the tag positioned horizontally on top of a worker hard hat. The mean value, minimum value, range (which is the maximum value subtracted from the minimum value), and standard deviation are calculated from the ten trials of each tag. The best performing orientation values of each tag values are bolded for each tag. Best performers were classified as trials having the highest mean value, lowest range value, and lowest standard deviation value when compared to the other orientations of the same tag.

Orientation 1 had the highest mean value, lowest range between the maximum and minimum distance, and the lowest standard deviation value for tag 1 and 3. These results were analysed for each of the four orientations for the following tag locations with the tag position in parenthesis: 1) Top of the hard hat (horizontal), 2) side of the hard hat (vertical), 3) front of the hard hat (vertical), 4) back of the hard hat (vertical), 5) Front pocket of the safety vest (vertical), 6) back pocket of the safety vest (vertical), 7) side of the shoulder (vertical), and 8) top of the shoulder (horizontal). Results of each of the eight individual configurations were compared to select the highest performing position and corresponding orientation. Table 2 shows the best performers of each possible tag position and orientation combination when compared to the four other configurations on the hard hat. A similar table was created for the safety vest summary values. The orientation of each tag is denoted in parenthesis beside each value.

Table 1: PPU Tag Orientation on the Top of a Hard Hat

		Tag 1	Tag 2	Tag 3
Orientation 1	Mean:	**37.7 m**	38.8 m	**37.8 m**
	Min.:	36.8 m	38.0 m	37.0 m
	Range:	**1.3 m**	**1.5 m**	**1.3 m**
	Std. Dev.:	**0.6**	**0.8**	**0.7**
Orientation 2	Mean:	21.9 m	10.8 m	11.3 m
	Min.:	19.0 m	10.0 m	9.5 m
	Range:	5.8 m	**1.5 m**	3.0 m
	Std. Dev.:	2.9	**0.8**	1.6
Orientation 3	Mean:	34.1 m	12.7 m	37.4 m
	Min.:	32.0 m	12.0 m	36.3 m
	Range:	4.3 m	**1.5 m**	2.8 m
	Std. Dev.:	2.1	**0.8**	1.4
Orientation 4	Mean:	13.5 m	12.3 m	12.6 m
	Min.:	9.8 m	11.0 m	11.5 m
	Range:	5.5 m	2.8 m	5.3 m
	Std. Dev.:	3.0	1.4	2.7

Table 2: PPU Tag Orientation Summary on the Hard Hat

		Tag 1	Tag 2	Tag 3
Top	Mean:	**37.3 m (1)**	**38.8 m (1)**	37.8 m (1)
	Min.:	11.5 m (4)	10.0 m (2)	12.5 m (2)
	Range:	1.3 m (1)	1.5 m (1)	**1.3 m (1)**
	Std. Dev.:	0.6 (1)	0.8 (1)	**0.7 (1)**
Side	Mean:	8.9 m (1)	5.7 m (1)	8.6 m (3)
	Min.:	1.5 m (3)	4.3 m (2)	4.5 m (2)
	Range:	**1.0 m (1)**	1.5 m (2)	5.3 m (2)
	Std. Dev.:	**0.5 (1)**	**0.3 (3)**	0.8 (2)
Front	Mean:	36.5 m (1)	38.2 m (1)	**38.4 m (1)**
	Min.:	4.5 m (4)	5.0 m (4)	12.5 m (4)
	Range:	3.0 m (1,2)	**0.5 m (3)**	1.5 m (2)
	Std. Dev.:	1.5 (1)	**0.3 (3)**	0.8 (2)
Back	Mean:	10.8 m (2)	28.8 m (3)	26.8 m (3)
	Min.:	2.0 m (4)	3.0 m (4)	4.0 m (2)
	Range:	1.3 m (2)	6.3 m (3)	7.8 m (3)
	Std. Dev.:	0.7 (2)	**0.3 (4)**	1.0 (1)

The top of the hard hat in orientation 1 recorded the highest mean value when compared to the other configurations. Orientation 3 had the lowest standard deviation value when mounted on both the side and front of the hard hat. Overall, orientation 1 was the best performer in most of the mounting positions on the hard hat. The tag mounted on the top of the hard hat had the highest number of top performing orientations when compared to the other mounting locations. However, the front mounting location statistical values were very similar to values recorded when placing the PPU tag on the top of the hard hat.

A similar analysis was performed on placing the PPU tag on a workers vest in four locations previously mentioned. Placing the tag on the front pocket of a safety vest recorded the largest mean value for all three tags, and all alert distance readings occurred when the tag was in orientation 1 or 3. The test person was able to touch the antenna before activating an alert during the approach when the PPU tag was located on the back of the safety vest and on the side of the shoulder.

5. Conclusion

One leading cause of construction fatalities is collisions between workers and objections or construction equipment. The construction industry must seek to achieve zero fatalities and injuries for all construction projects, and one method is to generate knowledge about real-time safety technologies such as proximity detection and alert systems. The purpose of this research was to evaluate the effectiveness of various positions and orientations of proximity detection and alert system components to provide alerts in real-time during hazardous proximity conditions. Results from the review and experiments suggest that proximity detection and alert systems can reliably alert ground workers during hazardous proximity conditions, and that tag position and orientation can increase the effectiveness of these systems. The executed experimental trials tested the various PPU positions and orientations attached to a reflective safety vest and construction hard hat. The audible alert of the system was to a sufficient volume so that it can be heard over the other loud construction noise.

When testing the PPU's best orientation among the four configurations on the construction hard hat, orientations 1 and 3 on the top and front of the hard hat were the best performers when compared to the other configurations evaluated. Orientations 1 and 3 on the front of the safety vest had the highest alert distance. After testing the tag placed on the side of the shoulder and back of the safety vest, the test person was able to reach the EPU antenna before an alert was activated in several independent approaches. The results indicate that the tags experience polarization effects when positioned vertically in orientation 2 or 4. More testing should be completed on these tag locations such as a test person approaching the EPU antenna while positioning his/her body such that their back is facing the EPU antenna.

The completed field trials for the proximity detection and alert system were deemed successful, but other parameters could potentially influence the system such as impacts on the signal propagation. These factors include the EPU antenna mounting location, other construction resources such as materials, specific alert range for individual pieces of construction equipment, and impacts of an integrated system of multiple EPU's and PPU's on an active construction site. These factors and others will require investigation to further evaluate the effectiveness of implementing a proximity detection and alert system in the construction environment. The system should eventually be deployed in extensive field trials conducted over extended project durations. During these long term field trials, data can be recorded, analysed, and used to improve positioning of workers and equipment to assist in the development of new safety concepts including advanced safety education and training courses.

References

Census of Fatal Occupational Injuries (2011) *Fatal occupational injuries by industry and selected event or exposure,* (available online http://www.bls.gov/iff/oshcfoil.htm [accessed on 10/21/2012]).

Census of Fatal Occupational Injuries (2009) *Fatal occupational injuries by industry and selected event or exposure,* (available online http://www.bls.gov/iff/oshcfoil.htm [accessed on 10/25/2012]).

Navon R and Sacks R (2006) "Assessing Research Issues in Automated Project Performance Control (APPC)." *Automation in Construction* **16**: 474-484.

Pratt S, Fosbroke D, and Marsh, S.M. (2001) "Building Safer Highway Work Zones: Measures to Prevent Worker Injuries from Vehicles and Equipment." *Department of Health and Human Services* **1**: 5-6.

Ruff T (2005) "Evaluation of a Radar-Based Proximity Warning System for Off-highway Dump Trucks." *Accident Analysis and Prevention* **38**: 92-98.

Ruff T (2001) "Monitoring Blind Spots - A Major Concern for Haul Trucks." *Engineering and Mining Journal* **202**: 17-26.

Steel J, Debrunner C, and Whitehorn M (2003) “Stereo Images for Object Detection in Surface Mine Safety Applications”, *Western Mining Resource Center Tech Report Number TR20030109*, Colorado School of Mines, Golden, Colorado.

Teizer J, Allread B, Fullerton C, and Hinze J (2010) "Autonomous Pro-Active Real-Time Construction Worker and Equipment Operator Proximity Safety Alert System." *Automation in Construction* **19**: 630-640.

Teizer J, Caldas C, Haas C (2007) "Real-Time Three-Dimensional Occupancy Grid Modeling for the Detection and Tracking of Construction Resources." *ASCE Journal of Construction Engineering and Management* **133**: 880-888.