Proximity Sensing and Warning Technology for Heavy Construction Equipment Operation

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ABSTRACT

The United States construction industry experienced 151 fatalities resulting from workers colliding with objects and equipment in 2009. These fatalities accounted for approximately 18% of the total construction fatalities and 3% of the total workplace fatalities experienced that year. Construction workers and equipment are often required to function at close proximity on construction jobsites. This paper evaluates the effectiveness of emerging radio frequency (RF) remote sensing technology that can promote safety in construction by providing real-time alerts for worker-on-foot and construction equipment operators when a potentially hazardous proximity situation exists. Numerous experiments designed to emulate typical interactions between workers-on-foot and construction equipment, including installing proximity sensing devices on actual construction equipment, were used to evaluate the proximity sensing technology. Results from the experiments indicate that real-time pro-active proximity sensing and warning technology can promote safety on construction jobsites.

KEYWORDS

Proximity Detection, Construction Equipment, Construction Worker, Safety, Radio Frequency Technology, Warning and Alert Device

INTRODUCTION

Each construction jobsite has a unique size and set of working conditions. Typical construction environments are comprised of multiple resources such as construction personnel, equipment and materials. These resources perform dynamic construction activities in a defined space, and they often are in close proximity to each other. A hazardous situation can exist when heavy construction equipment is operating in close proximity to ground workers. Contact collisions between ground workers and heavy construction equipment can increase the risk of injuries and fatalities for construction personnel.

Previous research efforts have reported construction statistics on injuries and fatalities due to 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). Equipment
operator visibility, specifically operator blind spots, also contributes to contact collisions between construction equipment and ground workers (Fullerton et al. 2009).

A real-time proximity detection and warning system capable of alerting construction personnel and equipment operators during hazardous proximity situations is needed to promote safety on construction jobsites. It is assumed that the construction industry can realize significant improvements in safety if technology is applied while implementing safety management practices (Fullerton et al. 2009).

A lack of scientific evaluation data currently exists for new and existing construction safety technologies. Minimal information exists to demonstrate how commercially-available technology can be used to warn construction personnel of the presence of hazards in real-time, specifically proximity issues. Emerging safety technology for construction needs to be thoroughly evaluated through experiments simulating conditions in the construction environment. Analysis of the data can reveal the validity and effectiveness of these emerging technologies.

These issues and others will be address in a review of current construction safety statistics, safety best practices and existing real-time safety technologies including real-time proximity sensing technology. Pro-active safety technologies using secure radio frequency (RF) will be reviewed for effectiveness in the construction environment. Recommendations for future work in this area including potential applications to promote construction safety will be discussed.

BACKGROUND REVIEW

The review discusses current injury and fatality statistics associated with proximity issues in the construction industry. Safety best practices including real-time pro-active safety approaches and technologies are evaluated. A current needs statement is derived from the reviewed information.

Injury Statistics Related to Workers and Construction Equipment

The construction industry continues to experience one of the largest accident fatalities rates per year when compared to other industries in the United States. A 2009 study found the construction industry accounted for 19% of the nation’s workplace fatalities (CFOI 2009A). The Bureau of Labor Statistics reported that of the 818 fatalities incurred by the construction industry in 2009, 18% (151 fatalities) were caused by workers being struck by an object or construction equipment. These 151 fatalities represent 3% of the total workplace fatalities experienced by the U.S. private industry sector in 2009 (CFOI 2009B). In 2008, the construction industry reported 201 fatalities resulting from collisions between construction personnel and equipment or objects. This value accounts for 21% of fatalities experienced by the construction industry in 2008, and 3.5% of the total fatalities reported by U.S. private industry sector in the same year. The construction industry has averaged 216 fatalities a year since 2003 resulting from construction equipment or other objects striking personnel on the jobsite (CFOI 2009B).

Current Safety Best Practices

Regulations established by OSHA are vital to promote safety in construction, but are not capable of preventing contact collisions between workers and construction
equipment. Passive safety devices such as hard hats, reflective safety vests and other personal protective equipment (PPE) are incapable of warning workers or operators of a potential collision. Pro-active safety measures, such as safety training and education, help to increase the awareness of close proximity issues for construction workers and operators.

Behavior of construction workers with regards to safety has been the focus of many research efforts. The Construction Industry Institute (CII) completed a study in which workers were monitored and later given suggestions about safe and unsafe practices that were observed. The method used provided real-time feedback during the monitoring period for the workers (Hinze and Gambatese 1996). Another CII study discovered that construction companies that conducted site-specific safety programs prepared early in the project experienced better safety records than others (Hinze 2003). It can therefore be assumed that increased efforts in front-end planning including design for safety will promote safety on construction projects.

**Real-time Pro-Active Proximity Warning and Alert Technology**

Pro-active 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). Existing safety technologies can potentially create a safety barrier providing workers with a “second chance” if previous safety best practices are deficient (Teizer et al. 2008). This new information and warning system can promote safety in construction and provide new data sources.

Ruff (2001) 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 these technologies to have limitations such as availability of signal, size, weight and feasibility in the construction environment (Ruff 2001).

The construction industry needs a wireless, reliable and rugged technology capable of sensing and alerting workers when hazardous proximity issues exist. Teizer et al. (2010) demonstrated that radio frequency (RF) can satisfy the jobsite safety requirements.

**OBJECTIVE AND METHODOLOGY TO EVALUATE PROXIMITY WARNING AND ALERT TECHNOLOGIES**

The objective of this research is to promote and increase construction jobsite safety for workers during heavy equipment operations by using radio frequency technology for real-time pro-active proximity warning devices. If two or more construction resources are in too close proximity to one another, the sensing technology will activate alarms to warn workers through devices called Equipment and Personal Protection Units (EPU and PPU).

The radio frequency technology will be evaluated using two different experimental configurations. The experiments were designed to measure the performance of the technology in a simulated outdoor construction environment. The experiment tested the device’s ability to detect and alert equipment operators of hazardous proximity issues.
The first experiment tested the proximity sensing devices in a mobile worker-static construction equipment situation. An EPU was placed inside the cab of a piece of construction equipment, and the PPU was attached to a ground worker outside of the equipment. The ground worker approached the static equipment at a specific distance from many angles. A theoretical safety zone was created by the perimeter location of points at which the alarm is triggered. The proximity distance at which the alarm is triggered is measured by manual methods. Positioning of the EPU inside the equipment cab will have an impact on the proximity range configuration.

Another test measured used mobile construction equipment and static workers to test the proximity sensing devices. The EPU and PPU devices were positioned in a similar manner as the previously describe experiment. The mobile construction equipment approached the static worker at a constant speed and stopped after the alert was activated. A Robotic Total Station (RTS) was used to measure the proximity detection distance. 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 selected proximity detection system used was previously tested in an open, flat area clear of obstructions. These preliminary tests were conducted outdoors on days with no precipitation. These control measurements were used as validation for the proximity detection system. The researcher found that the measurements of the system were within a one meter range from all approach angles.

EXPERIMENTS AND RESULTS

Each experiment was designed to evaluate the effectiveness of proximity detection technology in the construction environment. Each experiment attempted to simulate a typical construction environment and test the proximity detection devices in the created environment. The proximity detection system utilized for the experiments used a secure wireless communication line of Very High Frequency (VHF) active Radio Frequency (RF) technology near 700 MHz (Teizer et al. 2010).

Technology Tested

Radio frequency (RF) technology was employed for each of the proximity detection experiments. The EPU component of the proximity detection device contains a single antenna, reader, alert mechanism and can be powered by the existing battery on the piece of equipment. The PPU is a handheld device that can be installed on a hard hat of a construction worker. This device contains a chip, battery and alert mechanism. A signal broadcasted by the EPU is intercepted by the PPU when the devices are in close proximity of one another. 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 both the EPU and PPU alarms are activated instantaneously in real-time.

These proximity detection devices can have up to three different alarm methods: audible, visual and vibratory. The proximity detection system selected for this research only provides the equipment operator a visual and audible alert. The alert is only provided to the equipment operator because he/she ultimately has control to stop or correct the hazard. Alerts are not provided to ground workers to prevent
double-correction (both operator and worker avoiding the hazard in the same direction) and to prevent workers from placing themselves in a more hazardous situation.

Equipment operators are warned through audible sounds and visual flashing lights located on the device inside the equipment cabin. The audible alerts create ample noise so that workers and operators wearing hearing protection are still able to hear the alert. Because construction workers can become desensitized to audible alerts, the vibration and visual alerts provide more alert options (Orbitcoms 2010). The visual and audible alert method was received by only the equipment operator and was held constant for both field trials.

Experiments and Results with Proximity Warning Devices

A proximity detection device system was used based on the safety needs of the construction industry. This system was evaluated in two different experimental settings, both evaluating the different capabilities of the system including its ability to perform in the construction environment.

Field Trials – Stage 1

Stage 1 of the field trials was conducted in a clear, flat, asphalt paved testbed with no obstructions. The testbed was constructed using a Robotic Total Station (RTS) and traffic control devices. The RTS was positioned at the center of a 15.2 m (50 ft.) radius circle, and traffic cones were placed at 36 equal distant locations around the circumference of the circle. The traffic cones were placed at 10 degree offsets around the circle. Figure 1 displays the testbed used for these experiments.

![Figure 1. Stage 1 experimental testbed](image)

The center point of the circular testbed served as the antenna location of the EPU device. The equipment proximity detection devices were mounted inside the equipment cabin (when applicable) in view and audible range of the operator. The antenna component of the equipment proximity detection device was mounted on the operator’s side of the equipment at the highest point for the best detection range. The personal protection device was clipped into the hard hat of the mobile worker. These configurations can be viewed in figure 2.
A research team member equipped with a personal protection device approached the piece of equipment at a constant walking pace from 36 equal distance approach angles. Once the proximity detection device activated an alert, the worker stopped walking and measured the alert distance. This method was repeated twice for each approach angle around the circle. Three personal detection devices installed on the researcher’s hard hat were calibrated to different proximity alert ranges (short, medium and long) were tested for each piece of construction equipment. This experimental procedure was performed for nine different pieces of the following construction equipment: dump truck, mower, steel drum roller, wheel loader, grader, truck and trailer, asphalt paver, excavator, and pick-up truck.

The sample size for each piece of construction equipment was 432 measurements. A statistical analysis was performed on every personal proximity detection tag (short, medium and long range) for each sample of construction equipment. The data was also analyzed for false positive readings and nuisance alarms. For this research, false positives were defined as the worker striking the construction equipment before an alert is activated. Nuisance alerts were defined as alert distance values found to be 3 times larger than the upper quartile value. Percentage values of activated alerts were also available for each piece of construction equipment tested.

Table 1 shows results of the data analysis for the proximity detection alert distances of workers approaching a static asphalt paver. The medium range tag had the lowest standard deviation and range discrepancy when compared to the other tags tested on the asphalt paver. These numbers are marked in bold text in table 1. 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.

<table>
<thead>
<tr>
<th></th>
<th>Short Range</th>
<th>Medium Range</th>
<th>Long Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>13.8 m</td>
<td>14.8 m</td>
<td>16.9 m</td>
</tr>
<tr>
<td>Minimum Distance</td>
<td>0.0 m</td>
<td>10.3 m</td>
<td>12.2 m</td>
</tr>
<tr>
<td>Maximum Distance</td>
<td>18.5 m</td>
<td>17.8 m</td>
<td>31.9 m</td>
</tr>
<tr>
<td>Range</td>
<td>18.5 m</td>
<td>7.5 m</td>
<td>19.7 m</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.7</td>
<td>1.7</td>
<td>3.4</td>
</tr>
</tbody>
</table>

The obtained data from each piece of equipment was used to develop proximity 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 3 shows the recorded alert distant measurements of the medium range personal protective device. The two lines represent the two different trials from each approach location with the medium range device.

Field Trials – Stage 2

This stage of the field trials tested the effectiveness of the proximity detection devices on static workers and dynamic equipment. These tests were conducted on a flat, unobstructed paved surface similar to stage 1. The equipment detection device was installed inside a pick-up truck with the antenna mounted on top of the truck cabin on the driver’s side. A static worker stood next to a robotic total station (RTS), both of which were aligned on a straight path of the pick-up truck. Traffic cones were spaced 5 and 10 m. along the truck’s straight directional path. The truck approached the worker and RTS at a constant speed of 16 km/h (10 mph) and stopped once the alarm was activated. Three different personal detection devices with varied alert ranges (short, medium and long) were used in this experiment. Figure 4 shows the truck stopping after the alert was activated. Data obtained from this experiment was analyzed by the same statistical criteria used in stage 1. Results of the stage 2 trials can be viewed on the right side of figure 4.

Figure 4. Static worker and dynamic equipment experiment (left), boxplot of proximity detection distance for each personal tag (right)
Of the 32 samples taken for each range of personal protection unit, no false positive readings occurred during the experiments. In other words, the proximity detection alert was activated before the truck passed the worker and RTS. Also, no extreme outliers (defined as nuisance alarms) occurred during any of the trials.

LIMITATIONS, FUTURE WORK AND APPLICATION AREAS

The stated objective of this research was to evaluate the effectiveness of proximity detection and alert technologies on heavy equipment in the construction environment. If the devices are found to be effective in the construction environment, then criteria can be developed on which to base further investigation. As with all experimental research, each of the proximity detection and alert experiments had limitations. After evaluating the feasibility of the proximity detection and alert devices in the construction environment, many other parameters and potential influences on the system should be evaluated through future experimentation. Future studies should include, but not be limited to:

- Effects of temperature, humidity, precipitation and other ambient influences
- Mounting positions of the EPU and PPU devices including location of devices on workers and equipment
- Worker’s and operator’s reaction to using the devices including added weight of the device and its effect on their ability to complete construction tasks

Future research efforts should also address the following issues, as they were not addressed in the experiments performed in this paper:

- Calibration of the alert distances with respect to each specific piece of construction equipment including operator reaction and brake distance times as well as equipment stopping times
- Sensitivity analysis can be performed on a detection systems capable of calibration to a pre-defined numerical alert distances
- Investigate and assign appropriate proximity detection distances for specific construction activities
- Long-term construction field trials should be conducted with the devices
- Develop an effective implementation strategy including a cost-benefit analysis for the technology
- Collect and record “close-calls” or “near-misses” data to further educate construction workers on proximity issues in construction

Accidents on construction jobsites not only involve fatalities or injuries of workers, they can become very expensive after calculating 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 pro-active proximity detection and alert systems.

CONCLUSION

The construction industry desires to eventually obtain an accident free jobsite including a zero fatality rate for each construction project. Statistics specific to
proximity issues in construction demonstrate that current safety practices in construction are insufficient. The preliminary results of the described experiments propose that real-time pro-active proximity detection systems can promote safety in construction.

The proximity detection and alert device prototype demonstrated its ability to detect the presence of heavy construction equipment. The tested construction equipment included a wheel loader, forklift, scraper, dozer, excavator, motor grader, personnel mover, articulated dump truck, crane and pick-up truck. Once detected, the system simultaneously activated an alarm to warn the workers and equipment operators of the hazardous proximity issue. The system demonstrated its ability to warn construction personnel that they were too close to other construction resources. The audible alerts were loud enough to be heard over back up alarms and general construction noise.

The proximity detection and alert system also demonstrated its ability to measure and record when a proximity alert is activated. This collected data can later be used to analyze “close-calls” or “near-misses.” New safety concepts and training could evolve from the analysis of “near-miss” data collected from a construction project. Workers could be notified of historical hazardous project conditions and construction activities.

REFERENCES