Method for Testing Proximity Detection and Warning Technology for Construction Equipment Operation

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ABSTRACT

After experiencing 818 fatalities in 2009, the construction industry continues to be among the leading industries for workplace fatalities in the United States. Approximately 21 percent of these fatalities resulted from workers being struck-by an object or construction equipment. The nature of construction jobsites often produce hazardous conditions by requiring workers and equipment to operate at close proximity. The objective of this research is to evaluate the capability of emerging radio frequency (RF) remote sensing technology to provide alerts when heavy construction equipment and workers are in too close proximity to each other. This paper presents numerous field experiments designed to emulate typical interactions between workers-on-foot and construction equipment. These devices were installed on actual construction equipment in an outdoor environment to evaluate the proximity detection and warning technology. Experimental results show that proximity sensing and warning technologies can provide alerts to equipment operators at different pre-calibrated proximity alert ranges. The results suggest that safety can be promoted on construction jobsites by implementing real-time proximity sensing and warning technology.

KEYWORDS: Construction equipment, pro-active safety, proximity sensing and alert technology, workers-on-foot.

INTRODUCTION

Each construction jobsite is characterized by a unique size and set of working conditions. These construction jobsite environments are a mixture of multiple resources such as construction personnel, equipment and materials. Each of these resources performs dynamic construction activities in a defined space, and they often are in close proximity to each other. When construction equipment is operating in close proximity to ground workers, a hazardous situation is potentially created. Contact collisions between ground workers and heavy construction equipment can increase the risk of injuries and fatalities for construction personnel.

Previous researcher has discussed the proximity issue in construction including injury and fatality statistics of collisions between construction equipment and workers. Because construction projects often involve many repetitive tasks, construction workers can experience decreased awareness and loss of focus (Pratt et al. 2001, Teizer et al. 2010). Construction equipment operator visibility, specifically operator blind spots, can be a major factor in contact collisions between construction equipment and ground workers (Fullerton et al. 2009). A real-time proximity detection and warning system is needed on construction jobsites to warn equipment operators of hazardous proximity situations.

A lack of scientific evaluation data currently exists for construction safety technologies such as proximity detection and warning systems. Minimal information and data currently exists to evaluate how existing construction safety technologies can be implemented to warn construction personnel of the presence of hazardous proximity situations. Experiments designed to emulate the construction environment need to be developed to evaluate these emerging safety technologies. Data retrieved from these experiments can be used to demonstrate the validity and effectiveness of these safety technologies.

Historically, construction companies have been slow to implement new technology and innovation in comparison to other industries. Other industry sectors in the United States, such underground mining and railroad operations, have tested and began implementing various proximity detection technologies (Teizer et al. 2010). As demonstrated by these industry sectors, emerging safety technologies including real-time proximity detection and warning technology can be used to promote safety in construction.

A review of current construction safety statistics, safety best practices and existing safety technologies including proximity sensing technology will be executed. The review of existing safety technologies will include pro-active safety technologies using secure radio frequency (RF) technology. These technologies will be reviewed specifically for their effectiveness to perform in the construction environment. Recommendations for future work on this issue including potential applications to promote construction safety will be discussed.

LITERATURE REVIEW

Construction jobsites are characterized by movement and interaction between different construction resources. The dynamic nature, unique size and scope of each of construction project create hazardous proximity issues. The following review covers current injury and fatality incidents associated with proximity issues in the construction industry. The review will also cover safety best practices of real-time safety approaches and technologies. A research needs statement is derived from findings of the review.

Injury Statistics Related to Workers and Construction Equipment

The United States construction industry experiences one of the highest accident fatalities rates per year when compared to other industries. A study completed in 2009 reported the construction industry accounted for 19% of the nation's workplace fatalities (CFOI 2009). In 2009, the Bureau of Labor Statistics reported 818 fatalities in the construction industry. Of these construction fatalities, 18% (151 fatalities) resulted from workers being struck-by an object or piece of construction equipment. Fatalities resulting from workers being struck on the jobsite represented 3% of the totally workplace fatalities experienced in 2009 by the United States private industry sector (BLS 2009b). In 2008, the Bureau of Labor Statistics reported 201 fatalities resulting from collisions between construction personnel and equipment or objects. These fatalities account for 21% of all fatalities experienced by the construction industry in 2008, and 3.5% of the total fatalities experienced by the United States private industry sector. Since 2003, the construction industry has averaged 216 fatalities resulting from construction equipment or other objects striking workers per year (BLS 2009b).

Injuries and illnesses resulting from proximity issues also present safety concerns for the construction industry. These types of accidents negatively affect the success of a construction project through lost work time, increased medical costs, etc. In 2009, the Bureau of Labor Statistics found that the private sector of the construction industry reported 30,330 injuries and illnesses caused by ground workers colliding with construction equipment or other objects. These injuries and illnesses represent 33% of all the construction worker injuries and illnesses in that year. The injuries and illnesses experienced by the construction industries in 2009 were fewer than the 42,970 injuries and illnesses experienced in 2008 resulting from personnel collisions with equipment or objects. This value decreased from the 47,870 injuries and illnesses resulting from personnel collisions with construction equipment and objects in 2007. These injury and illness data accounted for 36% of all construction injuries and illnesses in 2008 and 35% in 2007. All reported injuries and illnesses values are limited to accidents involving personnel to be absent from work as a result of the injury or illness (BLS 2009a).

Current Safety Best Practices

Standards and regulations mandated by the Occupational Safety and Health Administration (OSHA) are imperative to promote safety in construction, but are currently not capable of preventing contact collisions between workers and construction equipment. Current safety regulations require passive safety devices such as hard hats, reflective safety vests and other personal protective equipment (PPE). These passive safety devices are incapable of alerting construction operators and workers in real-time during a hazardous proximity situation. Other safety regulations such as safety training and education can increase the awareness of close proximity issues for construction operators and workers.

Much research has been performed with regards to safety behavior of construction workers. A study completed by the Construction Industry Institute (CII) monitored construction workers and later provided suggestions about safe and unsafe practices that were observed. The method provided near real-time feedback during the monitoring period for the construction workers (Hinze and Gambatese 1996). Another study conducted by CII found that companies that implemented site-specific safety programs early in the project experienced better safety records than others (Hinze 2003). The study found that increased efforts in front-end planning including design for safety can improve safety on construction projects.

Construction Worker/Equipment Related Accidents

Various research efforts have been performed in an attempt to better understand hazardous proximity situations between construction workers equipment jobsites. One study found that the harsh outdoor environmental characteristic of construction jobsites integrated with the repetitive nature of construction tasks can cause workers to lose focus and awareness of their surroundings (Pratt et. al. 2001). Another study found the actual cause of proximity issues other safety incidents is neither being properly examined nor recorded. If the information is recorded, important details of the incident are not included (Fosbroke 2004). This study further identified two general problems resulting in proximity issues between construction equipment and workers in the industry:

1) Workers and equipment operators: Outdated or never implemented policies, a lack of knowledge of existing specific risk factors, and repetitive work tasks; and

2) Incident investigation: All incident causation data is collected after-the-fact resulting in no or limited real-time incident information.

Other research efforts focused on strategies for prevention of hazardous proximity situations on construction jobsites. Preventative measures include implementing a construction equipment maintenance checklist and internal traffic control plans (ITC) specific to each jobsite (Pratt et al. 2001). The ITC plan is created during the planning phase in an attempt to limit turning or reverse movements of construction equipment.

Real-time Pro-Active Proximity Warning and Alert Technology

A study performed in 2007 found that real-time safety technologies implemented on construction jobsites are capable of providing alerts to construction workers and equipment operators in real-time when a hazardous proximity issue is present (Teizer et al. 2010). These technologies can create a safety barrier and provide workers with a “second chance” if another safety best practice is disregarded (Teizer et al. 2008). Some of these technologies are also capable of recording safety data that currently not obtainable, such as “close calls” or “near misses.” This new information and warning system can present new data sources and potentially improve safety in construction.

In 2001, Ruff found several proximity warning systems including RADAR (Radio Detection and Ranging), sonar, Global Positioning System (GPS), radio transceiver tags, cameras, and combinations of the mentioned technologies. The study found each of the candidate technologies to have limitations such as availability of signal, size, weight, and feasibility in the construction environment (Ruff 2001). A list of these limitations can be viewed in table 1.

A few similar studies also investigated candidate technologies to combat hazardous proximity issues on construction jobsites. Technologies excluded from the study were those still in the prototype stage and not yet commercially available (Teizer et al. 2007). The evaluated technologies for this study included Radio Frequency Identification (RFID), Ultra Wideband (UWB), Global Positioning Systems (GPS), magnetic marking fields, vision detection devices including video cameras, sonar, laser, and radar based proximity warning technologies. Several parameters such as read range, ability to calibrate the system, alert method, precision, capability of performing in an outdoor environment, and others were used to assess each candidate technology (Teizer et al. 2007). Table 1 shows benefits and limitations of technologies thought to possibly be capable of not selected for this research.

Radio frequency technology has been implemented in other industries such as manufacturing, shipping and the railroad industry. The construction industry needs a wireless, reliable and rugged technology capable of detecting and alerting workers when hazardous proximity issues exist. Teizer et al. (2010) demonstrated that radio frequency (RF) can satisfy the jobsite safety requirements.

Radio frequency technology can:

- Decrease the risk of collisions
- Provide alerts in real-time for equipment operators
- Create a tool for managing risk
- Monitor with minimal distractions (e.g., nuisance alerts) during normal operation
- Create an additional protection layer for workers
- Capable of performing in most construction environments

This study also found these limitations to radio frequency technology

- System requires a power source
- Must be installed on workers and construction equipment
- Construction equipment and jobsite conditions have an impact on proximity sensing

Table 1: Benefits and limitations of candidate proximity detection technologies (NIOSH 2007, Ruff 2001, Teizer et al. 2007)

Technology	Benefits	Limitations
GPS	• Minimal required infrastructure • Low initial cost • Can function on any outdoor jobsite	• Not functional indoors • Not suited for short range detection
Laser	• High accuracy of data • High signal update rate • Capable of functioning in the construction environment	• High initial cost • Not able to identify a ground worker from other objects • Only accurate for short range detection
Magnetic marking fields	• Minimal required infrastructure • Proximity ranges can be varied • System can identify a ground worker from other objects	• Requires a system specific battery for power source • Two devices are required to be installed on a worker
RADAR	• Capable of multiple antenna integration • Can be used to supplement video	• No capable of detection in fast moving scenarios • Not able to identify a ground worker from other objects • Only accurate for short range detection
Sonar	• Minimal infrastructure required • Low initial cost	• Minimal detection range • Susceptible to elements in the construction environment
UWB	• System can identify a ground worker from other objects • Can function on outdoor/indoor jobsites • 3-D location values in real-time	• Sizeable amount of infrastructure • High initial cost • Can function on any outdoor jobsite
Vision	• System can identify a ground worker from other objects • Capable of detection at large/small ranges	• Poor visibility at night or in dusty areas • Line-of-sight segmentation • High data processing effort

Methods for Testing Proximity Warning and Alert Systems

Several past research ventures have incorporated methods to evaluate the capabilities of proximity detection and alert systems. A camera and radar systems were mounted on a large capacity haul truck and proximity alert distances were manually marked and measured on the ground (Ruff 2005). Trials included several activities typical of a large capacity haul truck in copper environments. The system detected obstructions approximately 30 feet in front and behind the vehicle.

A similar experiment deployed GPS systems on large capacity haul trucks and a base station was located on a nearby hill (Ruff 2004). Several trials were performed to test the accuracy of the system to track three mobile vehicles and six stationary objects. The system was able to track all vehicles and objects while the haul truck performed typical activities in a surface mining environment.

Other research integrated computer-assisted stereo vision with the previously discussed radar detection system to potentially realize the benefits of a combined proximity detection and alert system (Steele et al. 2003). This collaborative research effort with the National Institute of Occupational Safety and Health (NIOSH) Stereo cameras were mounted on the rear of an off-highway dump truck. Several field trials positioned a person and berm in the path of the truck to evaluate the system's proximity detection capabilities.

OBJECTIVE AND METHODOLOGY TO EVALUATE PROXIMITY WARNING AND ALERT TECHNOLOGIES

The primary objective of this research is to promote and increase construction jobsite safety for workers during heavy equipment operations by using RF technology for real-time pro-active proximity warning devices. A secondary objective is to investigate the performance of real-time proximity warning and alert technologies on construction jobsites during heavy equipment operations. When construction resources are in close proximity to one another, the sensing technology will sense the hazardous condition and activate an alarm to warn equipment operators through devices called Equipment and Personal Protection Units (EPU and PPU, respectfully). The research is limited to proximity issues between heavy construction equipment and ground workers located on outdoor construction jobsites.

The radio frequency technology will be evaluated through several experiments. Each experiment is designed to measure the performance of the technology in a simulated and actual outdoor construction environment. The set of experiments tested the device's ability to detect and alert equipment operators of hazardous proximity issues while subjected to a simulated and active construction environment.

The first experiment tested the proximity sensing devices in a mobile ground worker and static construction equipment scenario. The PPU was attached to a ground worker outside of the construction equipment and one EPU was placed inside the cabin of each tested piece of construction equipment. The ground worker equipped with the PPU device approached the piece of static construction equipment at a specified distance from many different approach angles. A theoretical safety zone was created by plotting the points at which the alert was activated. Positioning of the EPU device inside the construction equipment cabin impacts the proximity range configuration, and therefore the device was placed in a similar location on each piece of construction equipment.

Similarly to the previous experiment, a static ground worker was equipped with a PPU device in this setting. An EPU device was installed on one piece of construction equipment. For each experiment, the construction equipment approached the static ground worker at a constant speed. After the alert was activated, the equipment operator halted the piece of construction equipment and the distance between the equipment's stopped location and the static ground worker was measured. Because the proximity distance was measured after the equipment was stopped, the data represented the minimal distance required to stop the equipment before it struck the ground worker.

The final experiment featured several PPU and EPU devices installed on various ground personnel and construction equipment respectfully on an active construction jobsite. When an alarm was activated, both the ground worker and equipment operator halted and the distance between the two parties was measured using a Robotic Total Station as described in previous experiments.

Each of the experiments was designed to evaluate a specific characteristic of the construction environment. The methods used for measuring proximity alert distances and data collection were held constant for all experiments. The research team reviewed all relevant OSHA safety regulations for heavy construction equipment. The team followed all OSHA safety regulations while conducting experiments on active construction jobsites and only qualified construction equipment operators were used for testing.

EXPERIMENTS AND RESULTS

Each experiment was designed to evaluate the effectiveness of proximity detection technology in the construction environment specifically between construction equipment and workers. Each experiment attempted to simulate functions characteristic of a typical construction jobsite. The proximity detection system utilized for the experiments used a secure wireless communication line of Very High Frequency (VHF) at approximately 434 MHz.

Technology Tested

Radio frequency (RF) technology was implemented for all of the proximity detection experiments. The system is made up of an in-cab device (EPU) for construction equipment and a personal device (PPU) for ground workers. The EPU device contains a single antenna, reader, alert mechanism and can be connected to the central power source of construction equipment. The PPU device consists of a chip, battery, and alarm and can be installed on the hard hat of a construction worker. A signal broadcasted by the EPU is intercepted by the PPU when the devices are in too close of proximity which is defined by the calibrated alert distance. The signal is broadcasted by the EPU in a radial manner and loses strength as the distance increases from the EPU location. The proximity range can be manually modified by the user to lengthen or shorten the range of which an alert is activated. When the PPU intercepts the radio signal, it immediately returns a signal and an alert is activated from the EPU in real-time.

These proximity detection devices used for these experiments have two different alert methods. Construction equipment operators in a hazardous proximity location can receive a visual and audible alarm. Equipment operators receive an alert through an audible alarm and visual flashing lights located on the device inside the equipment cabin. The audible alert creates enough noise so that workers or operators wearing ear phones are still able to hear and distinguish the alert. The audible alarm is also different from other sounds and back-up alerts common to construction jobsites. The visual alerts provide more alert options because the workers can become desensitized to audible alerts. A series of red light-emitting-diodes (LEDs) activate upon a proximity breach. These lights are distinguishable among typical construction equipment controls. This visual alert can be viewed in figure 1 along with the PPU and EPU deployed in a simulated construction environment.

Figure 1: PPU device installed on a ground worker's hard hat (left), EPU device installed on an asphalt paver (right) with alert activated

The PPU and EPU devices were designed to be durable including sturdy casing capable of withstanding daily weathering. The PPU rechargeable battery power duration is approximately two average work days. A small LED located on the PPU is activated when the device is charged and working. The EPU can connect directly to the battery source of a piece of construction equipment and also displays a green LED when the system is functioning properly. The EPU unit can be installed in areas visible to the operator in the equipment cabin without obstructing the line-of-sight to objects outside of the cabin.

The proximity detecting and warning technology used in the experiments are capable of four different alert scenarios. These scenarios describe the action of the technology when the construction ground worker is located a safe distance from a piece of construction equipment and when the ground worker is in a hazardous proximity situation. The hazardous proximity region around a piece of construction equipment is pre-defined and calibrated into the proximity detecting and warning devices. The following four scenarios can occur when using these devices on construction jobsites:

True positive:	An alert is activated when a ground worker is in too close proximity with a piece of construction equipment.
False positive:	An alert is activated when a ground worker is located at a safe distance from a piece of construction equipment (also referred to as nuisance alarms).
True negative:	An alert is not activated when a ground worker is located at a safety distance from a piece of construction equipment.
False negative:	An alert is not activated when a ground worker is in too close proximity with a piece of construction equipment.

Of the four alert scenarios, false negative scenarios are the worst cases because the technology fails to alert the construction equipment operator of the hazardous proximity situation. False positive (nuisance alarms) are also undesirable because frequent non-hazardous alerts can desensitize equipment operators to potential hazardous proximity situations. Both true positive and true negative alerts are the most desirable alert scenarios because they accurately identify the status of proximity situations on construction jobsites. Figure 2 presents a flowchart of the four possible alert scenarios for the designed experiments.

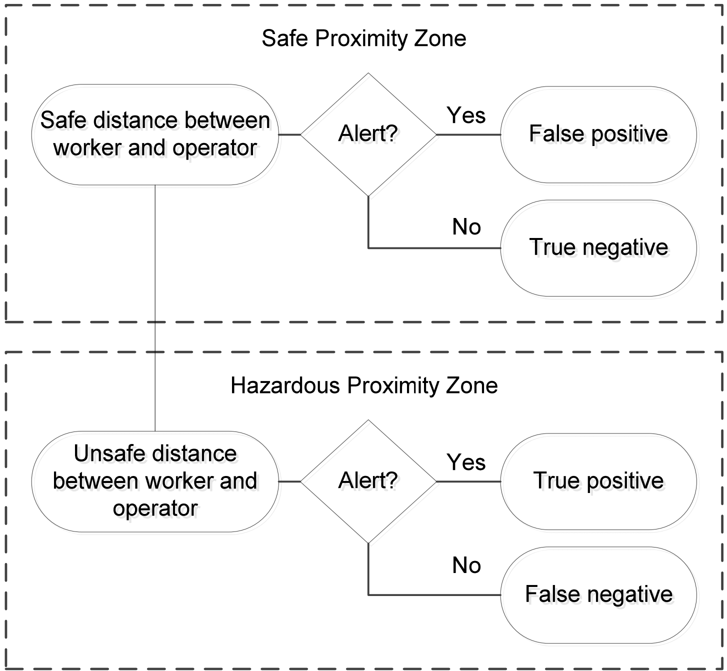


Figure 2: Flowchart of alert scenarios

Experiments and Results with Proximity Warning Devices
A proximity detection device prototype was used based on the safety needs of the construction industry. This system was evaluated in three different experimental settings, each evaluating the performance and capabilities of different aspects of the system.

Construction Field Conditions Trials – Stage 1
For the first experimental trials, an EPU device was placed in a simulated construction environment to evaluate the effectiveness of the proximity detection system in the outdoor field conditions. The testbed for these trials was a clear, flat, asphalt paved surface with no obstructions. A Robotic Total Station (RTS) and traffic control devices were used to create this testbed. The RTS was positioned at the center of a 15.2 m (50 ft.) radius circle, and traffic control devices were placed at 36 equal distant locations around the circumference of the circle. The traffic control devices were positioned at 10 degree offsets around the circle. Figure 3 shows the testbed used for these experiments.

Figure 3: Testbed for field experiments

The center point of the circular testbed served as the location for the EPU’s antenna component. The EPU was installed inside the equipment cabin (when applicable) in view and audible range of the operator. The antenna component of the EPU was mounted on top the operator’s side of the equipment at the highest point for the best detection range. The personal protection device was clipped to the hard hat of a worker-on-foot as was done in the previous experiment. These configurations can be viewed in Figure 4.

Figure 4: Mounting position of an EPU antenna on a wheel loader cabin (left); detail view of antenna location (right)

A worker wearing a hard hat equipped with a PPU approached each piece of construction equipment at a constant walking pace from 36 equal distance approach angles. After the EPU device activated an alert, the worker stopped walking and measured the alert distance using a measuring wheel (see Figure 5). This method was repeated twice for each approach angle and per piece of construction equipment. Three different personal detection devices with varied calibrated alert ranges (short, medium, and long) were tested for each piece of equipment. This experimental procedure was performed using the following pieces of construction equipment: dump truck, mower, steel drum roller, wheel loader, grader, truck and trailer, asphalt paver, excavator, and pick-up truck.

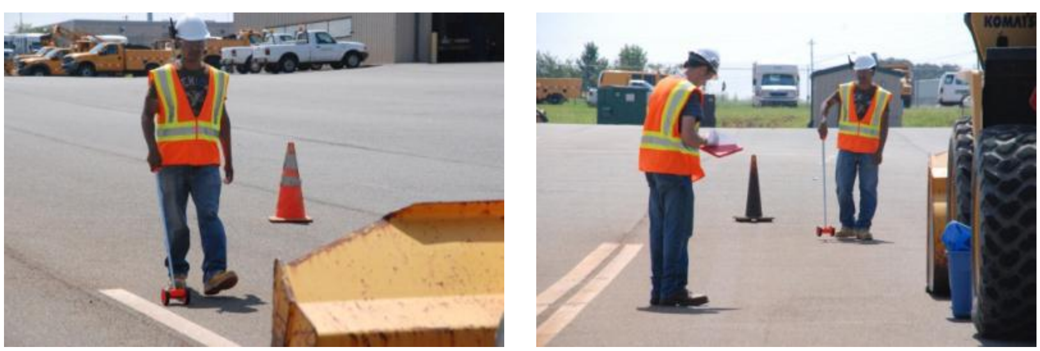


Figure 5: Measurement of the alert distance (left); Test person recording the measured alert distance (right)

The total sample size for each piece of construction equipment was 432 measurements. A statistical analysis was performed on each subsample (every calibrated alert distance and piece of construction equipment) of measured alert distance. The data was also analyzed for false positive (nuisance alerts) and false negative readings. False negatives were defined as the worker striking the construction equipment before an alert was activated. Percentage values of activated alerts were also calculated for each piece of construction equipment tested.

Table 2 shows results of the data analysis for the proximity detection alert distances of workers approaching a static asphalt paver. The medium range detection device had the lowest standard deviation and range discrepancy when compared to the other calibrated devices tested on the asphalt paver. Numbers denoted with bold text in Table 2 were the most precise performers of the three different alert ranges. 99.5% of the 432 worker approaches activated an alert from the system. In two cases, the worker struck the asphalt paver without activating an alert was recorded as a false negative reading.

Table 2: Statistical analysis of the alert measurements for the asphalt paver

	Short Range	Medium Range	Long Range
Median	13.8 m	14.8 m	16.9 m
Minimum Distance	0.0 m	10.3 m	12.2 m
Maximum Distance	18.5 m	17.8 m	31.9 m
Range	18.5 m	**7.5 m**	19.7 m
Standard Deviation	2.7	**1.7**	3.4

The obtained data from each piece of equipment was used to develop proximity alert range graphs. These graphs display the recorded distant measurement from the worker's position to the EPU antenna at the time the alert is activated. Figure 6 shows the recorded alert distant measurements of the medium alert range personal protective device. The two lines represent the two different trials from each approach location with the medium alert range device.

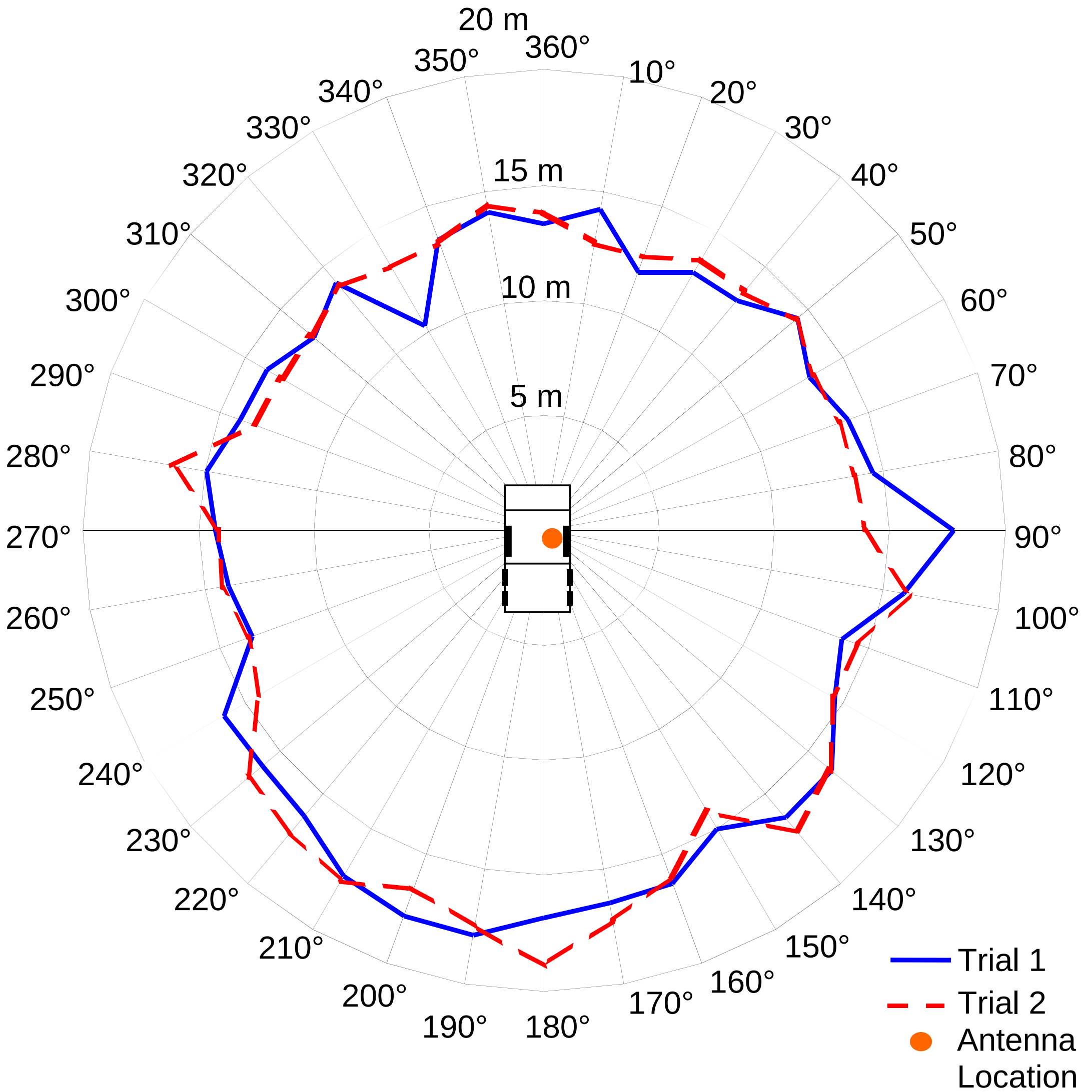


Figure 6: Active proximity warning zone for a specific alert range

Construction Field Conditions Trials – Stage 2

The final sets of field experiments were conducted to test the effectiveness of the proximity detection devices on mobile equipment and static workers. These tests were completed on a flat, unobstructed paved surface similar to the previous field experiment. The EPU device was installed in a pick-up truck with the antenna mounted on top of the truck's cabin on the driver's side. A static ground worker equipped with a PPU was positioned next to a Robotic Total Station (RTS), and was aligned on a straight path with the pick-up truck. Traffic control devices were spaced five and ten meters along the truck's trajectory towards the ground worker.

After maintaining a constant speed of 16 kilometers per hour (10 miles per hour), the truck driver stopped the vehicle after the alert triggered. As done in the previous field experiment, three different proximity detection devices with varied alert ranges (short, medium, and long) were tested in this experiment. Each of the three PPUs was tested 32 times. The left side of figure 7 shows the stopped truck after the EPU has activated an alert. Box plots of the three different ranges and 96 data points gathered from this experiment are shown on the right side of figure 7. All trials resulted in true positive alerts. No false alerts (including nuisance alarms) occurred during any of the 96 trial runs.

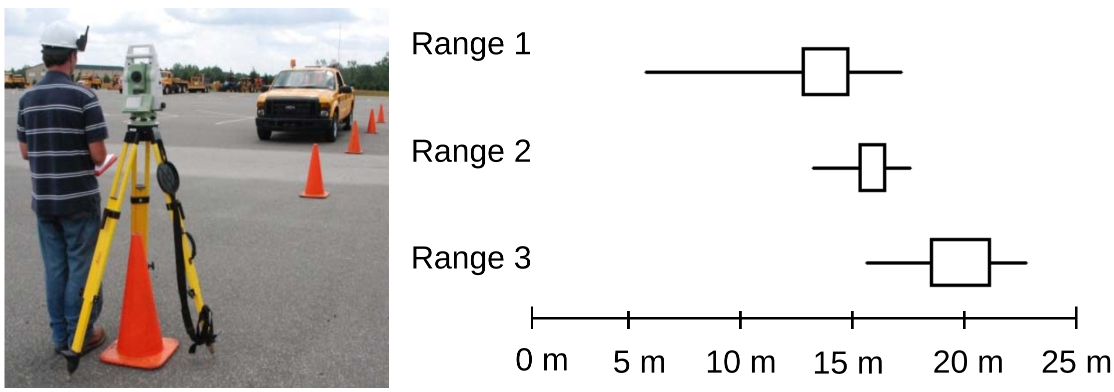


Figure 7: Static worker and dynamic equipment experiment (left) and box plot of proximity detection distance for each personal tag (right)

Long-term Construction Jobsite Trials

After completing the laboratory and both stages of the construction field trials, the research team evaluated the proximity sensing and alert devices on a long-term construction jobsite. This coal power plant extension project near Rome, Georgia was often referred to as the “Huffaker Site - Plant Hammond” and contained over 200 acres of active site work area. Over 1,000,000 cubic yards of soil was moved using off-road haul trucks, scrapers and compactors in order to build containment cells to store coal ash for the power plant. Typical ground personnel on the project included: Earthmoving subcontractors, owner representatives, geotechnical engineers, inspectors and visitors. The large project area, heavy earthmoving equipment and ground personnel exposure made this project a prime candidate for hazardous proximity situations between ground personnel and heavy construction equipment.

The general contractor had implemented several safety measures to protect ground workers on the jobsite. All required safety regulations (such as OSHA standards) were administered on the project. Visitors were required to sign-in at the project entrance, notify a supervisor, review construction equipment traffic patterns, notify operators of destination and proceed with an escort while on the jobsite. Equipment operators and ground workers followed OSHA regulations and company safety policies.

Results from the previous experiments were used to calibrate and configure the proximity sensing and detection system on construction equipment and ground personnel. For example, careful attention was used to not obstruct the equipment operator's line of site when installing the EPU devices. PPU devices were attached to ground personnel as described in the previous experiments.

While the construction project was active, the proximity sensing and alert system were deployed for several construction scenarios. Several EPU devices were mounted on various pieces of active construction equipment and PPU devices were installed on ground workers working near the equipment. The first of the two construction scenarios used was an EPU device was mounted on a stationary mobile crane and PPU devices were attached to workers completing tasks around the crane. For the second scenario, EPU devices were mounted to several pieces of construction equipment on the jobsite and the PPU device was attached to a stationary ground worker.

For both scenarios, the distance between the worker and the piece of construction equipment was measured using the RTS when proximity alerts were activated. During the testing period, approximately 200 alerts were activated and measured. The minimum alert distance was 2.8 meters and the maximum alert distance was 62.5 meters. Table 3 shows the minimum, maximum, and average recorded alert distances along with the standard deviation for each piece of construction equipment equipped with an EPU device.

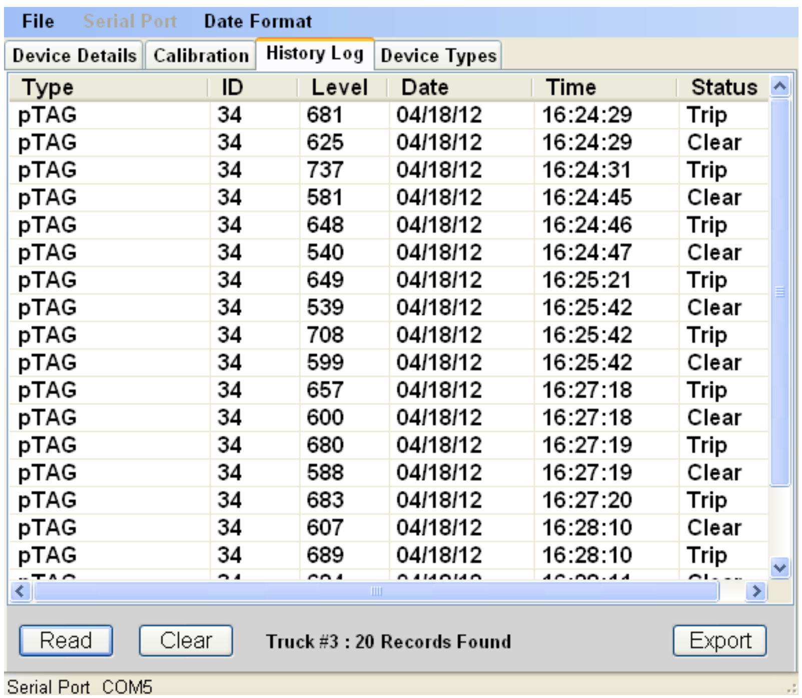
Table 3: Analysis of alert distance measurements of proximity sensing and alert system on real construction jobsites.

Equipment Type	Average Alert Distance (m)	Range of Alert Distance (m)	Standard Deviation of Alert Distance (m)
Static Equipment			
Articulated Dump Truck	35.61	31.00	7.42
Excavator	23.44	35.20	10.58
Mobile crane	33.95	53.61	16.01
Mobile Equipment			
Personal mover (RTV)	11.91	3.01	1.38
Wheel loader/forklift	17.83	17.20	6.06
Dozer	24.53	35.20	8.54

In a second experiment, the ground worker equipped with the PPU device was located inside of the project safety manager's pick-up truck. The pick-up truck traveled at a constant speed and trajectory towards a static motor grader. Once the alert was activated, the truck stopped and the distance was measured from the front of the pick-up truck to the EPU location on the motor grader. During this experiment, the pick-up truck stopped at least 30 meters from the static motor grader.

Data Recording

In addition to the location distance measured by the research team during all experimental trials, the proximity sensing and warning technology system has data recording and logging capabilities. During selected experiments previously described, the system recorded the ground PPU tag number, time and date of each proximity breach. A proximity breach included all instances in which a construction ground worker entered or exited the pre-calibrated hazardous proximity range around a piece of construction equipment. The column titled "level" indicates the relative distance at which the system trigged an alert to the equipment operator. The column titled "status" denotes if the worker entered ("Trip") or exited ("Clear") the pre-defined proximity distance of a piece of construction equipment. A sample interface of the data logged during these experiments can be viewed in Figure 8.



Type	ID	Level	Date	Time	Status
pTAG	34	681	04/18/12	16:24:29	Trip
pTAG	34	625	04/18/12	16:24:29	Clear
pTAG	34	737	04/18/12	16:24:31	Trip
pTAG	34	581	04/18/12	16:24:45	Clear
pTAG	34	648	04/18/12	16:24:46	Trip
pTAG	34	540	04/18/12	16:24:47	Clear
pTAG	34	649	04/18/12	16:25:21	Trip
pTAG	34	539	04/18/12	16:25:42	Clear
pTAG	34	708	04/18/12	16:25:42	Trip
pTAG	34	599	04/18/12	16:25:42	Clear
pTAG	34	657	04/18/12	16:27:18	Trip
pTAG	34	600	04/18/12	16:27:18	Clear
pTAG	34	680	04/18/12	16:27:19	Trip
pTAG	34	588	04/18/12	16:27:19	Clear
pTAG	34	683	04/18/12	16:27:20	Trip
pTAG	34	607	04/18/12	16:28:10	Clear
pTAG	34	689	04/18/12	16:28:10	Trip

Figure 8: Software interface of recorded proximity breaches.

Information from this system was exported into a database and further analyzed. Individuals involved with a large amount of proximity breaches when compared to co-workers were highlighted. From this point, construction safety managers can further explore details of the proximity breach by monitoring the individual on the project site, and providing further safety training specific to hazardous proximity issues to select ground workers and equipment operators. Construction safety personnel can also use this tool to provide preventative safety training by reviewing past recorded data and informing ground workers and equipment operators of past hazardous proximity situations during certain construction activities.

The proximity breach data record capabilities of the tested proximity detection and alert system are calibrated and function based on relative distances, or the distance from the PPU to the EPU relative to other detected devices. Proximity breach data for the both stages of the construction field condition trials were recorded and analyzed. The relative distance at which the PPU device was detected can be viewed in figure 8 under the column heading "Level." An alert was triggered (trip condition) or silenced (clear condition) by the EPU at these relative detected distances. Results indicate that physical features of construction equipment impact the correlation between the desired calibrated relative distance and the actual triggered alert relative distance. Table 4 shows an analysis of the calibrated alert distances and actual alert distances for stage 2 of the construction field condition trials using the normal distribution. For each of these trials, the PPU were calibrated as follows: Range 1: 640, Range 2: 580 and Range 3: 515. The software allows for calibrated relative alert distances between 0 and 1000.

Table 4: Analysis of recorded relative distances or level for alerts (unitless) of the stage 2 of the construction field condition trials

	Average alert level	Range of alert level	Standard deviation of alert level
Range 1	590.14	317	32.54
Range 2	575.73	118	19.75
Range 3	546.57	398	34.22

LIMITATIONS, FUTURE WORK, AND APPLICATION AREAS

The objective of this research was to evaluate the effectiveness of proximity detection and alert technologies on heavy equipment in the construction environment. After completing the four experiments, the research team found limitations to the tested proximity detection system. Many parameters and potential influences on the system should be evaluated through future experimentation. Future studies should include the following:

- Impact of temperature, humidity, precipitation and other ambient influences on warnings and alerts, and in particular on use of batteries on PPUs,
- Location and mounting positions of the EPU and PPU devices,
- Reaction of workers and equipment operators to implementing the devices,
- Calibration of specialized alert distances for individual pieces of construction equipment including operator and worker reaction time, operator brake distances, ground surface preparation, weather conditions and object mitigation strategy,
- Record and analyze "near-miss" data to further education construction workers on proximity issues,
- Analysis of calibrated alert distance and actual alert distances on various pieces of construction equipment in different environmental settings,
- Collect and analyze "nuisance alerts" to evaluate reliability of system,

- Create an implementation strategy for proximity detection systems in construction, and
- Extended construction field trials with the proximity detection devices.

Illnesses, injuries and fatalities resulting from hazardous proximity issues can become very expensive after summing medical costs, insurance costs, productivity decrease resulting from time lost, and possible litigation costs. Some of these costs could potentially be avoided by implementing emerging safety technologies such as real-time proximity detection and alert systems. This safety technology can improve safety on construction jobsites by giving construction equipment operators a warning during a hazardous proximity situation.

CONCLUSION

Current safety practices for proximity issues in construction have proven inadequate as demonstrated by the number of fatalities, accidents, and illnesses resulted from proximity issues. The ultimate goal of the construction industry must be to achieve zero accidents and injuries for all construction jobsites. The purpose of this research was to determine a method that tests if proximity detection and alert systems are capable of functioning in the construction environment and if they can promote safety when resources (e.g., workers, equipment) are in too close proximity. Results obtained from the review and experiments suggest that the method of testing real-time proximity sensing and alert systems works successfully and furthermore, that the tested technology has the potential to improve equipment-worker safety in construction.

The proximity sensing and alert device prototype demonstrated its ability to perform by detecting the presence of hazardous proximity situations on construction jobsites. The designed experiments tested different pieces of construction equipment including a wheel loader, mower, dump truck, steel drum roller, excavator, motor grader, pick-up truck, asphalt paver and truck and trailer combination. In nearly all trials, the proximity detection system was able to detect and activate an alert when construction resources were in too close proximity to each other. In one instance, the radio frequency signal was block by a metal pipe, asking eventually multiple antennas to be installed on a piece of equipment to cover all signal blind spots. The audible alerts were to a sufficient volume to be heard over back-up alarms and other general and loud construction noise. The equipment operator was also able to see the visual alert provided by the EPU device. Overall, the system demonstrated its ability to perform in the simulated construction environment by warning equipment operators when they were operating in too close proximity to ground workers.

Although the field trials with the proximity detection and alert system were deemed successful, other parameters were noted that could potentially have an influence on the system, specifically the signal propagation. These factors include ambient temperature, relative humidity, mounting position and orientation of the devices on ground workers, construction equipment and other objects. These barriers along with others require further investigation to better evaluate the effectiveness of implementing proximity detection and alert devices in the construction environment.

REFERENCES

Bureau of Labor Statistics (2009a). “Census of Fatal Occupational Injuries (CFOI) – Current and Revised Data.” *Bureau of Labor Statistics*, <http://www.bls.gov/iff/oshcfooil.htm#2007> (May 10, 2011).

Bureau of Labor Statistics (2009b). “Census of Fatal Occupational Injuries (CFOI) – Current and Revised Data.” *Bureau of Labor Statistics,* <http://www.bls.gov/iff/oshcfooil.htm#2008> (May 15, 2011).

Census of Fatal Occupational Injuries (2009). “Fatal occupational injuries by industry and selected event or exposure.” *U.S. Bureau of Labor Statistics,* <http://www.bls.gov/news.release/cfoi.t02.htm> (Nov. 15, 2011).

Fosbroke, D.E. (2004). “NIOSH Reports! Studies on Heavy Equipment Blind Spots and Internal Traffic Control.” *NIOSH,* <https://www.workzonesafety.org/files/documents/news_events/wz_conference_2004/heavy_equipment.pdf> (May 16, 2011).

Fullerton, C.E., Allread, B.S., and J. Teizer, J. (2009). “Pro-Active Real-time Personnel Warning System.” *Proceedings of the Construction Research Congress,* CRC, Seattle, Washington, 31-40.

Hinze, J. and Gambatese J.A. (1996). “Addressing Construction Worker Safety in the Project Design.” *Research Report RR101-11 to the Construction Industry Institute*, Austin, TX, 1-149.

Hinze, J. (2003). “CII: Safety Plus: Making Zero Accidents A Reality. Research.” University of Texas at Austin, Summary 160-1, 2003.

Navon, R. and Sacks R. (2006). “Assessing research issues in automated project performance control (APPC).” *Automation in Construction*, 16(4), 474–484.

NIOSH (2007). “Recommendations for Evaluating & Implementing Proximity Warning Systems on Surface Mining Equipment.” *Report of Investigations RI 9672*, Department of Health and Human Services: CDC, Atlanta, GA.

Pratt, S. G., Fosbroke, D.E., 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: CDC, NIOSH, 5-6.

Ruff, T.M. (2001). "Monitoring Blind Spots - A Major Concern for Haul Trucks." *Engineering and Mining Journal*, 202(12), 17–26.

Ruff, T.M. (2004). "Advances in Proximity Detection Technologies for Surface Mining." *Proceeding of the 24th Annual Institute on Mining Health*, Health, Safety and Research, Salt Lake City.

Ruff, T.M. (2005). "Evaluation of a Radar-Based Proximity Warning System for Off-Highway Dump Trucks." *Accident Analysis & Prevention,* 38(1), 92-98.

Steele, J., Debrunner C., 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.S., Fullerton, C.E. and Hinze, J. (2010). "Autonomous Pro-Active Real-Time Construction Worker and Equipment Operator Proximity Safety Alert System." *Automation in Construction,* 19(5), 630-640.

Teizer, J., Caldas, C.H., and Haas, C.T. (2007). "Real-Time Three-Dimensional Occupancy Grid Modeling for the Detection and Tracking of Construction Resources." A*SCE Journal of Construction Engineering and Management,* 133(11), 880-888.

Teizer, J., Venugopal, M., and Walia, A. (2008). "Ultra Wideband for Automated Real-time Three-Dimensional Location Sensing for Workforce, Equipment, and Material Positioning and Tracking." *Transportation Research Record: Journal of the Transportation Research Board*, 208(1), 13-20.