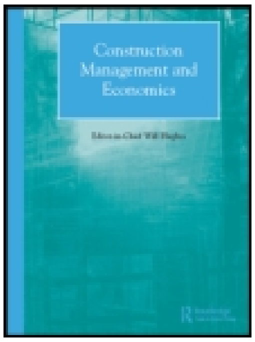

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Eric Daniel Marks & Jochen Teizer

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Method for testing proximity detection and alert technology for safe construction equipment operation

ERIC DANIEL MARKS and JOCHEN TEIZER*

School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, USA

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The US construction industry continues to be among the leading industries for workplace fatalities after experiencing 818 fatalities in 2009. Approximately 21% of these fatalities resulted from workers being struck by an object or piece of construction equipment. The nature of construction sites often produces hazardous conditions by requiring ground workers and heavy construction equipment to operate in close proximity. The primary objective is to present a method for testing proximity detection and alert systems. Experimental trials were designed to deploy emerging radio frequency (RF) remote sensing technology to demonstrate the ability of the test method to evaluate the capability of proximity detection and alert systems to provide alerts when heavy construction equipment and workers are in too close proximity to each other. Numerous field experiments were designed and conducted to emulate typical interactions between workers on foot and construction equipment. These devices were installed on pieces of construction equipment in an outdoor environment to evaluate the test method for proximity detection and alert systems. Experimental results show that proximity detection and alert technologies can provide alerts to equipment operators at different pre-calibrated proximity alert ranges. The results suggest that the presented testing method adequately evaluated the reliability and effectiveness of the proximity detection and alert technology in the construction environment.

Keywords: Construction equipment, risk identification, safety, technological innovation, workforce.

Introduction

Each construction site is characterized by a unique size and set of working conditions. These construction work environments are a mixture of multiple resources such as construction personnel, equipment and materials. Each of these resources performs a multitude of dynamic construction activities in a defined space and it is often required that they operate at 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 researchers have discussed the proximity issue in construction including injury and fatality statistics of collisions between construction equipment and workers. Because construction activities often involve many repetitive tasks, construction workers can experience decreased awareness (Pratt *et al.*, 2001). Construction equipment operator visibility, specifically blind spots, is a major factor in contact collisions between construction equipment and ground workers (Hinze and Teizer, 2011; Ray and Teizer, 2012; Cheng and Teizer, 2013). A real-time proximity detection and alert system is needed on construction sites to warn equipment operators of hazardous proximity situations.

There are few scientific evaluation data for construction safety technologies such as proximity detection and alert systems including limited testing methods for evaluating these systems. Minimal information and data currently exist 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

*Author for correspondence. E-mail: teizer@gatech.edu

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 US, such as underground mining and railroad operations, have tested and have begun implementing various proximity detection technologies (Teizer *et al.*, 2010). As demonstrated by these industry sectors, emerging safety technologies including real-time proximity detection and alert systems can be used to provide ground workers with alerts during hazardous proximity situations.

A review of current construction safety statistics, safety best practices and existing safety technologies including proximity sensing technology will be undertaken. The review of existing safety technologies will include proactive safety technologies. These proximity detection and alert systems will be reviewed specifically for their effectiveness when performing in the construction environment. The review will also cover current testing methods for proximity detection and alert systems. Recommendations for future work on this issue including potential applications to improve construction safety will be discussed.

Literature review

Construction sites are characterized by movement and interaction between different construction resources. The dynamic nature, unique size, and scope of each construction project can create hazardous proximity issues. The following review covers current injury and fatality incidents associated with proximity issues in the construction industry as well as current practices of 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 US construction industry experiences one of the highest accident fatalities rates per year when compared to other industries. A study completed in 2009 reported that the construction industry accounted for 19% of the nation's workplace fatalities (Census of Fatal Occupational Injuries, 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 represented 3% of the total workplace fatalities experienced in 2009 by the US private industry sector (Bureau of Labor Statistics, 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 US private industry sector. Since 2003, the construction industry has averaged 216 fatalities resulting from construction equipment or other objects striking workers per year (Bureau of Labor Statistics, 2009b).

Injuries and illnesses resulting from proximity issues also present safety concerns for the construction industry. These types of accidents negatively impact on 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 industry in 2009 were fewer than the 42 970 injuries and illnesses experienced in 2008 resulting from personnel collisions with equipment or objects. This number was a decrease from the 47 870 injuries and illnesses resulting from worker 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 numbers are limited to accidents causing personnel to be absent from work as a result of the injury or illness (Bureau of Labor Statistics, 2009a).

Current safety best practices

Standards and regulations mandated by the Occupational Safety and Health Administration (OSHA) are imperative to improve 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 carried out with regard to safety behaviour 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 programmes 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 undertaken in an attempt to better understand hazardous proximity situations between construction workers and equipment. One study found that the harsh outdoor environmental characteristics of construction sites 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 are 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.
(2) Incident investigation: All incident causation data are 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 sites. Preventative measures include implementing a construction equipment maintenance checklist and internal traffic control (ITC) plans specific to each project (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 proactive proximity detection and alert technology

A study performed in 2007 found that real-time safety technologies implemented on construction sites are capable of providing alerts to ground workers and construction 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 are not obtainable, such as 'close calls' or 'near misses'. This new information can present new data sources for construction safety.

In 2001, Ruff found several proximity detection and alert systems including radar (radio detection and ranging), sonar, Global Positioning System (GPS), radio transceiver tags, cameras, and combinations of the 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 sites. Technologies excluded from the study were those still in the prototype stage and not yet commercially available (Teizer *et al.*, 2007). The evaluated technologies 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 detection and alert 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). Benefits and limitations of these candidate technologies are listed in Table 1.

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 site 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;
- perform in most construction environments.

This study also found these limitations to radio frequency technology:

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

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

- the system requires a power source;
- it must be installed on workers and construction equipment;
- construction equipment and site conditions have an impact on wireless sensing.

Methods for testing proximity detection 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, 2006). Trials included several activities typical of a large capacity haul truck in copper environments. The system detected obstructions approximately 30 feet in front of and behind the vehicle.

A similar experiment deployed GPS 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). Stereo cameras were mounted on the rear of an off-highway dump truck. Several field trials positioned a person and a berm in the path of the truck to evaluate the system's proximity detection and alert capabilities. The testing method was effective but required a large amount of time and resources (people) to conduct.

Objective and methodology to evaluate proximity detection and alert technologies

The primary objective is to create a testing method for evaluating the effectiveness and reliability of proximity detection and alert technologies in the construction environment. A secondary objective is to evaluate the capabilities of emerging radio frequency (RF) remote sensing technology to provide alerts when heavy construction equipment and workers are in too close proximity. When construction resources are in close proximity to one another, the sensing technology will detect the hazardous condition and activate an alarm to warn equipment operators through devices called equipment protection units and personal protection units (EPUs and PPUs, respectively). The scope includes proximity issues between heavy construction equipment and ground workers located on outdoor construction sites.

The radio frequency technology will be evaluated through several experiments. Each experiment is designed to measure the performance of the presented testing method and 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 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 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 inside the construction equipment cabin affects the proximity range configuration, and therefore the device was placed in a similar location on each piece of construction equipment.

In the next experiment, similar to the previous one, a static ground worker was equipped with a PPU in this setting. An EPU 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 point where the equipment was stopped 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 PPUs and EPUs installed on various ground personnel and construction equipment respectively on an active construction site. 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 (RTS) 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 followed all OSHA safety regulations while conducting experiments on active construction sites and only qualified construction equipment operators were used for testing.

Experiments and results

Each experiment was designed to evaluate the effectiveness of the proposed testing method for proximity detection technology in the construction environment specifically between construction equipment and ground worker. Each experiment attempted to simulate functional characteristics of a typical construction site. 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 contains a single antenna, a reader and an alert mechanism, and can be connected to the central power source of construction equipment. The PPU consists of a chip, a battery and an alarm, and can be installed on the hard hat of a construction worker. A signal broadcast by the EPU is intercepted by the PPU when the devices are in too close proximity which is defined by the calibrated alert distance. The signal is broadcast 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 in 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 alarm and an 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 operators are able to hear and distinguish the alert. The audible alarm is also different from other sounds and back-up alerts common to construction sites. The visual alerts provide more alert options because the operators 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.

The PPUs and EPUs were designed to be durable including sturdy casing capable of withstanding daily weathering. The PPU rechargeable battery power duration is approximately two work days. During the experiments, the proximity detection and alert system demonstrated similar signal strength throughout the battery's duration. 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 can be installed in areas visible to the operator in the equipment cabin without obstructing the line of sight to objects outside the cabin.

The proximity detection and alert technologies 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 predefined and calibrated into the proximity detecting and alert devices. The following four scenarios can occur when using these devices on construction sites:

(1) True positive: An alert is activated when a ground worker is in too close proximity to a piece of construction equipment.
(2) 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).
(3) True negative: An alert is not activated when a ground worker is located at a safe distance from a piece of construction equipment.
(4) False negative: An alert is not activated when a ground worker is in too close proximity to 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 sites. Figure 1 presents a flowchart of the four possible alert scenarios for the designed experiments.

Experiments and results with proximity detection and alert 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 was placed in a simulated construction environment to evaluate the effectiveness of the proximity detection system in the outdoor field conditions. The test bed for these trials was a clear, flat, asphalt paved surface with no obstructions. A RTS and traffic control devices were used to create this test bed. The RTS was positioned at the centre of a 15.2 metre (50 foot) 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.

The centre point of the circular test bed 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.

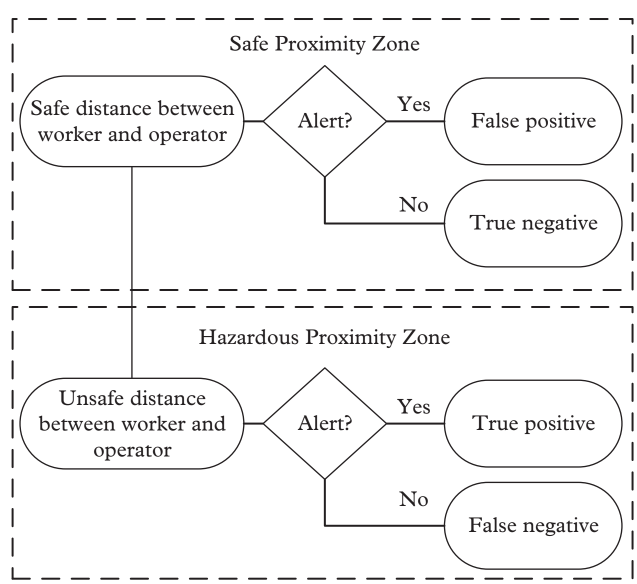

Figure 1 Flowchart of alert scenarios

The antenna component of the EPU was mounted on top of the operator's side of the equipment at the highest point for the best detection range. The PPU was clipped to the hard hat of a worker on foot as was done in the previous experiment.

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 activated an alert, the worker stopped walking and measured the alert distance using a measuring wheel. 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.

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 were also analysed 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. In all, 99.5% of the 432 worker approaches activated an alert from the system. The two cases where the worker struck the asphalt paver without activating an alert were recorded as false negative readings.

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

	Short range(m)	Medium range(m)	Long range(m)
Median	13.8	14.8	16.9
Minimum distance	0.0	10.3	12.2
Maximum distance	18.5	17.8	31.9
Range	18.5	**7.5**	19.7
Standard deviation	2.7	**1.7**	3.4

The data obtained from each piece of construction equipment were used to create 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 2 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.

Construction field conditions trials: stage 2

Another set 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 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 the RTS, and was aligned on a straight path with the pick-up truck. Traffic control devices were spaced 5 and 10 metres along the truck's trajectory towards the ground worker.

After maintaining a constant speed of 16 kilometres 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

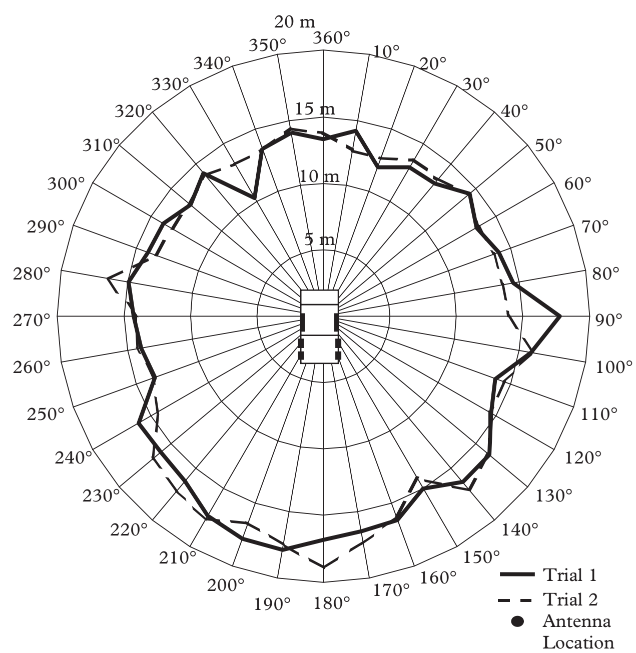

Figure 2 Active proximity alert zone for a specific alert range

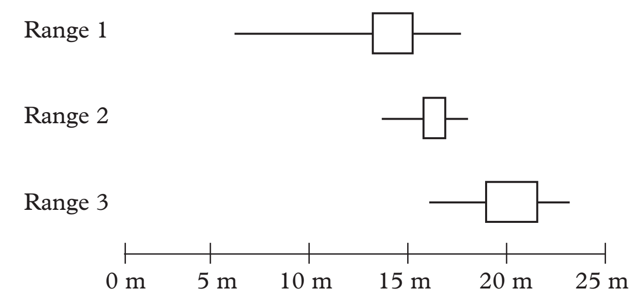

Figure 3 Box plot of proximity detection distance for each personal tag

detection devices with varied alert ranges (short, medium, and long) were tested in this experiment. Each of the three PPUs was tested 32 times. Box plots of the three different ranges and 96 data points gathered from this experiment are shown on the right side of Figure 3. All trials resulted in true positive alerts. No false alerts (including nuisance alarms) occurred during any of the 96 trial runs.

Long-term construction site trials

After completing the laboratory stage and both stages of the construction field trials, the research team evaluated the proposed testing method of proximity detection and alert devices on a long-term construction site. 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 million 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 both static and dynamic ground personnel and heavy construction equipment.

The general contractor had implemented several safety measures to protect ground workers. 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 construction site. 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 detection and alert system on construction equipment and ground personnel. For example, care was taken to not obstruct the equipment operator's line of sight when installing the EPUs. PPUs were attached to ground personnel as described in the previous experiments.

While the construction project was active, the proximity detection and alert system was deployed for several construction scenarios. Several EPUs were mounted on various pieces of active construction equipment and PPUs were installed on ground workers near the equipment. The first of the two construction scenarios used an EPU mounted on a stationary mobile crane and PPUs attached to workers completing tasks around the crane. For the second scenario, EPUs were mounted to several pieces of construction equipment and the PPU 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. The presented testing method for proximity detection and alert systems was used on the construction site. During the testing period, approximately 200 alerts were activated and measured. The minimum alert distance was 2.8 metres and the maximum alert distance was 62.5 metres. Table 3 shows the average recorded alert distances along with the range and standard deviation for each piece of construction equipment equipped with an EPU. As can be seen in the high range distances, the particular technology tested was unreliable in repeating the same alert distance.

Table 3 Analysis of alert distance measurements of proximity sensing and alert system on real construction sites

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

Table 4 Analysis of recorded relative distances or level for alerts (unitless) of 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

In a second experiment using the previously described proximity detection and alert technology, the ground worker equipped with the PPU was located inside the project safety manager's pick-up truck. The pick-up truck travelled 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 located on the motor grader. During this experiment, the pick-up truck stopped at least 30 metres from the static motor grader.

Data recording

In addition to the location distance measured by the research team during all experimental trials of the presented testing method, the proximity detection and alert system has data recording and logging capabilities. During the previously described experiments, the system recorded the ground PPU tag number, time-stamp, 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 sample output of the data logged during these experiments can be viewed in Table 5. 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 predefined proximity distance of a piece of construction equipment.

Information from this system was exported into a database for further analysis. 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 can provide further safety training specific to hazardous proximity issues to selected 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.

Table 5 Sample output data of recorded proximity breaches

Tag ID	Level	Date	Time	Status
34	681	18 April 2012	16:24:29	Trip
34	625	18 April 2012	16:24:29	Clear
34	737	18 April 2012	16:24:31	Trip
34	581	18 April 2012	16:24:45	Clear
34	648	18 April 2012	16:24:46	Trip
34	540	18 April 2012	16:24:47	Clear
34	649	18 April 2012	16:25:21	Trip
34	539	18 April 2012	16:25:42	Clear
34	708	18 April 2012	16:25:42	Trip
34	599	18 April 2012	16:25:42	Clear
34	657	18 April 2012	16:27:18	Trip
34	600	18 April 2012	16:27:18	Clear
34	680	18 April 2012	16:27:19	Trip
34	588	18 April 2012	16:27:19	Clear
34	683	18 April 2012	16:27:20	Trip
34	607	18 April 2012	16:28:10	Clear
34	689	18 April 2012	16:28:10	Trip

The proximity breach ranges 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 both stages of the construction field condition trials were recorded and analysed. The relative distance at which the PPU was detected can be viewed in Table 5 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 affect 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 PPUs 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.

Limitations, future work, and application areas

The objective was to present a testing method capable of evaluating the reliability and effectiveness of proximity detection and alert systems used in the construction environment. After completing the three experiments, the testing method revealed limitations to the tested proximity detection and alert system. Many parameters of 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 EPUs and PPUs.
- 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.
- Recording and analysis of 'near-miss' data to improve education construction workers on proximity issues.
- Identification in real time and recording of the position and trajectory of the hazard.
- Analysis of calibrated alert distances and actual alert distances on various pieces of construction equipment in different environmental settings including obstacles blocking the line of sight between the PPU and EPU.
- Collection and analysis of 'nuisance alerts' to evaluate reliability of system.
- Creation of an implementation strategy for proximity detection systems in construction.
- 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 sites 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 resulting from proximity issues. The ultimate goal of the construction industry must be to achieve zero accidents and injuries for all construction sites. The purpose was to determine a method that tests whether proximity detection and alert systems are capable of functioning in the construction environment both reliably and effectively when construction 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 proposed testing method demonstrated its ability to evaluate the effectiveness and reliability of proximity detection and alert systems. The proximity detection and alert device prototype demonstrated its ability to perform by detecting the presence of hazardous proximity situations on construction sites. 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 blocked by a metal pipe, eventually requiring multiple antennas to be installed on a piece of construction equipment to cover all signal blind spots. The audible alerts were at 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. 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, the test method revealed other parameters 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.

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