www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

WEARABLE, WIRELESS IDENTIFICATION SENSING PLATFORM: SELF-MONITORING ALERT AND REPORTING TECHNOLOGY FOR HAZARD AVOIDANCE AND TRAINING (SMARTHAT)

SUBMITTED: December 2014
REVISED: May 2015
PUBLISHED: May 2015 at http://www.itcon.org/2015/19
EDITOR: Rezgui Y.

Jochen Teizer, Ph.D., Dipl.-Ing.
RAPIDS Construction Safety and Technology Laboratory, Germany
email: jochen@teizer.com and http://www.teizer.com

SUMMARY: *The construction industry continues to be one of the leading industries for injuries and fatalities throughout the world. Deaths in the United States resulting from construction workers colliding with an object or equipment accounted in 2010 for 17% of the total construction fatalities. A reason might be the dynamic interaction of resources characteristic on many construction sites. Often poorly engineered site layouts produce dangerous situations in which workers and heavy equipment have to operate in too close proximity. The primary objective of this article is to present innovative research that evaluates the capability of the developed Self-Monitoring Alert and Reporting Technology for Hazard Avoidance and Training (SmartHat) technology, a novel battery-free sensing and communication prototype that also provides alerts in real-time when hazardous proximity conditions are present between heavy construction equipment and ground workers. Various field experiments designed to emulate typical interactions between ground workers and heavy equipment on construction sites are executed. While recent advances in construction safety research provide numerous examples on the use of pro-active technologies for protecting the workforce, the conducted benchmark tests were limited to comparative active (battery-powered) radio frequency devices only. As such, the experimental trials included various personnel tag positions and orientations on personal protective equipment (PPE) in an outdoor environment to simulate worker movement while performing construction tasks. The overall contribution of this research indicates that the SmartHat proximity detection and alert system, once deployed as a wearable technology in PPE, is reliable and effective and has potential to provide alerts to ground workers in various hazard proximity positions and orientations.*

KEYWORDS: *back-up incidents, vehicle blind spots; contact collisions, equipment operator visibility, heavy construction equipment, injury and fatality statistics, pro-active real-time safety, proximity detection and alert systems, site layout design and planning, workers-on-foot.*

REFERENCE: *Jochen Teizer (2015). Wearable, wireless identification sensing platform: Self-Monitoring Alert and Reporting Technology for Hazard Avoidance and Training (SmartHat). Journal of Information Technology in Construction (ITcon), Vol. 20, pg. 295-312, http://www.itcon.org/2015/19*

1. INTRODUCTION

Construction sites are typically characterized as dynamic environments each having a unique size and set of working conditions. These environments consist of multiple construction resources including personnel, heavy equipment, and materials each performing various tasks in a defined, often constrained space. When heavy construction equipment is operating in too close proximity to ground workers, hazardous proximity conditions are present. These conditions can create contact collisions between one or multiple workers and heavy equipment, which increase the risk of injuries or fatalities for construction personnel, collateral and other damage.

Human-heavy equipment interaction on construction sites has been discussed in previous research efforts, including a recent publication in ITcon (see Choe et al. 2014). The presented research focused on injury and fatality statistics of contact collisions between ground workers and heavy equipment. The repetitive nature of construction tasks can cause workers to experience a decrease in awareness (Pratt et al., 2001), as well as limited visibility for heavy equipment operators (Ruff, 2001; Fosbroke, 2004; Teizer et al., 2007; Teizer et al., 2010b, Marks et al., 2013; Cheng and Teizer, 2014; Ray and Teizer, 2012; Ray and Teizer, 2013; Bostelman et al., 2014). If other safety measures such as administrative policy, worker training, and safety work practices fail, a reliable real-time proximity detection and alert system is needed on construction sites to provide ground workers with another layer of safety protection (see Fig. 1).

Historically, construction companies have been slow in adapting automated technologies and innovation when compared to other industries (Pratt et al., 2001). Industries such as freight transportation, ship building, the mining industry, railroad operations, and manufacturing have been testing various prototype safety technologies including proximity detection and alert systems. Case studies of these industries have demonstrated emerging safety technologies can be used to enhance safety by providing workers another layer of protection through technology (Arif et al., 2014; Teizer et al., 2010a; Choe et al., 2014).

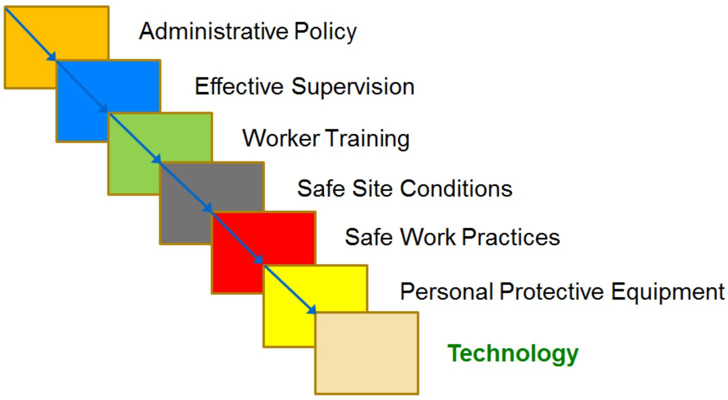

FIG. 1: Technology as an additional layer of safety protection for workers (Teizer et al., 2010a)

A lack of scientific evaluation data and results currently exists for construction safety technologies, specifically passive (battery-free) proximity detection and alert systems. Research has concluded already that any such technology must work reliably and be comfortable to wear (Teizer et al., 2010a; Choe et al., 2014). An ultimate design suggests small, thin, and battery-free devices that could eventually be attached to personal protective equipment workers wear already, and thus are easily to control and detect. Such technology has yet to be designed and explored in research. A novel battery-free proximity detection and alert system named the Self-Monitoring, Analysis, and Reporting Technology for Hazard Avoidance and Training (SmartHat) is presented and evaluated through various experiments designed to simulate a typical construction environment. Results and concluding remarks of the experiments are presented and recommendations are made for further development and implementation of passive proximity detection and alert systems.

2. LITERATURE REVIEW

Every construction site has a unique workspace and set of working conditions. Construction sites are typically characterized by dynamic interaction between various construction resources including workers, equipment, and materials. Available space on construction sites can be limited due to the unstructured and at times random movement of resources involving various trades. These resources are often required to function in close proximity to one another creating dangerous situations for ground workers. Incidents in which construction equipment strikes a ground worker can occur as a result of the construction site conditions. Ground workers in too close proximity to construction equipment has been discussed extensively in previous research (Ray and Teizer, 2012; Hinze and Teizer, 2011), but as injury and fatality statistics indicate, it remains a key problem in the construction industry.

The following review discusses injury and fatality incidents associate with hazardous proximity situations in the construction industry. The review also covers current safety practices in construction, proximity detection and alert systems, and methods for testing these systems. A research needs statement concludes the review.

2.1 Industry Statistics Related to Human-Equipment Interactions

When compared to other industries in the US, the construction industry continues to rank as one of the highest for workplace accident fatalities rates per year. In 2011, the construction industry experienced 721 fatalities which represented 16% of the nation's total workplace fatalities (CFOI, 2011a). 17% of these construction fatalities resulted from workers colliding with objects or equipment on the construction site. These 123 construction fatalities resulting from workers colliding with objects or equipment represented 2.6% of the US private sector workplace fatalities experienced in 2011 (CFOI, 2011a). Even in companies that have good safety records the proportion of equipment related fatalities is high. Following the commonly known safety pyramid it is likely that the number of injury and near misses is even higher.

The US Bureau of Labor Statistics (BLS) recorded 138 fatalities resulting from ground workers colliding with objects or equipment which accounted for 18% of the private construction industry fatalities and 2.9% of the total workplace fatalities experienced in 2010 (CFOI, 2010). Since 2003, the construction industry averaged 197 fatalities per year resulting from workers being struck-by construction equipment or other objects (CFOI, 2009).

Other than fatalities, these human-equipment interactions can also result in worker injuries which negatively impact the success of a project, for example, decreased worker productivity and increased company medical costs. The Census of Fatal Occupational Injuries (CFOI, 2011) recorded 24,710 injuries caused by workers colliding with construction equipment or other objects in 2010 within the construction industry. These injuries accounted for 12% of all construction worker injuries in that year. Injuries resulting from worker contact with construction equipment or objects decreased in 2010 from the previous 30,330 injuries of the same cause in 2009. Since 2003, the construction industry has experienced an average of 45,746 injuries resulting from workers colliding with equipment and objects on construction sites. All recorded injuries are limited to incidents requiring injured personnel to be absent from the project at least one working day (CFOI, 2011b).

A study of the construction worker fatality database recorded by OSHA from 1990 to 2007 identified the following major causes of construction equipment-related worker deaths: running over workers, crashing into other vehicles, crushed between objects, pinned- or hit-by equipment or materials, crashing into other objects, and struck-by incidents (Hinze and Teizer, 2011). Of the equipment-related fatality cases reviewed, 88% involved workers-on-foot. The most frequently noted causes were crushed-by, struck-by, pinned-by, run-over, and rollovers.

2.2 Causes of Human-Equipment Interactions

Much research has been performed to better understand hazardous proximity situations between construction workers and equipment and potential causes. One study indicated that characteristics of the harsh outdoor environment indicative of construction sites combined with the often repetitive nature of construction tasks can cause workers to decrease their awareness of surroundings (Pratt et al., 2001). Lower awareness and loss of focus due to worker fatigue through task repetition and limited operator visibility were two conditions of construction sites that could increase the level of human-equipment interaction. Fosbroke (2004) found that causes of hazardous proximity situations on construction sites is neither being properly examined nor recorded.

Three general problems that result in hazardous proximity situations between construction equipment and ground workers were identified:

- Outdated or never implemented policies, a lack of knowledge of existing risk factors, and repetitive work tasks for ground worker and equipment operators,
- All incident causation data is collected after-the-fact resulting in limited real-time incident information if any is available, and
- No real-time information is gathered during the incident.

Another study found that most equipment-human accidents resulted from missing safety features on the heavy equipment (OSHA, 1990). The missing devices included devices intended to alert workers of their close proximity to the equipment. Strategies for decreasing or preventing hazardous proximity situations on construction sites were the focus of other research efforts. Preventative measures including implementation of maintenance checklists for construction equipment and internal traffic control plans (ITC) were discussed as possible causes of the heavy equipment-human interaction problem on construction sites (Pratt et al., 2001). The goal of the ITC plan is to limit turning or reverse movements of construction equipment to limit the non-visible areas experienced by the equipment operator.

2.3 Safety Best Practices

Previous studies in construction safety has mainly focused on training and education. According to the Construction Industry Institute (CII, 2005; CII; 2006), training workers in construction safety best practices can reduce accidents by more than half, after passive safety tools such as safety cones, guard rails, and training are implemented. Much of the previous studies concentrates on construction safety best practices in design, education, and training for safety. These best safety practices typically do not generate feedback during performing the work task and they are unable to provide alerts in real-time. Best practices are often not innovative products of research, as they rather synthesize existing, well working practices employed by companies.

The Occupational Safety and Health Administration (OSHA) has created and implemented multiple passive safety regulations requiring safety devices such as hard hats, reflective safety vests and other personal protective equipment (PPE). These standards and regulations are imperative to improve safety in construction, but are not capable of providing alerts for ground workers and equipment operators in real-time during hazardous proximity situations. Other regulations such as incident recording and worker safety training can increase the awareness of close proximity issues for equipment operators and ground workers.

Construction worker safety behavior has been the focus of many research endeavors. One such work completed by the Construction Industry Institute (CII) monitored the behavior of construction workers and classified observed practices as safe or unsafe (Hinze and Gambatese, 1996). Another study performed by CII reported that companies that implemented site-specific safety programs at the beginning of a project experienced higher safety performance when compared to others (Hinze, 2003). The study concluded that increased efforts in front-end planning, also often referred to as Design for Safety (DfS) (Gambatese et al., 2005) can improve safety on construction projects.

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

Automation has been cited as capable of simplifying and improving some of the most important construction engineering and management problems (Navon and Sacks, 2006). Technology implemented to enhance safety on construction sites are categorized as re-active and pro-active. Re-active technology collects data in real-time, but later requires data collection processing effort after the event. Pro-active technology functions in real-time to warn and alert personnel of dangerous situations occurring instantaneously (Teizer et al., 2015a). Even pro-active technology may later employ data logging and processing to create safety leading indicators (Pradhananga and Teizer, 2013).

Real-time safety technologies implemented on construction sites have been proven to provide alerts to ground workers and equipment operators in real-time when a hazardous proximity situation exists (Teizer et al. 2010a). Construction safety technologies can provide ground workers with another layer of protection when other safety best practices are not implemented (Teizer et al., 2008). The construction industry requires a reliable technology capable of detection and providing alerts to workers in real-time during hazardous proximity situations.

A prototype proximity detection and alert technology created by NIOSH (National Institute for Occupational Safety and Health) implements a magnetic sensing system called HASARD (Hazardous Area Signaling and Ranging Device). Magnetic waves emitted from a transmitter were used to activate an alarm when a person entered the magnetic field. The prototype was evaluated for six months in the harsh conditions of an underground mine (Schiffbauer and Mowrey, 2012). The sensors were placed on workers and walls in an attempt to prevent collisions from underground mining machines.

Many of these technologies (see Fig. 2) such as RADAR (Radio Detection and Ranging), sonar, Global Positioning System (GPS), radio transceiver tags, and vision have unique limitations when deployed in a construction environment such as availability of signal, weight, size, power source, and feasibility in the construction environment (Ruff, 2001). Similar studies investigated several technologies thought to be capable of providing alerts to construction personnel during hazardous proximity situations. These technologies included Radio Frequency Identification (RFID), Global Positioning System (GPS), magnetic marking fields, vision detection devices, sonar, laser and radar based proximity detection (Teizer et al., 2010a; Marks and Teizer, 2012; Marks and Teizer, 2013). Multiple parameters specific to the construction environment such as read range, alert method, precision, reliability, capability of performing in an outdoor environment, and many others were used to assess each proximity detection technology. Radio frequency (RF) technology was cited as demonstrating potential to satisfy many of the constraints offered by the construction environment.

(a) (b) (c) (d)

FIG. 2: Examples of real-time pro-active obstacle detection and alert technologies that do not automatically recognize persons: (a) sonar, (b) side- and rear-view vision cameras, (c) RADAR and (d) 360° surround view vision cameras (Teizer et al., 2015a)

RF technology has been successfully implemented in other industries such as manufacturing, ship building, and transportation applications including the railroad industry (Teizer et al. 2010a). It has also been deployed in warehouses on forklifts known to have limited operator visibility and operate in small spaces (Teizer et al., 2010b). Ultra-High Frequency (UHF) near 434 MHz was used to warn workers-on-foot during hazardous proximity situations (Teizer et al., 2010a).

This review found that radio frequency technology, perhaps in addition to or combination with other real-time detection and alert technologies can (1) decrease the risk of collisions, (2) provide alerts in real-time for workers-on-foot inside construction environments, (3) record leading indicator data such as “near miss” events, (4) operate with minimal nuisance alerts, and (5) provide real-time alerts at different pre-calibrated proximity ranges. Some cited limitations of radio frequency technology for proximity detection on construction sites include (1) the system requires a power source for both equipment and ground worker component, (2) must be mounted on ground workers and construction equipment, and (3) construction equipment and unique site conditions can impact the system’s performance. Although applications of RFID technology for construction applications has a long history (Jaselskis et al., 1995), minimal research has been conducted to investigate the potential of passive RFID technology for enhancing construction safety.

2.5 Test Methods for Proximity Detection and Alert Systems

Past researchers have developed methods to evaluate the capabilities and reliability of proximity detection and alert systems. One study implemented manual methods to measure and mark proximity alert distances for a camera and radar system (Ruff 2005). Several large capacity haul trucks performing typical construction maneuvers were used for experimental trials. Results indicate the system was able to detect obstructions approximately 10 meters in front and behind of the trucks.

Measuring alert distances using manual methods were also implemented to test the accuracy of a Global Positioning System (GPS) for proximity detection. GPS devices were mounted on large haul capacity trucks and a base station was positioned on a nearby dirt mound. In total, three mobile vehicles and six stationary objects were tracked during a surface mining operation (Ruff, 2004). An integrated computer-assisted stereo vision and radar proximity detection system were also implemented on large haul capacity trucks. The proximity detection system’s reliability was evaluated through field trials with the large haul capacity trucks and ground workers (Steele et al., 2003).

Very High Frequency (VHF) Radio Frequency has also been deployed on heavy construction equipment and ground workers in simulated outdoor construction environments (Teizer et al., 2010a). A testing method for proximity detection and alert system was presented for the following cases: (1) Static equipment/mobile worker and (2) mobile equipment/mobile worker (Marks and Teizer, 2013). Experimental results indicate VHF radio frequency systems can provide alerts in real-time to ground workers, but radio waves are blocked or distorted by components of the construction equipment.

A lack of scientific evaluation data currently exists for new and existing automated safety technology for implementation on construction sites. Emerging safety technologies, specifically proximity detection and alert systems using radio frequency technology, need to be thoroughly evaluated in research through current or newly developed experimental methods, case studies, and resulting data analysis. A need exists to evaluate the effectiveness and reliability of the developed SmartHat proximity detection and alert system in the construction environment (Thomas et al., 2010, Stewart et al. 2011, Thomas et al. 2012).

3. RESEARCH OBJECTIVES, SCOPE AND EXPERIMENTAL PLAN

The objective was to design a passive, battery-free proximity detection and alert system capable of functioning in the construction environment. A secondary objective was to evaluate the reliability of the developed SmartHat proximity detection system that provides alerts in real-time when heavy construction equipment and workers are in too close proximity. This includes evaluating the effectiveness of various SmartHat device positions and orientations (to simulate ground worker and body movements) to provide alerts in real-time when deployed in a simulated construction environment. When heavy construction equipment and ground workers are in too close proximity, the SmartHat system should detect the situation and activate a real-time alert for the ground worker. The scope includes hazardous proximity situations between heavy construction equipment and ground workers on outdoor construction sites or simulated construction-like environments.

Each experiment was designed to evaluate the effectiveness of the SmartHat proximity detection and alert technology in an outdoor environment. The coverage area of the SmartHat devices was tested for three different Personal Protection Units (PPU) in the first set of experimental trials. Another set of experimental trials evaluated the effectiveness of various tag positions and orientations that are typical PPU mounting locations of existing Personal Protective Equipment (PPE) for construction ground workers.

4. SMARTHAT TECHNOLOGY DESIGN

The SmartHat proximity detection and alert system utilizes radio frequency (RF) technology to detect proximity breaches of construction equipment and ground workers. Novel, fully passive radio frequency technology is used for the SmartHat proximity detection and alert system meaning, there is no battery to supply operating power for the alert device on the PPU. Instead, the PPU's operating power is supplied by the EPU's radio frequency energy produced by the system antenna(s) mounted on the equipment. This allows for all electronic components (except the antenna) to be integrated into a single integrated circuit. The absence of a battery power source allows the SmartHat system to not be compromised by battery failure during construction operations and reduces cost of the overall system. A potential drawback of a battery-less device is the decreased alert range when compared to an active RFID system. The SmartHat proximity detection and alert system also used long range ultra-high frequency (UHF) radio frequency. The detection range of the SmartHat system can be calibrated by adjusting the power of the radio frequency signal generated by the Equipment Protection Unit (EPU) antenna. Configurations for both an active and passive RFID tag including the power source, antenna and data exchange are presented in Fig. 3. Drawbacks of both, active and passive RFID, approaches may still be the precision and repeatability of results (i.e., alert distances).

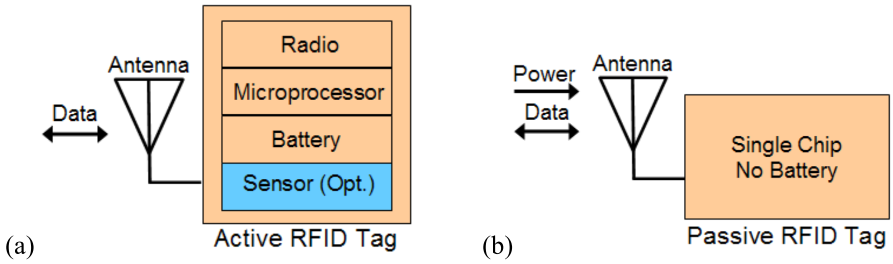

FIG. 3: (a) Active and (b) Passive RFID configuration (Thomas et al., 2010)

The SmartHat prototype system is comprised of two components:

- An Equipment Protection Unit (EPU) equipped with a single or multiple directional antenna(s) that serve(s) as a transceiver device by transmitting and receiving tag information including the magnitude and phase of the reflected radio frequency signal (see Fig. 4) and
- A Personal Protective Unit (PPU) that provides ground workers with a battery-less tag, or transponder, that has power harvesting capabilities (derives operating power from an incoming radio signal) and a bidirectional communication single chip circuit. The PPU is fully plastic-encapsulated square device (10 or less centimeters in length) and resistant to environmental degradation or accidental damage. Eventually, the PPU will be installed on a construction worker's hard hat or weaved into a safety vest. This provides easy recognition for safety inspectors to make sure all workers wear the devices. Both the EPU and PPU can be viewed in Fig. 4.

(a) (b) (c)

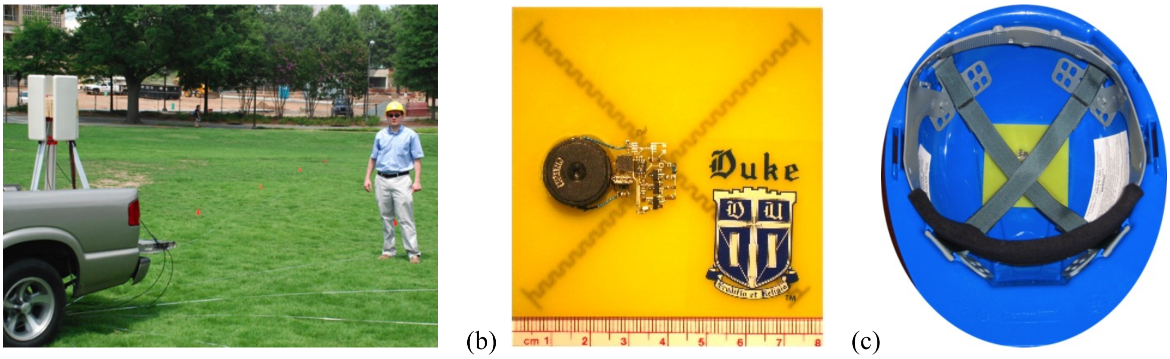

FIG. 4: (a) Antenna of Equipment Protection Unit (EPU), (b) geometry and current distribution for the "X" style antenna of the Personal Protection Unit (PPU) and (c) embedded in a construction hard hat

After the PPU intercepts the frequency generated by the EPU, the PPU activates an alert and the information on the chip is sent back to the EPU reader. When the alert is activated, the EPU stores, for example, the personnel tag's information. The sending and receiving of information is instantaneous, meaning the entire process occurs in real-time.

The PPU implements a crossed-dipole planar antenna fabricated from 3 mm thick printed circuit board material that is designed for horizontal polarization which as much omnidirectional performance as possible. The PPU contains a mechanism to alert ground workers in real-time when the signal broadcasted by the EPU is intercepted by the PPU (when the two construction resources are in too close proximity). An energy storage circuit installed in the PPU accumulates energy in a capacitor from the reader's transmitted signal. An ultra-low power microprocessor is used to manage the stored electromagnetic energy used to produce an alert when activated. The microprocessor controls the frequency synthesizer to generate a 902-928 MHz carrier. A 4-stage voltage multiplier was implemented in the SmartHat device because it delivered the highest RF-DC conversion efficiency at the 40k load impedance point, which is the appropriate load impedance of the SmartHat digital circuitry and piezo speaker when delivering and alert sound. The voltage delivered to the microcontroller in the PPU is limited to 2.5V. When delivering a pulsed alert, the tag's average operating power is approximately 1.8V. Low power consumption is key to operate the device in a reliable manner in a potentially harsh work environment.

The EPU's signal is broadcasted in a radial manner and loses strength as it moves farther from the EPU location. A piezoelectric speaker installed on the PPU is used to produce a unique audible sound, approximately 110 db Sound Pressure Level (SPL) at a frequency of 2.5 KHz, which is easily heard by ground workers on construction sites. During the experimental trials, the strength of the signal emitted by the EPU remained consistent. The EPU can be connected directly to the battery source of a piece of construction equipment. The EPU's antenna should be installed in locations such that the line-of-sight to objects is not obstructed. Signal line-of-sight issues are a major limitation of high frequency RF applications. Fig. 5 shows a schematic drawing of the SmartHat warning device (left) and the PPU installed in a different, possible setting inside a worker's hard hat.

The SmartHat proximity detection and alert system also possesses data logging capabilities. The accompanying software of the system records the tag identification number, EPU antenna identification number, time stamp of the proximity breach, and cumulative count of proximity breach per tag. This information can be analyzed and used for further safety training for equipment operators and ground workers concerning hazardous proximity situations on construction sites.

Other proximity detection and alert systems using radio frequency were evaluated during the experimental trials to provide comparison to the SmartHat system. Both systems deploy a methodology similar to the SmartHat system; however one uses fully passive RF personnel tag in which the EPU activates the alert during a proximity breach. The other system uses a fully active PPU that contains a chip and battery, and is installed on the hard hat of a construction worker. The EPU component of this system contained a single antenna, reader, alert mechanism and can be powered by the existing battery on a piece of equipment. The EPU component also provides an audible and visual alert to the equipment operator rather than the PPU activating an alert as is true with the SmartHat system.

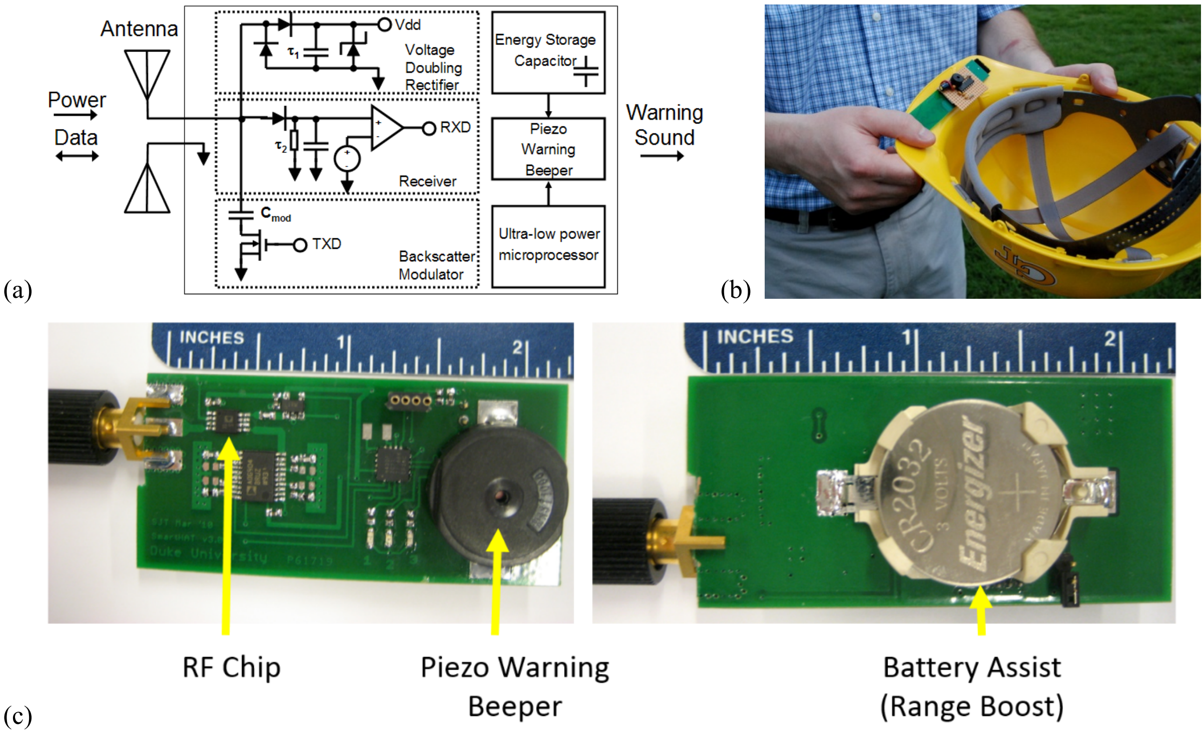

FIG. 5: (a) Passive UHF RFID SmartHat schematic drawing, (b) installed on the brim of hard hat, and (c) detail of the speaker device on a later version of the SmartHat once leveraging a semi-passive approach to boost range

5. EXPERIMENTS

Three experimental test beds and procedures were constructed and executed to measure the reliability and effectiveness of the SmartHat system both between system specific SmartHat devices, and against other proximity detection and alert systems using both passive and active RFID technology. All experiments were conducted in an outdoor environment to emulate conditions of an actual construction site. For each set of experimental trials, the outdoor weather conditions were mostly clear, mostly sunny, temperature was 26°C, wind speed of 8 km/h and 36 percent humidity.

5.1 Field Trial A: System Coverage Area

The objective of the system coverage area experimental trials was to evaluate the coverage area for the SmartHat between different SmartHat devices, and compare these results to other proximity detection and alert systems. The test bed for these trials was a clear, flat, grass ground surface with no obstructions. A Robotic Total Station was used to outline a 15 meter radius semi-circle using survey markers places 18 equal distance locations (every 10 degrees) around the circumference of the semi-circle. Fig. 6a shows the test bed used for these experimental trials.

FIG. 6: (a) Coverage area of the experimental test bed and (b) mounting position and orientation of passive SmartHat

Four of the EPU's antenna components were attached to a cart and only the antenna facing the semicircle was activated during the experiments. The activated antenna was positioned directly above the center point of the semicircle which can be viewed in Figure 5. There were no obstructions between the antenna's line-of-sight and all points along the arc of the semicircle.

The EPU antenna and cart assembly can be viewed in Fig.4a. Each of PPU tested was attached to a cardboard rectangle such that the test person could control the orientation of the device without contacting and possibly obstructing the PPU's antenna. An example of the PPU configuration is displayed in Figure 6b.

To evaluate the coverage area of the SmartHat system, a test person held the width of the cardboard perpendicular to the ground with the PPU surface face directed towards the EPU. This is described in subsequent section as vertically positioned in orientation 1. The tag was held 1.15 meters above the ground which was the same vertical elevation as the center of the EPU antenna. The test person holding the tag at a constant elevation approached the EPU at a constant walking pace from each of the 18 equal distance approach angles. Once an alert was activated, the test person stopped walking and measured the alert distance using a commercially available laser distance meter. This procedure was repeated three times for each approach angle per each tag tested.

The obtained data (alert distance measurements) from each tag were used to create proximity coverage area graphs. These graphs show the recorded distance measurement from the test person's position to the EPU antenna when the alert is activated. The recorded alert distance measurements and resulting coverage area graph for tag 3 of the SmartHat system is presented in Fig. 7. The three lines represent the three different trials from each approach angle. Similar graphs were created for all tags and systems tested. The black arrow represents the line-of-sight of the antenna in relation to the approach angles.

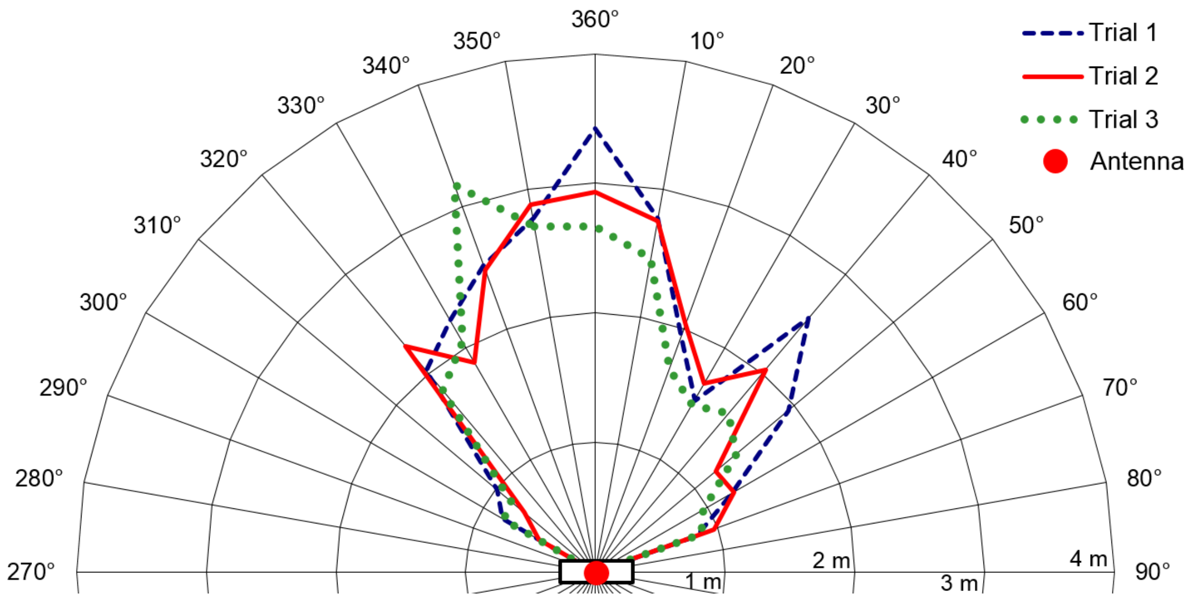

FIG. 7: Proximity alert distance coverage for one passive SmartHat device (plan view)

A total of 54 samples were taken for each tag when combining each approach angle and each trial. The SmartHat system EPU antennas are directional meaning they are only capable of reading 60 degrees in both directions parallel to the face plane of the antenna. A statistical analysis was performed on the sample data from each tag, specifically on readings in the 120 degree read range (between approach angle 300 degrees and 60 degrees on Fig. 7) of the directional antenna. Fig. 7 indicates the EPU's antenna field-of-view was covered for the entire 120 degree signal propagation area. A statistical analysis was performed on the obtained data from all systems and tags tested. Results of that analysis for the three tested tags of the SmartHat system tested are shown in Table 1. In the table, the degrees noted in the first column correspond to the approach angles in the coverage area graph (Fig. 7).

Table 1: Statistical analysis of the alert measurements of passive SmartHat tags

	Tag 1			Tag 2			Tag 3		
Approach Angle	Median (m)	Range (m)	Std. Dev.	Median (m)	Range (m)	Std. Dev.	Median (m)	Range (m)	Std. Dev.
300°	1.1	0.3	**0.1**	0.6	0.3	**0.1**	0.7	0.3	0.2
310°	1.1	0.5	0.3	0.5	0.3	0.2	0.9	0.3	**0.1**
320°	1.6	0.6	0.3	0.7	0.2	**0.1**	2.0	0.5	0.2
330°	1.4	**0.2**	**0.1**	1.0	0.2	**0.1**	2.1	0.4	0.2
340°	2.8	**0.2**	**0.1**	1.2	0.2	**0.1**	2.7	0.7	0.4
350°	2.9	0.4	0.2	1.5	0.6	0.3	2.8	**0.2**	**0.1**
360°	**3.1**	1.5	0.7	**2.0**	1.0	0.6	**3.0**	0.8	0.4
10°	2.7	0.5	0.2	1.8	1.1	0.6	2.7	0.3	0.2
20°	2.3	0.4	0.2	1.0	0.2	**0.1**	1.9	0.4	0.2
30°	1.9	1.3	0.6	1.4	0.9	0.4	1.6	**0.2**	**0.1**
40°	2.1	0.6	0.4	0.9	0.4	0.2	2.1	1.0	0.5
50°	0.7	**0.2**	**0.1**	1.1	0.5	0.3	1.5	0.7	0.4
60°	0.8	**0.2**	**0.1**	1.5	**0.1**	**0.1**	1.1	0.3	0.2
Correlation	**- 0.9**	- 0.4	- 0.4	**- 0.7**	**- 0.6**	**- 0.6**	**- 0.9**	- 0.1	- 0.1

Bolded values in Table 1 represent the highest performers (highest median range, smallest range and smallest standard deviation) among the trials of each tag. The last row titled "Correlation" displays the correlation value of each column to the approach angle. For example, the correlation value of the median for tag 1 when compared to each corresponding approach angle is -0.9. (Albright et al., 2011). The values noted in bold text display categories of correlation that are considered statistically signification for a 95 percent confidence interval.

Results in Table 2 indicate that the 360 degree approach angle (tag orientation is perpendicular to the plane of the antenna) gives the highest median alert distances between trials for each tag. The standard deviation of each tag becomes larger as the approach angles near the perpendicular approach angle (360 degrees). A statistically significant correlation exists between the approach angle and median alert distance measurements for every tag. Tag 2 has a statically significant correlation value for all three statistical measures (median, range, and standard deviation) for each approach angle based on a 95 percent confidence interval. Little correlation is realized for values of range and standard deviation for both tags 1 and 3.

Table 2: Statistical analysis of the alert measurements for the passive SmartHat tags

	SmartHat			Active	Passive
Alert Distance	Tag 1	Tag 2	Tag 3	Tag 4	Tag 5
Median	2.5 m	1.0 m	1.1 m	**22.4 m**	4.8 m
Minimum	0.9 m	0.0 m	0.0 m	5.0 m	1.2 m
Maximum	3.8 m	3.1 m	2.8 m	38.2 m	6.1 m
Range	2.9 m	3.1 m	**2.8 m**	33.2 m	4.9 m
Std. Deviation	**0.9**	1.0	1.0	12.4	2.3

One active and one passive RFID proximity detection and alert system were also subjected to the same experimental trials and used for comparison to the SmartHat system. Results of the tags from all three systems are shown in Table 2. The calculated values of median, range, standard deviation and overall coverage area were used to compare the performance of each proximity detection and alert system. The coverage area represents the area within the 180 degree semicircle in which an alert was activated for the test person in close proximity to the antenna. Values printed in bold represent the best performers (highest median alert distance, smallest range and smallest standard deviation) when compared to the other systems tested.

The active proximity detection and alert system demonstrated the highest alert range and coverage area when compared to the passive system and all three tags of the SmartHat system. The alert distance measurements from all three tags of SmartHat system recorded the smallest range values indicating their high precision level of the tested approach angles when compared to the other systems.

5.2 Field Trial B: Tag Position and Orientation

The objective of these experimental trials was to identify the best position and orientation among multiple variations for the SmartHat system. The same clear, flat, grass ground surface with no obstructions was used as the test bed for the experimental trials. An RTS was used to place markers along a straight path perpendicular to the face plane of the EPU antenna. Markers placed at consistent 3 meter intervals outlined the walking path for the test person. The test bed for these trials is displayed in Fig. 8.

FIG. 8: EPU position and orientation test bed

Similarly to the previous experiment, the SmartHat devices were attached to a piece of cardboard, and held by the test person at 1.15 meters above the ground surface which is the same as the centroid elevation for the EPU antenna. This elevation allowed for a direct horizontal line-of-sight between the EPU antenna and PPU. The test person started outside of the alert range (approximately 30 meters from the antenna) and walked towards the antenna on the straight marked path at a constant walking pace. As detailed in the previous experiment, the alert distance was measured and recorded using a commercially available laser distance meter. This procedure was repeated ten times for each combination of tag position and orientation.

Eight combinations of tag positions and orientations were tested during this set of experimental trials. For the purposes of this experiment, the term "position" was defined as the location of the face plane of the device in relation to the ground surface. For example, a horizontal position is represented by the face plane of the device being parallel to the ground surface and perpendicular to the EPU antenna face. Likewise, a vertically positioned device has the face plane perpendicular to the ground surface and parallel to the EPU antenna face. Both of these positions are shown in Fig. 9.

(a) (b)

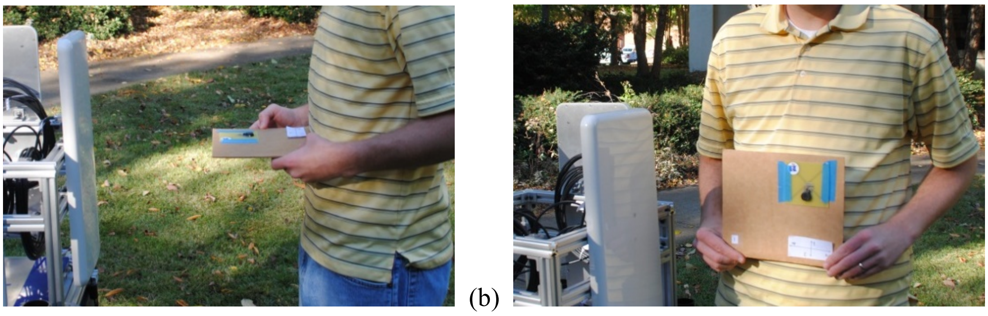

FIG. 9: (a) Passive SmartHat (PPU) horizontally positioned and (b) tag vertically positioned

Four different tags orientations were used in combinations with the tag positions. The orientations were based on the location of the tag antenna in relation to the EPU antenna or the sky. Each of the four tag orientations was given a number (1, 2, 3, or 4) depending on the location of tag components such that each of the four possible orthogonal tag orientations was tested. Each subsequent orientation after the first initial orientation (orientation 1) was achieved by rotating the tag counter clockwise 90 degrees. The diagram in Fig. 10 shows how the tags were oriented in relationship to the system antenna or the sky and ground surface.

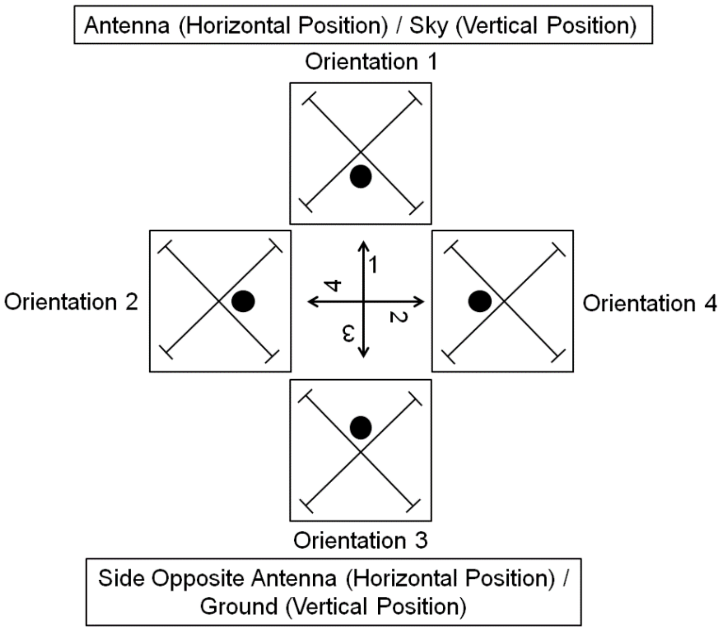

FIG. 10: Passive SmartHat (PPU) orientation in relation to the EPU antenna and ground surface

A statistical analysis was performed on each of the set of experimental trials. Results were divided into categories of tag position (horizontal or vertical) and tag orientation number (1, 2, 3 or 4). Table 3 shows the best and worst performers of each of the possible tag position and orientation combinations. Best performers were classified as trials having the highest median value, lowest range value and lowest standard deviation value when compared to the other orientations tested using the same tag in the same position. Worst performers were classified as trials recording the lowest median value, highest range value and highest standard deviation value when compared to the other orientations tested using the same tag in the same position. Bolded values indicate the best performers when compared to results of the other two tags in that position. The abbreviation "Or." Is used for the term "orientation" in Table 3.

Table 3: Best and worst performers among experimental trials for tag position and orientation

Horizontal Position						
	Tag 1		Tag 2		Tag 3	
	Best	Worst	Best	Worst	Best	Worst
Median	Or. 2 (2.8 m)	Or. 3 (2.2 m)	Or. 2 (2.5 m)	Or. 1 (0.8 m)	**Or. 2 (2.9 m)**	Or. 4 (1.9 m)
Range	**Or. 3 (0.7 m)**	Or. 1 (1.4 m)	Or. 2 (0.7 m)	Or. 3 (1.0 m)	**Or. 2 (0.7 m)**	Or. 3 (1.3 m)
Standard Deviation	**Or. 2 (0.1m)**	Or. 1 (0.5 m)	Or. 2 (0.3 m)	Or. 3 (0.4 m)	Or. 2 (0.2 m)	Or. 4 (0.5 m)
Vertical Position						
	Tag 1		Tag 2		Tag 3	
	Best	Worst	Best	Worst	Best	Worst
Median	**Or. 1 (3.5 m)**	Or. 2 (2.1 m)	Or. 2 (2.4 m)	Or. 3 (1.9 m)	Or. 2 (2.5 m)	Or. 4 (2.1 m)
Range	Or. 3 (0.7 m)	Or. 1 (1.4 m)	**Or. 1 (0.6 m)**	Or. 3 (1.2 m)	**Or. 1 (0.6 m)**	Or. 3 (1.1 m)
Standard Deviation	**Or. 3 (0.2 m)**	Or. 1 (0.4 m)	**Or. 1 (0.2 m)**	Or. 3 (0.4 m)	**Or. 1 (0.2 m)**	Or. 3 (0.4 m)

For the horizontally positioned tag, orientation 2 had the highest median range recorded and lowest standard deviation value for each of the three tested tags. Tag 2 showed a 1.7 meter difference between the median value of orientation 2 and orientation 1. Orientation 2 was the best performer for all statistical categories evaluated when compared to the other orientations in the horizontal position. For the vertically positioned tag, orientation 1 was the best performer for range and standard deviation for tag 2 and tag 3. Orientation 1 was the best performer for all statistical categories evaluated when compared to the other orientations in the vertical position. These results indicate that position and orientation of the PPU directly impacts the alert distance meaning devices mounted on moving ground workers could alert workers at varying distances depending on the worker's orientation and position.

5.3 Field Trial C: Comparison to Wearable Tag-based Detection and Alert Methods

A final test was conducted to compare competing wearable, tag-based proximity detection and alert methods. The purpose of this test was not to select high vs. low performance, rather to identify ranges where technologies might offer suitable solutions to practitioners. Since the author has done extensive research with several of these technologies, their performance was tested and evaluated.

All of the technologies had a single antenna mounted at the center or the rear of a piece of construction equipment. Magnetic field and active UHF RFID antennas were both centered on the equipment since they create an omnidirectional field. All other antennas (Semi-passive, passive UHF RFID, and SmartHat) used directional antennas that were mounted at the rear of the equipment. As such the results vary. The lowest performer in range are passive UHF RFID tags. In the coverage area the signal reached about 3 meters. The SmartHat tag like the passive UHF RFID tags is not battery powered. The range extended to between 4 to 5 meters. However, the advantage of the SmartHat tag is that it carries a speaker and thus is able to warn the worker who carries the SmartHat. The warning is also not possible with a commercially-available semi-passive tag although it alert distance extends to about 35 meters. While active UHF RFID tags (depending on the type of tag used) provide alerts, any of the tested technologies that rely on UHF signals might fail. An example is shown in Fig. 11 (ative UHF RFID at 310°). While this is a major drawback for any UHF RFID based method, it is not the case for magnetic field detection and alert technology. Magnetic field sensing user a much lower bandwidth that and therefore is resistant to multipath as it could potentially exist in a construction setting and other issues that make other technologies fail. Existing commercially-available magnetic field sensing technology though also relies on an active (battery-powered) tag-based approach to warn the worker-on-foot.

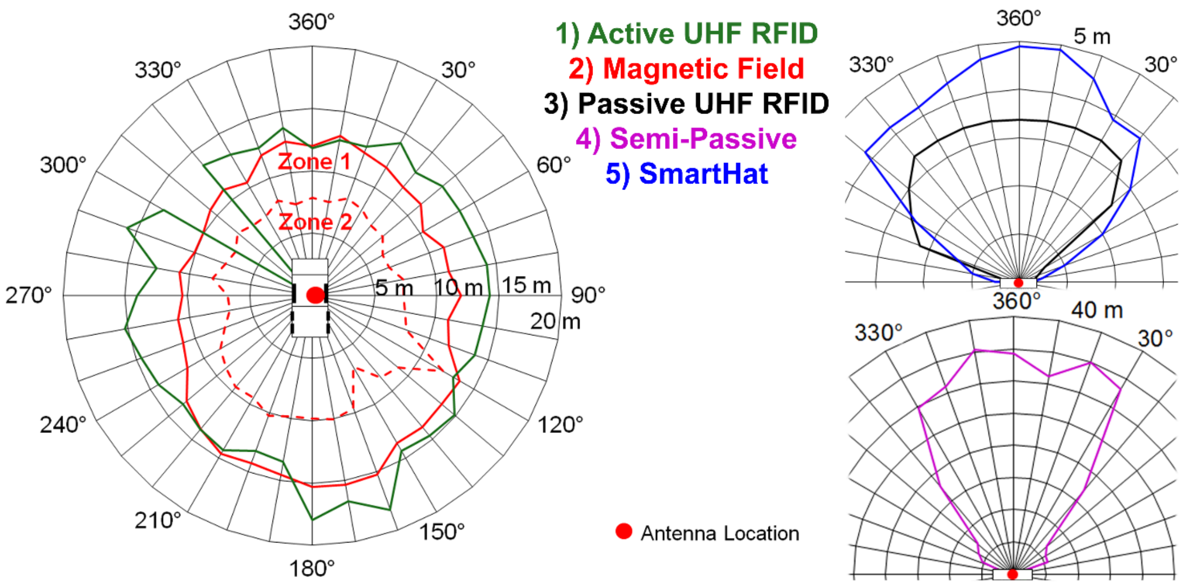

FIG. 11: Evaluation of wearable tag-based proximity detection and alert methods

The design of the SmartHat technology is therefore the first passive UHF RFID tag approach that also provides a warning alert for the worker-on-foot in real-time. Future research might be focus on taking advantage of the power source in semi-passive tags to extend the range of the SmartHat tag. This might be a much needed development task, since construction practitioners demand worker-on-foot proximity detection and alert ranges of at least 15 meters to stop a fast moving vehicle on construction sites (note: the speed limit is typically 5 km/h) in time. In combination with other passive (non-tag based obstacle detection and alert technologies (e.g. cameras, RADAR, sonar) (Choe et al., 2014; Rinneberg et al. 2015), a further refined SmartHat might offer a potential fix to a long-existing safety problem in construction and elsewhere.

6. CONCLUSIONS

One leading cause of construction fatalities is collisions between workers-on-foot and objects or construction equipment. Current implemented safety practices for hazardous proximity situations on construction sites have proven inadequate as indicated by the resulting fatalities and accidents. The construction industry and other industries that have heavy material handling equipment, for example forklifts in warehouses, must seek alternative approaches to achieve zero fatalities and injuries for all construction projects. The purpose of this research was to present a proximity detection and alert system called the SmartHat system and evaluate its reliability and effectiveness in the laboratory and construction environment. Results from experimental benchmark tests suggest that the system can effectively and reliability alert ground workers during hazardous proximity conditions.

The SmartHat proximity detection and alert system relies on passive (battery-free) radio frequency (RF) technology only. It demonstrated its ability to detect the presence of hazardous proximity conditions on construction sites. The executed experimental trials tested the coverage area of the EPU antenna as well as various PPU positions and orientations attached to a reflected safety vest and construction hard hat. The audible alert for the ground workers was to a sufficient volume so that it was heard over other loud construction noise. The system also demonstrated its capability to record safety leading indicator data or near-miss events. As such, the SmartHat has advantages over other tag-based systems that require frequent recharging or replacement of batteries, which is often challenging from an investment return perspective as well as the construction workforce often has a lower literacy level (i.e., caused by language barriers).

The three SmartHat PPU's evaluated for coverage area all demonstrated similar values for median, range, and standard deviation for corresponding approach angles. The coverage areas of the three SmartHat system tags were similar, but smaller than the coverage area for the tested passive and active RF systems evaluated. The overall median range for the SmartHat system was also smaller when compared to both the active and passive systems. Active systems with battery equipped PPU's allow for higher alert range values than the passive systems. However, active systems typically require a higher cost investment than their passive counterparts. Like the active and passive proximity detection and alert systems tested, the coverage area for the SmartHat system is limited to the output range of the EPU antenna. Multiple EPU antennas might be required to cover the immediate hazardous proximity area around one piece of construction equipment, or to cover all of the operator blind spots.

When testing the SmartHat PPU's best orientation among the four tested when positioned horizontally, orientation 2 and three were the best performers. Orientation 1 was the highest performer among the four tested in the vertical position. The SmartHat proximity detection and alert system demonstrated polarization between orientations in the horizontal and vertical position indicating that various movements and body positions of ground workers on construction sites can impact the reliability of the alerts. The SmartHat PPU's should be attached to several locations on the PPE of ground workers to maintain the effectiveness of the system by addressing every possible ground worker position and orientation. Further research and development is required on new innovation such as the design of a 3D tag for the PPU that eliminates polarization effects of the proximity detection as well as solutions for suitable, wearable product design solutions that are accepted by the workforce.

The completed field trials of the SmartHat proximity detection and alert system were deemed successful, other parameters could potentially influence the system such as impacts on the signal propagation. These factors include the EPU antenna mounting location, other construction resources such as materials, specific alert range for individual pieces of construction equipment, and impacts of an integrated system of multiple EPU's and PPU's on an active construction site. These factors and others will require investigation to further evaluate the effectiveness of implementing the SmartHat proximity detection and alert devices in the construction environment. The system should eventually be deployed in extensive field trials conducted over extended project durations. During these long term field trials, data can be recorded, analyzed, and used to improve positioning of workers and equipment to assist in the development of new safety concepts including advanced safety education and training courses (Pradhananga and Teizer, 2015; Teizer et al. 2015b-d; Zhang et al., 2015).

7. ACKNOWLEDGEMENTS

This work would have not been possible without the contributions of M.S. Reynolds, M. Stewart, S.J. Thomas, and E. Marks. The project was funded by grants from the National Science Foundation under Award Numbers CMMI #0800858 and CBET #0931924. The support of the collaborators and NSF is gratefully acknowledged.

8. REFERENCES

Albright, S.C., Winston, W.L., Zappe, C.J. (2011a). Data Analysis and Decision Making, 4th Ed., South-Western CENGAGE Learning, Mason, OH.

Arif, O., Ray, S.J., Vela, P.A., and Teizer, J. (2013). Potential of Time-of-Flight (TOF) Range Imaging for Object Manipulation and Identification in Construction, ASCE Journal of Computing in Civil Engineering, Reston, Virginia, 28(6), 06014005.

Bostelman, R., Teizer, J., Ray, S.J., Agronind, M., and Albanesee, D. (2014). Improved Methods for Evaluation of Visibility for Industrial Vehicles Towards Improved Safety Standards, Safety Science, Elsevier, Vol. 62, pg. 257-270.

Census of Fatal Occupational Injuries (2009). Fatal occupational injuries by industry and selected event or exposure. U.S. Bureau of Labor Statistics, <http://www.bls.gov/iif/oshcfoi1.htm> (Oct. 25, 2012).

Census of Fatal Occupational Injuries (2010). Fatal occupational injuries by industry and selected event or exposure. U.S. Bureau of Labor Statistics, <http://www.bls.gov/iff/oshcfoil.htm#2010> (Nov. 11, 2012).

Census of Fatal Occupational Injuries (2011a). Fatal occupational injuries by industry and selected event or exposure. U.S. Bureau of Labor Statistics, <http://www.bls.gov/iff/oshcfoil.htm#2011> (Nov. 8, 2012).

Census of Fatal Occupational Injuries (2011b). Fatal occupational injuries by industry and selected event or exposure. U.S. Bureau of Labor Statistics, <http://www.bls.gov/iif/oshsum.htm> (Oct. 21, 2012).

Cheng, T. and Teizer, J. (2014). Modeling Tower Crane Operator Visibility to Minimize the Risk of Limited Situational Awareness, ASCE Journal of Computing in Civil Engineering, 28(3), 04014004.

Choe, S., Leite, F., Seedah, D., Caldas, C. (2014). Evaluation of Sensing Technology for the Prevention of Backover Accidents in Construction Work Zones, ITcon Vol. 19, pg. 1-19, http://www.itcon.org/2014/1.

Fosbroke, D.E. (2004). NIOSH Reports! Studies on Heavy Equipment Blind Spots and Internal Traffic Control. NIOSH, <https://www.workzonesafety.org/files/documents/news_events/wz_conference_2004/heavy_equipment.pdf> (August 16, 2012).

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

Gambatese, J.A., Behm, M., and Hinze, J. (2005). Viability of Designing for Construction Worker Safety. Journal of Construction Engineering and Management, 131(9), pg. 1029-1036.

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

Hinze, J., and J. Teizer (2011). Visibility-Related Fatalities Related to Construction Equipment. Safety Science, 49(5), pg. 709-718.

Jaselskis, E., Anderson, M., Jahren, C., Rodriguez, Y., Njos, S. (1995). Radio-Frequency Identification Applications in Construction Industry. Journal of Construction Engineering and Management, 121(2), pg. 189-196.

Marks, E. and Teizer, J. (2012). Safety First: Real-Time Proactive Equipment Operator and Ground Worker Warning and Alert System in Steel Manufacturing. Iron & Steel Technology, AIST, 9(10), pg. 56-69.

Marks, E. and Teizer, J. (2013). Method for Testing Proximity Detection and Alert Technology for Safe Construction Equipment Operation, Construction Management and Economics, Taylor & Francis, Special Issue on Occupational Health and Safety in the Construction Industry, 31(6), pg. 636-646.

Marks, E., Cheng, T., Teizer, J. (2013). Laser Scanning for Safe Equipment Design that Increases Operator Visibility by Measuring Blind Spots. ASCE Journal of Construction Engineering and Management, 139, 1006-1014.

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

OSHA (1990). Occupational Safety and Health Standards - Excavation Final Rule. Occupational Safety and Health Administration, Federal Register, U.S. Department of Labor, Washington, D.C., 54, 209.

Pradhananga, N., Teizer, J. (2013). Automatic Spatio-Temporal Analysis of Construction Equipment Operations using GPS Data, Automation in Construction, Elsevier, Vol. 29, pg. 107-122.

Pradhananga, N. and Teizer, J. (2015). "Spatial Temporal Mapping and Analysis of Near Miss Events between Workers and Equipment on Construction Sites using GPS Data", Visualization in Engineering, Springer Verlag.

Pratt, S. G., Fosbroke, D.E., and Marsh, S.M. (2001). Building Safer Highway Work Zones: Measures to Prevent Worker Injuries From Vehicles and Equipment, Department of Health and Human Services: CDC, NIOSH, 5-6.

Ray, J.S., and Teizer, J. (2012). Coarse Head Pose Estimation of Construction Equipment Operators to Formulate Dynamic Blind Spots, Advanced Engineering Informatics, Elsevier, 26(1), pg. 117-130.

Ray, S.J., and Teizer, J. (2013). Computing 3D Blind Spots of Construction Equipment: Implementation and Evaluation of an Automated Measurement and Visualization Method Utilizing Range Point Cloud Data, Automation in Construction, Elsevier, 36, pg. 95-107.

Rinneberg, S., Teizer, J., Kessler, S., Günthner, W.A. (2015). "Smart Quick Coupling System for Safe Equipment Attachment Selection and Operation", Proceedings of the 32nd International Symposium on Automation and Robotics in Construction, Oulu, Finland.

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

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

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

Schiffbauer, W.H., and Mowrey, G.L. (2012). An Environmentally Robust Proximity Warning System for Surface and Underground Mining Applications, Pittsburg, PA: National Institute of Safety and Health, NIOSH, <http://www.cdc. gov/niosh/mining/topics/ machinesafety/equipmentdsgn/hasardsystem.htm> (Sept. 5, 2012).

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

Stewart, M., Teizer, J., Reynolds, M. (2011). SmartHat: A Battery-free Worker Safety Device Employing Passive UHF RFID Technology, RFID 2011, Orlando, Florida.

Thomas, S., Reynolds, M., Teizer, J. (2010). Electromagnetic Energy Harvesting for Sensing, Communication, and Actuation, Proceedings of the 27th International Symposium on Automation and Robotics in Construction, Bratislava, Slovakia, June 25-27, 2010.

Thomas, S.J., Wheeler, E., Teizer, J., Reynolds, M.S. (2012). Quadrature Amplitude Modulated Backscatter in Passive and Semipassive UHF RFID Systems. IEEE Transactions on Microwave Theory and Techniques, 60(4), pg. 1175-1183.

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

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

Teizer, J., Allread B.S., Fullerton, C.E. and Hinze, J. (2010a). Autonomous Pro-Active Real-Time Construction Worker and Equipment Operator Proximity Safety Alert System. Automation in Construction, 19(5), pg. 630-640.

Teizer, J., Allread, B.S., and Mantripragada, U. (2010b). “Automating the Blind Spot Measurement of Construction Equipment”. Automation in Construction, Elsevier, 19(4), 491-501.

Teizer., J. (2015a). “Safety 360: Surround View And Alerts To Protect Workers From Hazardous Equipment”, Proc.32nd International Symposium on Automation and Robotics in Construction, Oulu, Finland.

Teizer, J. (2015b). “Status Quo and Open Challenges in Vision-Based Sensing and Tracking of Temporary Resources on Infrastructure Construction Sites”, Advanced Engineering Informatics, Special Issue Infrastructure Computer Vision, Elsevier, 29, 225-238.

Teizer, J., Golovina, O., Wang, D., and Pradhananga, N. (2015c). “Automated Collection, Identification, Localization, and Analysis of Worker-Related Proximity Hazard Events in Heavy Construction Equipment Operation”, 32nd ISARC, Oulu, Finland.

Teizer., J. (2015d). “Magnetic Field Worker Proximity Detection And Alert Technology For Safe Heavy Construction Equipment Operation”, Proceedings of the 32nd International Symposium on Automation and Robotics in Construction, Oulu, Finland.

Zhang, S., Teizer, J., and Pradhananga, N. (2015). “Global Positioning System Data To Model And Visualize Workspace Density In Construction Safety Planning”, Proceedings of the 32nd International Symposium on Automation and Robotics in Construction, Oulu, Finland.