Magnetic Field Proximity Detection and Alert Technology for Safe Heavy Construction Equipment Operation

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ABSTRACT

Approximately 17% of the 721 fatalities in the US in 2011 resulted from workers colliding with objects or equipment in the work environment. Construction site conditions often create hazardous proximity situations by requiring workers-on-foot and heavy equipment to be in close proximity. Current safety management, incl. industry safety best practices, to protect construction workers-on-foot have proven inadequate. This article evaluates the reliability and effectiveness of magnetic field sensing and actuation technology that brings final change to this problem. Introduced are the design and characteristics of novel magnetic field proximity detection and alert technology that alerts workers-on-foot from being too close to equipment in real-time. Field-realistic experimental trials highlight successful tests to various possible interaction scenarios. Results indicate that the developed magnetic field proximity detection and alert technology provides reliable and accurate warnings or alerts to equipment operators and workers-on-foot at pre-calibrated distances, and even can slow or shut down the equipment if the hazardous situation remains in effect. Technology and experimental knowledge further suggest workers-on-foot and construction equipment operators can be provided with an additional layer of protection by receiving advanced safety education and training from the analysis of near-miss data that is geo-referenced to the construction site layout.

Keywords - Construction workers-on-foot, Hazardous proximity situations, Injuries and fatalities, Heavy construction equipment, Proximity detection and alert technology, Magnetic field sensing and actuation, Construction safety.

1 Introduction

The unique setting of construction projects (size of sites, type of construction and methods, number of personnel, equipment, and materials) creates ever changing new sets of working conditions. Construction sites, different than manufacturing environments, perform dynamic activities in a defined space. This often requires construction resources, such as workers-on-foot and heavy construction equipment to operate at close proximity to each other creating potential hazardous proximity situations. The risk of injury or fatality increases as contact collisions between workers-on-foot and heavy construction equipment occur.

Many of the past research efforts analyzed safety statistics for potentially hazardous proximity situations. As they searched for causes, they found that the repetitive nature of work tasks on construction sites led to decreased awareness and loss of focus [1]. Other research determined that few technologies currently exist that pro-actively aid workers-on-foot or equipment operators in proximity situations [2].

In the past, the construction industry has been lagging when compared to other industries with regards to implementing emerging technology and innovation. Industry sectors such as underground mining and manufacturing have tested and began implementing various proximity sensing technologies to alert personnel of hazardous proximity situations [2].

Minimal information and data also exists on how existing safety technologies can be implemented into construction environments to create an additional layer of safety protection for workers-on-foot during hazardous proximity situations. Thorough evaluation of emerging safety technologies through experimentation in live, field-realistic, or simulated conditions of a typical construction environment is required. Evaluation data and analysis can show the reliability and effectiveness of these technologies, including proximity detection and alert systems.

This article is structured as follows: First, it reviews current construction worker injury and fatality statistics, known safety best practices, and existing real-time safety technologies including proximity detection and alert technology. Second, it introduces magnetic field sensing and actuation technology to the problem. Third, the experimental test methodology is explained. Fourth, test results are presented and discussed, followed by a discussion of the discovered benefits, current limitations, steps ahead to introduce such technology to construction.

2 Background

A multitude of movements of construction resources coupled with the densely populated nature of construction sites can account for safety concerns resulting from proximity issues [3]. The following review covers injury and fatality incidents associated with proximity issues in the construction industry, current industry safety practices, results to tests with state-of-the-art proximity detection and alert technology.

2.1 Human-Equipment Interaction Related Injuries and Fatalities

The US construction industry experiences one of the highest accident fatality rates per year when compared to other industries. In 2011, the US Bureau of Labor Statistics reported the construction industry is responsible for 16% of the nation's workplace fatalities [4]. Of the fatalities experienced in this year, 123 resulted from workers coming into too close contact with objects or construction equipment. Although the number fatalities experienced decreased (averages are around 195 fatalities per year), approximately one-fourth of construction accidents involve construction equipment [5].

Although workplace fatalities are the worst safety incident possible for construction workers, non-fatal injuries and illnesses negatively impact the success of a construction project through medical costs, lost work time, increase in insurance costs, and possible decrease in worker morale [6]. As such, the US construction industry recorded 71,600 injuries and illnesses in 2011 accounting for approximately 6% of the total injuries and illnesses experienced by the U.S. workforce in that same year. Hazardous proximity conditions between ground workers and construction equipment resulted in 33% of the total injuries and illnesses experienced by the construction industry in 2011 [7]. Regulations in many countries record values for injuries and illnesses only when accidents required personnel to be absent from work as a result of the injury or illness.

2.2 Site Conditions

Many research efforts have been conducted to better understand hazardous proximity situations between workers-on-foot and heavy equipment. A combination of a harsh environment and the often repetitive nature of construction tasks can cause workers to lose focus and awareness of their surroundings [1]. Additionally, Fosbroke [8] stated that hazardous proximity issues are not properly examined nor recorded by safety personnel, including near miss events [9]. In particular, information that is recorded through incident investigations is not recorded in real-time providing only lagging safety indicator measures [1].

Many proximity-related accidents (injuries and fatalities) in construction are attributed to visibility issues for heavy equipment operators [10]. Non-visible areas, or blind spots, cause heavy equipment operators to run over ground workers, contact other equipment, or rollovers of the operated construction equipment [5]. Policies for these visibility related issues as well as hazardous proximity issues in general are outdated or rarely implemented by the industry resulting in a lack of knowledge for the construction workforce about specific risk factors [1].

Frequent movements of personnel in limited spaces on construction sites therefore can create hazardous proximity situations between ground workers and heavy equipment that yet have to be solved adequately.

2.3 Current Industry Best Practices

The Occupational Safety and Health Administration (OSHA) implements safety regulations for construction, but many of these standards are not capable of preventing contact collisions between ground workers and heavy construction equipment [11]. Personal protective equipment (PPE) including hard hats and reflective safety vests are passive methods required by OSHA in an attempt to improve visibility in hazardous proximity situations on construction sites. Pro-active safety measures also mandated by OSHA including safety training and education can increase the awareness of close proximity issues for workers-on-foot and equipment operators. OSHA also requires construction equipment with obstructed rear view (mirrors) to have back-up alerts to warn nearby workers when traveling in reverse. These passive alerts and other safety implementations are incapable of alerting construction operators and workers in real-time during hazardous proximity situations, because they are often ignored due to desensitation or other background noise [2].

Change in construction worker behavior has also been investigated as a potential solution for solving safety problems in the construction industry. Accident causation models have been developed to better understand what factors lead to a worker injury, illness, or fatality [12-13]. Safety culture has also been linked to construction worker behavior with regards to safety [14-15]. An Accident Root Causes Tracing Model (ARCTM) identified the following root causes of construction accidents [16]:

1. Failing to identify an unsafe condition that existed before an activity was started or that developed after an activity was started;
2. Deciding to proceed with work after the worker identifies an existing unsafe condition; and
3. Deciding to act unsafely regardless of the initial conditions of the work environment.

2.4 Proximity Detection and Alert Systems

Initial testing and evaluation has occurred for proximity detection and alert systems in other industries requiring workers-on-foot and heavy equipment to operate in close proximity, such as underground mining [17], the railroad industry [18], and manufacturing [19]. Researchers found that safety technologies implemented on construction sites can provide alerts to ground workers and equipment operators in real-time when hazardous proximity situations exists [2]. These technologies provide workers with a "second chance" by creating an additional layer of protection [3].

Various technologies and system combinations [20] are thought to be capable of alerting construction personnel in real-time of hazardous proximity situations. Several proximity detection and alert systems were reviewed for their capabilities to function in the mining environment including RADAR (Radio Detection and Ranging) [21], sonar, Global Positioning System (GPS), radio transceiver tags, cameras, and combinations [22-23]. A similar study reviewed technologies thought to be capable of providing alerts in real-time during hazardous proximity situations on construction sites [2]. The evaluated technologies included Radio Frequency Identification (RFID), Ultra Wideband (UWB), Global Positioning Systems (GPS), magnetic marking fields, vision detection devices including video cameras, laser, and radar based proximity detection and alert technologies [24].

Several parameters were used to assess each system including detection area, alert method, precision, size, weight, calibration functionality, power source, ability to identify people from objects, and others. Benefits and limitations of each technology were identified. For example, systems utilizing radio frequency technology can be impacted by direct contact with metallic objects [25] and experiences multipath or "crosstalk" that limit the system's ability to distinguish individual worker proximity breaches [26-27]. Some of the evaluated systems such as laser, sonar, and RADAR were incapable of identifying people versus objects such as dirt mounds or construction materials [17,28-29].

These benefiting and limitating criteria were used to identify a wireless, reliable, and rugged technology capable of detecting and alerting workers during hazardous proximity situations that is needed for construction sites [28]. Results from the review indicate that proximity detection and alert systems utilizing magnetic field technology can potentially be reliable when deployed in the construction environment.

2.5 Magnetic Field Sensors and Actuators

Magnetic fields are created from motion of electric charges and are often accompanied by electric field waves creating electromagnetic fields. The strength of these electric charges (or current) is strongest close to the generating source and diminishes as the distance from the source increases. These currents are present in overhead high voltage transmission lines, near household appliances, and industrial settings such as near induction furnaces. Little confirmed experimental evidence exists that magnetic fields can affect human physiology and behavior in strengths levels found in our environment [30].

The technology has improved in compatibility with other electronic systems, sensitivity, and smaller size [31]. Magnetic sensors indirectly measure direction, presence, rotation, current, angle, and more through indirect changes or disturbances in the generated magnetic field. For proximity detection applications, magnetic fields are generated from a permanent magnetic, electromagnetic, or current source. Magnetic fields to detect the presence of workers-on-foot near heavy equipment operate at low radio frequency (~60-75 kHz) and require a worker to wear a tag [32]. Once the tag is in pre-calibrated distances to the magnetic-field it sets off a warning or alert, either audible, vibratory, or visual to both operator, worker-on-foot, or neither one (in case only near miss recording is the goal) [2]. In contrary to other real-time warning and alert technologies, magnetic fields even offer the opportinity to penetrate objects or obstacles [24]. A shell-based model of the magnetic flux density distribution lays the foundation for identifying a worker's location during hazardous proximity situations (see Figure 1) [33-34].

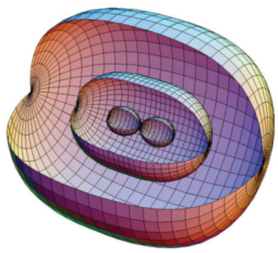

Figure 1. Three-dimensional oval shape of the magnetic field & pre-calibrated alert distances [34]

2.6 Testing Methods of Proximity Detection and Alert Systems

Past research has developed preliminary testing methods to evaluate various proximity detection and alert systems [2, 35-36]. Testing methods integrated various trials of movement from the worker-on-foot towards heavy equipment to evaluate the reliability and effectiveness of the proximity detection and alert systems [35]. Ground markings are typically placed to outline the alert detection area of a system in an outdoor environment.

3 Objective, Methodology, and Scope

The objective of this article is to highlight results to an experimental evaluation of the reliability and effectiveness of the developed magnetic field proximity detection and alert system in a typical construction environment. The system provides an alert in real-time to workers-on-foot and construction equipment operators during hazardous proximity situations, for example, when a worker and the equipment get into too close proximity. Although magentic field signals penetrate obstalces and detect the tags that the potentially obstructed workers wear, the experiments are conducted on a flat, unobstructed outdoor surface. Components of the magnetic field proximity detection and alert system were deployed on the construction personnel and equipment. Interviews with the volunteering workers before and after the experiment explain the benefits and current limitations of magnetic field technology in proximity alerting applications.

4 Experiments and Results

4.1 Testbed Environment for Magnetic Field Proximity Detection and Alert System

The magnetic field proximity detection and alert system used for the experiments is comprised of components that communicate in real-time to provide alerts to workers-on-foot (the subject) and equipment operators during hazardous proximity situations. The components and the installation and experimental test procedures are:

1. Install alert technology on equipment (antenna with ferrite core, processing hub, display, speaker) and workers (each subject receives one personal tag) (see Figure 2).
2. Calibrate the alert distances and zones (safe, warning, alert, stop) based on needs (Figure 3).
3. Allow test subject to approach equipment at slow pace from angles (e.g., every 10°).
4. Record distance to each alert once it activates.

While the distances of the alert zones and their shapes can be calibrated for each equipment type, the approaching subject, once within range, automatically triggers multiple signals for the equipment operator (i.e., voice or visual):

a) Zone 1: System OK = “Subject warning only.”
b) Zone 2: Warning/Alert = “Subject or other equipment too close!”
c) Zone 3: Slow = “Automatic vehicle slowdown.”
d) Zone 4: Stop = “Automatic vehicle shutdown.”

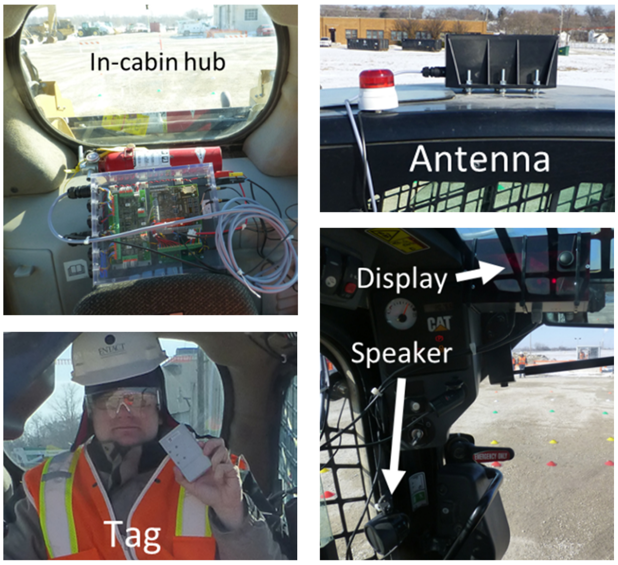

Figure 2. Magnetic field sensing and actuation technology in the testbed environment

Figure 3. Alert zones and distances

4.2 Results to Alert Distances and Area

Experiments were conducted: the first with a skid steer loader and one magnetic field antenna and the second with a wheel loader and two magnetic field antennas.

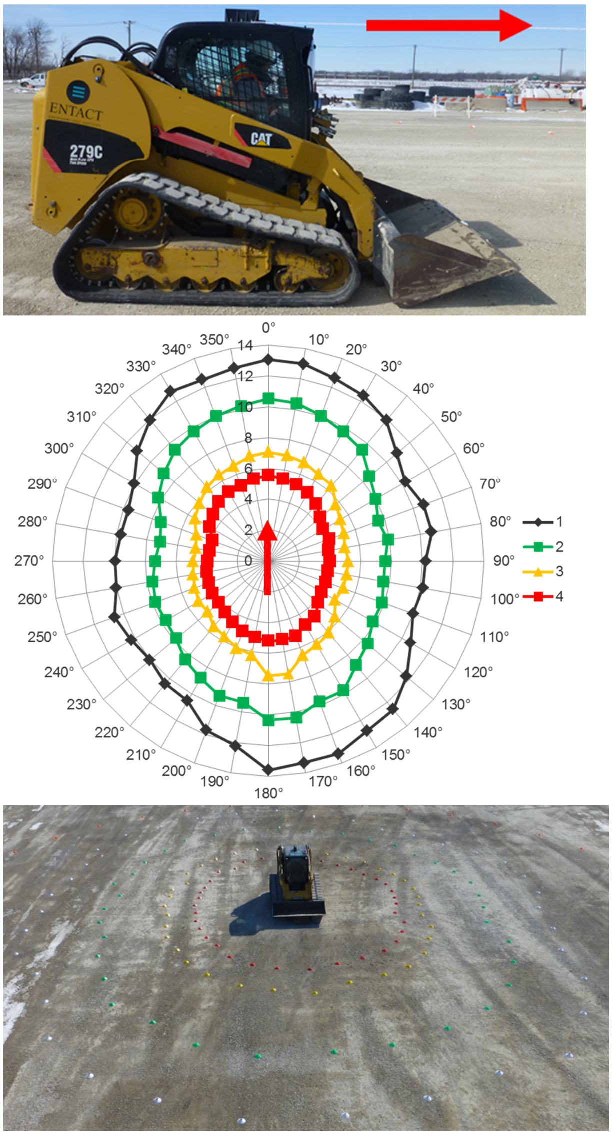

Figure 4. Results to a skid steer loader with one antenna, in [m]

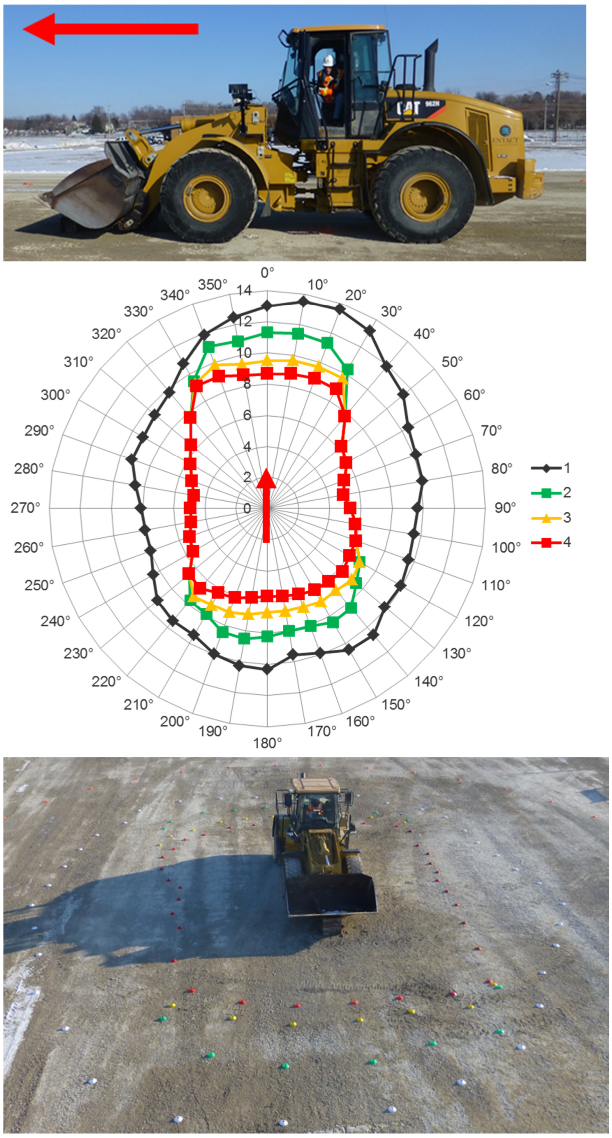

Figure 5. Results to a wheel loader with two antennas, in [m]

Results to static skid steer loader: Using one antenna generates a magnetic field similar to Figure 1. It has extended length in the front and back of the equipment, while on the sides the alert distances are shorter. Figure 4 illustrates the orientation of the equipment and the alert zones in a spider diagram as well as photo. This alert setting is particularly useful for equipment that can rotate frequently on the spot (e.g., skid steer loader, excavators). The repeatability of the result was tested by having the subject move at slow speed (<0.3 m/s) three times from each angle towards the center of the static equipment. Although the readings from each angle were within a few cm, the closest reading was recorded upon activation of the alert. No nuisance or false positive alerts were recorded during the experimental trial.

Results to static wheel loader: Using two antennas generates a magnetic field that allows forming rectangular alert shapes. This is of particular importance to equipment types that frequently move forward and backwards, without having the option of rotating too quickly (e.g., dump trucks, pavers, compactors). Figure 5 illustrates the results to the experiment with two calibrated antennas. It can be seen that while the front and rear alert distances remain almost similar, both sides combine all alert zones to a straight line. These were pre-calibrated at 1.5 m distance from the vehicle. This reduced distance on the side of the equipment keeps workers-on-foot or other equipment in active mode (e.g., working or passing by), without creating a nuisance alert to the equipment operator. This is very important for forward and rear driving equipment, as it keeps up the productivity of all participants in the work environment while maintaining safe distances to pass by.

A statistical analysis was performed for all trials. The data was also analyzed for false positive readings and nuisance alerts. The following circumstances were used for each of the following:

a) *False positive alert:* Instances in which the subject strikes the construction equipment before an alert is activated.
b) *Nuisance alert:* Alert distance measurements three times larger than the upper quartile value for each specific approach angle.

No false positive alers or nuisance alerts were recorded during the experimental trials.

Further experiments were conducted to test the effectiveness of the magnetic field proximity detection and alert system on a static and mobile subject (in the static case: a dummy) and on mobile equipment. The purpose of these additional experiments was less a scientific evaluation at this time, rather a demonstration of other practical applications of the technology in daily use cases that can be expected on construction sites.

Results to mobile equipment and static/mobile subject: The approximate speeds of the equipment were measured 5 (low) and 13 km/h (high). It traveled in straight paths 10 times towards the subject/dummy (see Figures 6 and 7) and stopped immediately when the operator heard the alert signal that was actived inside the equipment cabin. The distance from the closest point of the equipment to the test subject/dummy was measured. The results in Tables 1 and 2 include added distances the equipment travelled due to operator's reaction and break times, and even some distance due to the skid steer sliding on a frozen ground surface. Table 2 refers to results for the subject traveling as well.

Table 1. Results to mobile equipment and static subject/dummy (see Figure 6), in [m]

Experiment No.	1	2	Experiment No.	3	4
Forward	Speed		Reverse	Speed	
10 Runs	High	Low	10 Runs	High	Low
Avg.	4.97	7.21	Avg.	6.00	7.77
Min.	4.40	6.70	Min.	4.30	6.80
Max.	5.80	7.70	Max.	6.70	8.20

Table 2. Results to mobile equipment and mobile subject/dummy (see Figure 7), in [m]

Experiment No.	5	6	Experiment No.	7	8
Reverse	Speed		Forward	Speed	
10 Runs	High	Low	10 Runs	High	Low
Avg.	4.01	5.67	Avg.	2.82	5.67
Min.	3.50	4.50	Min.	1.30	5.00
Max.	5.00	7.50	Max.	4.10	6.20

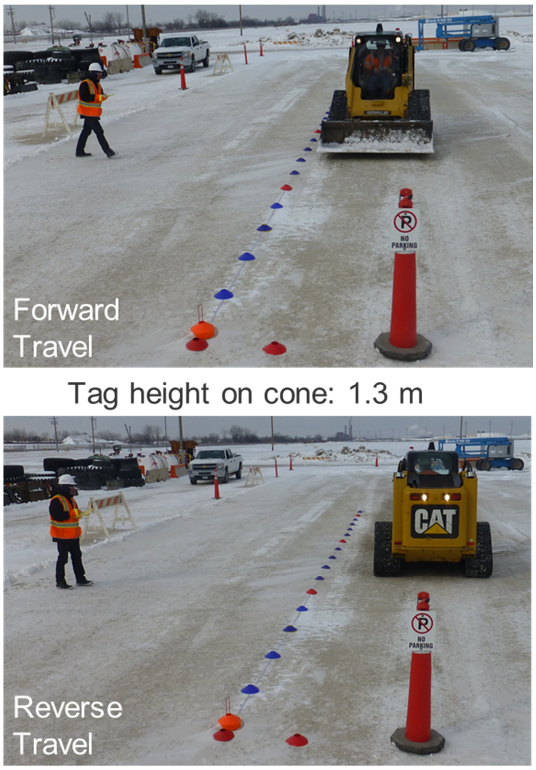

Figure 6. Mobile equipment and static subject (here: tag placed on safety cone)

Figure 7. Mobile equipment and subject travelling towards the equipment in a safe lane

4.3 Results to Interviews and Discussion

In none of the experiments was the subject/dummy "run over" by the equipment. Furthermore, feedback of workers-on-foot (the subjects) and equipment operators was collected. Although such opinion-based collection of feedback might be subjective, it provides valuable input into future research and development of the technology as well as how it is integreated into existing best practices in construction site safety engineering and management.

Selected comments are related to the use of the system: "Easy to understand." "Can save lives!" "Training and demonstration before use would be helpful." "Make it a requirement to wear it like it is for PPE!" "Should be part of daily safety attire" "Automated equipment shutdown and emergency shutdown (button) is helpful when operator does not react." "Data logging is good for objective safety assessment and overall site safety." "Useful for sites with a lot of pedestrian workforce-machine interaction."

Some concerns were also raised: "Experienced or older workforce might be resistant." "May get some workers or operators in trouble." "Equipment design needs to accommodate hardware." "Alert range might increase for other vehicle types." "Provide various additional alert types!"

A general feedback was that technology only does good when the workforce accepts it. "I would continue relying on my senses to enhance the use of the system." In summary, the technology can become a good best practice that is intended to give workers "a second chance" when traditional safety barriers have already failed. The design and testing of the technology included also a data logger, however, the results have yet to be analysed. Collecting near-miss data, like explained by Teizer et al. [9] adds a second additional layer of protection in equipment safety. As stated in the research framework, workforce can receive advanced education and training through the analysis of leading indicator data and use of new safety knowledge that is generated from it.

5 Conclusions and Future Work

The safety practices currently used in the construction industry for workers-on-foot and heavy equipment operating in too close proximity to each other have proven inadequate by looking at the continued injuries and fatalities resulting from workers being struck by equipment or objects. The construction industry must strive to achieve zero accidents, injuries, and fatalities on all of its projects. The purpose of this research was to introduce and evaluate the reliability of a magnetic field proximity detection and alert system when tested in the harsh construction environment. Results obtained from the review and experiments indicate that magnetic field proximity detection and alert systems could provide an additional layer of protection for workers-on-foot on construction sites.

Experiments were designed to specifically reveal the system's ability to provide alerts in real-time for workers-on-foot and heavy equipment operators during hazardous proximity situations. Multiple experiments simulating various human and heavy equipment interactions were completed to test the proximity detection and alert system and draw distance charts.

Furthermore, worker surveys indicate the audible alert was differentiated from other common equipment alarms and construction site noise. The equipment operator was also able to see the visual alert displayed inside the equipment cabin. The alert activated successfully for each trial resulting in no false negative alarms, meaning the system activated an alert each time a proximity breach occurred.

Further testing, like it has been suggested by [37-42], is required to explore other types of vehicles in different settings, among other research or development tasks that integrate the technology into existing construction site safety engineering and management approaches.

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