Automated Collection, Identification, Localization, and Analysis of Worker-Related Proximity Hazard Events in Heavy Construction Equipment Operation

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ABSTRACT

The construction industry measures worker safety performance through lagging indicators such as counting numbers of illnesses, injuries, and fatalities. Active leading indicators, such as capturing hazardous proximity situations between ground workers and heavy construction equipment, provide an additional metric for construction site personnel safety performance without incurring worker accidents. This article presents an algorithm for recording, identifying, and analyzing interactive hazardous proximity situations between ground workers and heavy construction equipment. Spatial-temporal GPS data of ground worker and heavy equipment movements are analyzed to automatically measure the frequency and duration of identified hazardous proximity situations. Individual periodic ground worker and equipment operator safety performance with regards to exposure to hazardous proximity situations is reported in detail. The results are integrated with previous research on blind spots and other safety deficiencies of the equipment. By measuring and analyzing leading indicator data of ground workers and heavy equipment, safety managers can identify hazardous situations that may otherwise lead to incidents. Knowledge generated about hazardous proximity issues are disseminated to construction personnel through enhanced safety training and education. Mitigation measures can also be taken for safer construction equipment operation.

Keywords - Accidents, injuries, and fatalities; Heavy construction equipment; Proximity and struck-by hazards; Lagging and leading indicators; Safety; Workforce; Risk.

1 Introduction

Construction sites are characterized by a multitude of interactions between construction equipment, workers, and materials. This dynamic environment creates many visibility-related issues for construction workers and equipment operators to recognize each other. Non-visible areas, called blind spots, are one of the leading causes of contact collisions between ground workers and construction equipment in the construction industry [1-5]. Blind spots impede the line-of-sight of a construction equipment operator creating non-visible spaces for the operator outside of the equipment cab. Contact collisions occur, among other reasons, when workers, equipment, or materials enter these blind spots undetected by the equipment operator. The goal of this research is to extract new safety information by capturing and analyzing the spatial-temporal interactions between the ground workers and heavy equipment.

2 Background Review

Of the construction fatalities experienced in 2012, 17% (135 fatalities) resulted from workers being struck-by an object or piece of construction equipment [6]. In 2011, the US Bureau of Labor Statistics reported 122 fatalities resulting from collisions between construction personnel and equipment or objects. These fatalities accounted for 17% of all fatalities experienced in the construction industry in 2011 and 2.5% of the total fatalities experienced in the U.S. private industry sector [7]. In 2012 this number increased to 3% [8]. Since 2003 and over a period of time now, the US construction industry has averaged 192 fatalities resulting from construction equipment or other objects striking workers per year [8].

2.1 Operator Visibility

Visibility related issues have an impact on the overall safety of the construction industry. One of the causes of contact collisions between construction equipment and workers are equipment blind spots [7]. Blind spots are a product of poor visibility in which an equipment operator's line-of-sight is impeded by components of the construction equipment. The close proximity of workers on the ground to construction equipment creates many visibility-related instances for operators. Statistics found in research by Hinze and Teizer [9] show evidence of this concern. Many accident investigations and research studies found that visibility-related issues created by blind spots caused operators to (1) run over workers and materials, (2) have contact with other equipment, and (3) roll over while operating their own construction equipment [9].

2.2 Hazardous Proximity Situations

Proximity is a significant indicator of potential collision events. They generally can be prevented from occurring by (1) the consciousness and awareness of the operator and ground worker, (2) education and training, (3) safety equipment (e.g., high-reflectivity safety vests or apparel), or (4) pro-active real-time detection and alert systems. Many researchers have attempted to increase the consciousness of the equipment operator by examining the visibility of typical construction equipment and identifying the blind spot which may cause accidental collision [4-5,10]. Other preventive methods are based on techniques implementing proximity detection and pro-active warning systems - a method that alerts workers in advance before entering a blind spot or getting too close the operating equipment-related hazards. In particular, technologies based on magnetic signals show promising results in being effective in providing alerts to equipment operator and ground workers when hazardous proximity situations occur between them [10-11].

Multiple other technologies have been studied and evaluated including vision cameras [12-13], radio detection and ranging (RADAR) [14], radio-frequency-identification (RFID) [11, 15-16], ultra wideband (UWB) [17-18], range imaging cameras [19-21], and global positioning system (GPS) [22-23] for potential deployment in the construction environment. Although some of these systems were capable of detecting and alerting workers in real-time of hazards, many are infrastructure-heavy as they require expensive setup of sensing infrastructure. Many of these technologies were also not able to proof to be reliable enough in the harsh construction environment. For example, wireless passive-RFID technologies based on a Gen2 offered a low-cost approach, but remain to have issues with line-of-sight of signals, tag orientation, and limited range. Other scenarios when alert technology failed were documented, for example, when a worker had been (partially) obstructed by as-built structures, the signal or camera was unable to detect the worker. Subsequently, record of useful proximity information for leading indicator [24] analysis failed, because data could not be collected (infrequently, with errors).

3 Research Objectives and Scope

The objective of this research was to test a method that collects data to proximity events on construction sites. Secondly, to create a computational algorithm that analyses the recorded GPS trajectory data of construction equipment and ground workers for, among other statistical data, the frequency and duration of hazardous proximity issues between operating equipment and workers. The goal was to create a rich set of new statistical safety data that can be used to enhance the education and training of all project stakeholders, especially of workers and equipment operators exposed to proximity issues. The results can further be used to evaluate and rate an individual's safety performance, seriousness of equipment blind spots that are currently undervalued, and general worker-to-equipment proximity awareness purposes.

This study presents preliminary, but promising results. For computational reasons, it assumes for now a single plane two-dimensional workspace in which workers and equipment navigate. The definitions of blind spot and proximity are presented next, before computational methods and results will be presented.

4 Methods for Data Collection, Analysis and Visualization

4.1 Technology for Measuring Equipment Blind Spots and Location Tracking of Human-Equipment Interactions

Blind spots of construction equipment are spaces around the equipment that cannot be directly observed by the driver. The blind spots can be eliminated or alleviated by appropriate adjustment of mirrors and use of other technical solutions. The Centers for Disease Control and Prevention provides corresponding blind area diagrams to typical construction equipment models [2]. This work relates to previous work, as new methods were used to capture the equipment blind spots. These can be found in [3-5]. This study further links equipment visibility data with identified hazardous proximity locations. The location of workers and equipment was recorded using a GPS-based localization method developed by Teizer et al. [19]. Data was fused and analyzed as described in [20. A software user-interface was developed to allow easy interaction of users (e.g., safety managers) with the collected and analyzed data. The interface is explained in the following paragraph..

4.2 User Interface

After selecting the vehicle type and size, the previously recorded and analyzed blind spot information to the equipment was loaded from a database that contains multiple blind spot diagrams for equipment. Figure 1 one displays the information that is available for a dozer CAT D5G. As shown in Figure 1, the equipment specifications, including name, width, length, type and range of blind spots on the ground level become available in the user interface.

The event of a worker being present in a blind spot is defined by a worker entering the grey shaded-areas around the construction equipment (see blind spot in Figure 1). The root cause of a hazard may stem from a ground worker's limited awareness of surrounding activities, including nearby or too close equipment. In addition, factors such as equipment operating or not, static or no, and others play a key role in identifying an even as a potential struck-by event that could harm the ground worker and cause other consequences (e.g., collateral damage to vehicle).

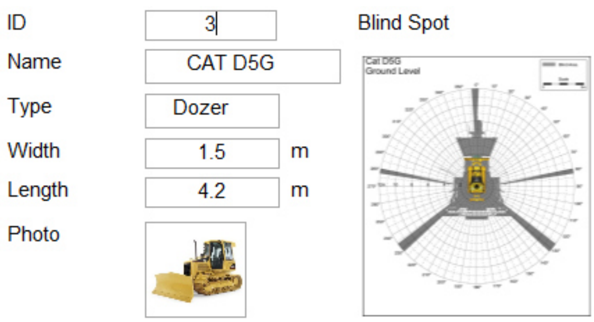


Figure 1. Equipment information database (note: the blind spot diagram was measured using a manual approach [2]

The developed computational algorithm uses a high level of detail of the equipment blind spots. For example, it takes the complex shape of blind spots into account when determining if a worker is in a blind spot or not. It also differentiates between the blinds spots that are available for the various pieces of equipment. These are analyzed separately for each piece of construction equipment using 3D laser scanning technology, as explained in [3-5].

The algorithm further distinguishes between the multiple blind spot areas that are available for each piece of equipment and in each of these blind spot diagrams. Often one machine has multiple blind spot regions. Some workers might be aware of many of them, but eventually not of all of them. For this reason, the blind spot areas were separated by zones. For example, while a worker might be aware of the blind spot zones 4 and 5 that relate to the rear blind spots of a skid steer loader, the worker might not be aware of potential blind spots in zone 2 and zone 3 (the side of the equipment). Accurate and detailed bling spot diagrams on their own, provide value to the workforce if shown frequently before operation equipment. Thus, this work easily falls into Prevention through Design (PtD) concepts and tools that try to eliminate hazardous work conditions before construction starts [26].

This study further defines hazardous proximity situations as any worker entering one or multiple dangerous zone(s) around the equipment where the distance between the worker and equipment is less than the pre-defined value(s). In this study we simplify, and apply two radii around the equipment. The sizes of the radii (or other shapes) largely depend on the type and function of each piece of construction equipment. A 12m (warning ground worker only) and 6m (alerting equipment operator and slowing/shutting down equipment) were selected. The shape of the warning/alert zones matters. For example, an excavator or skid steer loader that turn frequently might have circular protection areas, whereas a dump truck may have larger protection areas to the front and rear. Defining the proximity and later the alert zones is also important to reduce nuisance alerts to equipment operators.

4.3 Database Structure

The trajectories of the construction equipment and ground workers are collected using GPS data loggers. The technology is explained in detail in Pradhananga and Teizer [22]. The data is stored in a database and linked to worker and equipment information. Most construction sites carry a worker database already for hiring/firing purposes. An inventory to equipment may exit, and can be linked to the developed database that contains worker, equipment, blind spot, proximity and alert zone data.

Since the relationships between equipment and ground workers are interactive, each piece of equipment can have multiple workers within a hazardous proximity zone (see 6m (dark blue) and 12m (light blue) radii in Figure 2).

A database was created with an entity relationship model (shown in Figure 3) to account for the potential interactive spatial relationships. Queries were designed to obtain hazardous proximity occurrences for each zone of each piece of construction equipment and for each worker.

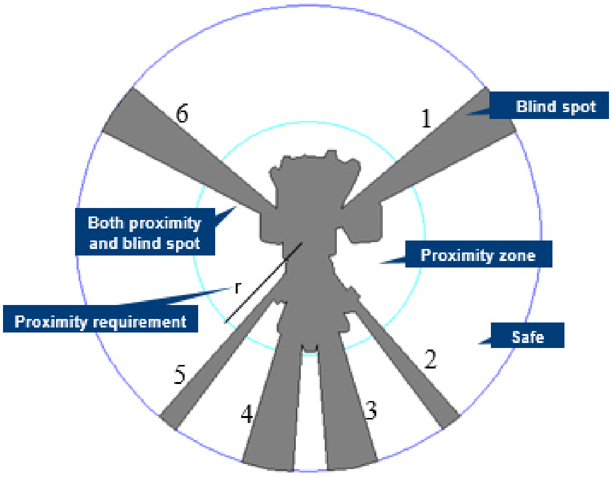


Figure 2. Automatically measured blind spot diagram [4-5] and the identified proximity and blind spot zones for a skid steer loader

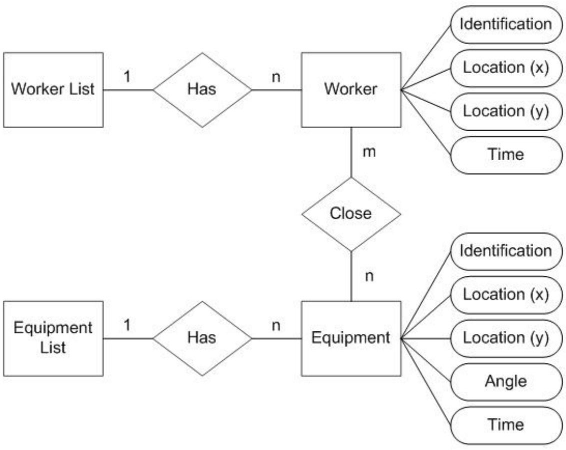


Figure 3. Entity relationship of database

Figure 4. Secure database containing worker information

The worker list contains the information of each worker, which includes the worker ID, name, age, gender, and photo. The worker list can have multiple workers. The worker ID is the reference key of the worker list table. Through the worker ID, the worker list relates to the table of an individual worker.

The table of each worker contains the latitude (x in meters), longitude (y in meters) from the collected GPS data, the corresponding time stamp, and the worker ID. One typical example of the information from the worker table is illustrated in Figure 4. The information displayed is limited, but can easily expanded to carry other useful information, e.g., safety training and equipment operation certificates, previous violations, other statistical work and safety records). However, as such ideas are outside the scope of this work, it was not implemented in this study and might find application in future research and/or development.

Similarly, the equipment list contains equipment specifications including the type, width, length, and blind spot locations. The equipment list table relates to the individual equipment table through the equipment ID. The table of each piece of construction equipment contains the latitude (x in meters), longitude (y in meters), GPS data, the corresponding time stamp, and the equipment ID. More importantly, the table contains the orientation (angle in degrees) of the equipment. This data is important to have, because the locations of the blind spot around a piece of equipment matter once worker location data is related to it. Especially if equipment is dynamic (e.g., moves or rotates) precise knowledge in which proximity and blind spot zone a worker is, is necessary of reliable and precise safety data analysis.

4.4 Data Mining for Safety Performance Analysis

The judgmental criteria of whether the worker is in a hazardous proximity situation or equipment blind spot is shown in the flowchart in Figure 5. The distance between the worker and heavy equipment can be simply calculated by Equation (1).

$$Dist = \sqrt{(x_w - x_e)^2 + (y_w - y_e)^2} \qquad (1)$$

To locate the ground worker more precisely, vectors are used to determine in which blind spot zine the ground worker is located in. Assume a first vector (v_1) corresponds to the travel direction and speed of the equipment, while the second vector (v_2) is related to the trajectory of the equipment to the ground worker. The angle α between the two vectors is defined in the clockwise direction from v_1 to v_2. Because the range of the angle is 2π, sine and cosine values are required to simultaneously determine the hazard zone number. From the concept of dot and cross product of vectors, the following equation is adopted, where the instantaneous coordinates of the equipment is (X_e,Y_e), the moving direction with respect to geographical north is θ, and the instantaneous coordinates of the ground worker is (X_w,Y_w). The sine and cosine value of α can be determined from Equations (2) and (3).

$$\sin\alpha = \frac{\tan\theta(Y_w - Y_e) - (X_w - X_e)}{\left|\sqrt{\tan^2\theta + 1}\right| Dist} \qquad (2)$$

$$\cos\alpha = \frac{\tan\theta(X_e - X_w) + (Y_e - Y_w)}{\left|\sqrt{\tan^2\theta + 1}\right| Dist} \qquad (3)$$

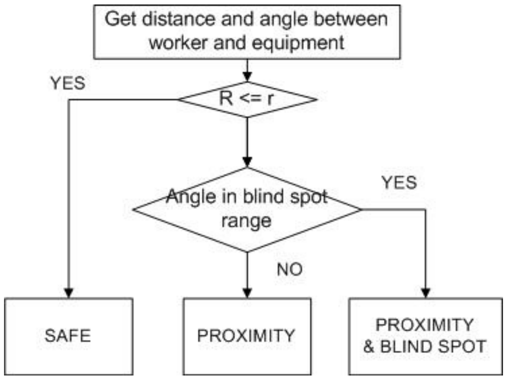


Figure 5. Criteria to determine hazardous proximity situation and presence in an equipment blind spot

Table 1 is used to determine the value of α and its relationship to each blind spot zone. The numbered zones and their locations are shown in Figure 2.

Table 1: Zones and the corresponding sin α and cos α

Zone	Sine	Cosine
1	0.247-0.327	0.945-0.969
2	0.661-0.702	0.712-0.750
3	0.794-0.826	0.608-0.563
4	0.856-0.884	0.468-0.517
5	0.940-0.957	0.289-0.342
6	0.984-0.995	-0.178-(-)0.096

Resulting from the distance and angle between workers and ground equipment, the following criteria are defined to quantify their safety performance. The duration when the distance between worker and equipment is less than or equal to the pre-defined hazardous radius will be counted as total time of the proximity hazard. From the angle defined above, workers can be tracked and identified when they are in a hazardous proximity situation or in an equipment blind spot. Equipment rotations are accounted for.

Under this situation, whenever the distance is less than the distance of the previous time stamp, the worker can be denoted as moving towards the equipment. In contrast, if the distance is increasing, the worker is moving away from the equipment. If the speed of the equipment is zero and the distance is constant within the alert zone, it can be inferred that the worker stopped. If the speed of the equipment is not zero, and the distance stays constant, it indicates the worker is moving at the same speed as the equipment travels.

5 Results to Field Trial and Discussion

5.1 Data Collection on Active Construction Site

A controlled experiment was conducted to test and verify the designed data sensors, database and data mining method. Data was collected on an active construction site of a university building on the Georgia Institute of Technology's campus (see Figure 6).

Figure 6. Overview of the site and work task

Figure 7. GPS tags and receiver (yellow circles).

Two ground workers and two skid steer loaders on the site were used for data collection and analysis. GPS data loggers were tagged to the equipment and worker helmet. Location data to workers and equipment was recorded for 1.5 hours on one work day. Some scenarios were performed in controlled and under safe conditions to ensure that the experiment could be validated. As shown in Figure 7, two GPS data logger tags were attached to the skid steer loader. They obtained the position of the equipment at a 1Hz update rate as well as the orientation of the equipment.

A controlled experiment was conducted to test and verify the designed database and data mining methods. The results of the analysis were manually validated through a camera. The results focus on: (1) Individual performance reports which focus on creating a safety score/performance card for each individual worker, and (2) reports to the interaction of workers on the ground and equipment.

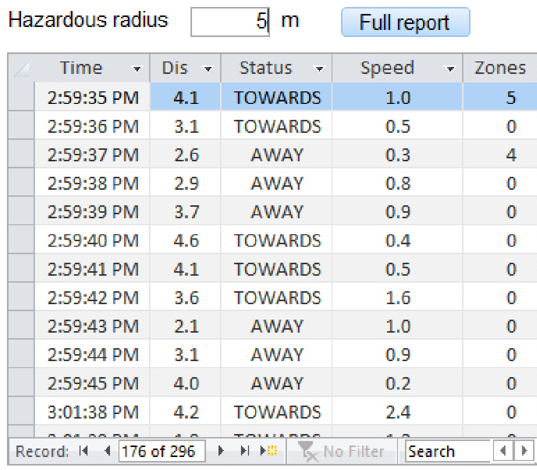
5.2 Safety Performance Reports

The developed database can automatically report and visualize the worker and equipment location for each time stamp on a map. A user needs to enter three values to draw results from the database: First, the proximity distance that should be evaluated, secondly, the worker ID (see Figure 4), and thirdly, the blind spot information by selecting the equipment ID. Latter may infer to pre-defined proximity zones (size of radii) that are based on the type and function of the construction equipment. For example, a dump truck moving will require less protection to its sides than front and rear. A dozer, as shown in Figure 1, may operate at maximum speeds of 4.5 m/s. Protection to front and rear is important, but also to its sides as it can rotate suddenly. The skid steer loader in this experiment was assumed to have a 4.5 m/s maximum speed, a -2m/s deceleration rate, and a brake distance of 5 meters.

The skid steer loader blind spots depend on the type and its condition on site (see Figure 2). After selecting the values in the user interface, a worker-specific safety performance report to the skid steer loader is automatically calculated (as shown in Figure 8).

Hazardous proximity zones and detailed information are listed in the report. For example, at 2:59:35 PM., the worker approached the construction equipment with a speed of 1.0 m/s in blind spot zone 5. The worker may not have detected the potential danger and continued to move in and out of the proximity zones existing around the equipment. This entire event lasted 29 seconds (note: only a portion of the data is shown in Figure 8).

By reviewing the full data analysis, more details to potential struck-by/proximity hazards can be viewed. The interface in Figure 8 shows the duration, start and end times, and closet distance of each hazardous proximity event. The longer the worker stays inside the proximity zone, the higher might be the probability of a worker-equipment collision. The generated report can be seen in Table 2. It provides additional results to the experiment, for example, the closest distance between the worker and equipment was 0.4m and the fastest traveling speed of the worker was 3m/s.



Time	Dis	Status	Speed	Zones
2:59:35 PM	4.1	TOWARDS	1.0	5
2:59:36 PM	3.1	TOWARDS	0.5	0
2:59:37 PM	2.6	AWAY	0.3	4
2:59:38 PM	2.9	AWAY	0.8	0
2:59:39 PM	3.7	AWAY	0.9	0
2:59:40 PM	4.6	TOWARDS	0.4	0
2:59:41 PM	4.1	TOWARDS	0.5	0
2:59:42 PM	3.6	TOWARDS	1.6	0
2:59:43 PM	2.1	AWAY	1.0	0
2:59:44 PM	3.1	AWAY	0.9	0
2:59:45 PM	4.0	AWAY	0.2	0
3:01:38 PM	4.2	TOWARDS	2.4	0

Figure 8. Proximity hazard report (note: Zone 0 indicates that the worker did not appear in any of the blind spot zones. The distance is in meters and speed is in m/s).

Table 2: Event logging of a worker being closer than 5m to the equipment

Event [No.]	Start Time	End Time [hh:mm:ss]	Duration [mm:ss]	Min. Dist. [m]
1	14:28:39	14:28:41	00:03	4.3
2	14:31:32	14:31:59	00:27	0.6
…				
20	15:03:54	15:04:24	00:30	0.6
21	15:06:13	15:07:06	00:53	0.6
Max	-	-	00:53	5.0
Min	-	-	00:01	0.4

The safety performance of each individual worker was rated through the worker and equipment trajectories. For example, worker 1 appeared in the blind spot zone 2 and zone 5 for 3 seconds each. Zones 2 and 5 in Figure 2 are symmetric blind spots, indicating that worker 1 was probably unaware of the potential danger in those regions in the rear of the equipment. In contrast, worker 2 never appeared in any blind spot zones, concluding potential eye-contact with the operator or blind spot awareness. The report for each piece of construction equipment can be generated as shown in Table 3.

Table 3: Data report to skid steer loader No. 1

Type	Skid Steer Loader	
Operator	Worker 3	
Machine ID	01	
Time [hh:mm:ss]	Proximity Event [No.]	Worker/Status/Speed/ Blind Spot Zone [ID / Direction / m/s / No.]
13:56:05	1	1/Away/0.5/0
13:56:06	1	1 /Toward /0.7/0
13:56:07	1	1/Away/1.1/0
13:56:08	1	1/Away/1.8/0
13:56:09	0	0
…	…	…

5.3 Data Mining and Visualization to Enhance Site Layout and Safety Education and Training

Multiple workers can appear in a hazardous proximity zone of one piece of construction equipment and one worker can be located in several hazardous proximity zones of several pieces of construction equipment. Although many workers are aware of the hazards surrounding equipment they are familiar with, they might ignore potential dangers around others. Therefore, proposed is data mining and visualization of trajectory and proximity events to sensitize workers. This can become helpful in delivering effective and goal-oriented safety education and training for workers.

Figure 9. Mapping dangerous proximity events on aerial site photogrammetry [27].

The information can also be used to evaluate existing site layout plan. Figure 9, for example, displays the location of potentially hazardous proximity events (red dots). In such a situation, the safety manager or superintendent on duty, once provided with the information automatically on a mobile device, might mitigate the potential danger by taking pro-active means and resolve the issue, for example, by pulling the worker from the confined work area where a skid steer loader unloads material.

5.4 Discussion

The individual safety performance for each resource (worker or equipment) provides valuable information to all project stakeholders: safety manager, superintendents, foreman, workers, equipment operators, site layout designers and managers, supply chain managers. There are many examples that can be made about the usefulness of the data itself. For example, equipment operators are now able to received detailed quantitative leading indicator data and maps which areas surrounding their equipment is potentially dangerous. Workers unaware of their behavior around equipment can now also be alerted by visualizing the entry and duration in zones that might be hazardous. Many more examples exist how this information can become very beneficial in future education and training scenarios that uses a personalized approach rather than presenting and repeating lagging indicator data only. The developed method therefore is pro-active in multiple ways: (1) in conjunction with real-time and pro-active warning and alert technology it prevents accidents, (2) it collects data that can be analyzed for and used in worker training and improved site layout design, and (3) empowering workers with personalized data rather than punishing or firing them.

The algorithm and resulting statistics can potentially be utilized in two ways: (1) Generate real time warning on site to the operatives, and (2) analyze the behavior of each individual and from which to conduct goal-directed education.

If the evaluation of the individual worker can be performed in real time, timely warnings can be generated to alert an operator of the location, speed and direction of the ground worker. Further information might be useful, such as, is the worker located in a blind spot? Combining the approach with operator head pose tracking [28] and real-time pro-active alert technology [10,29-32] are probably extensions and guide next steps in research.

6 Conclusion

Contact collisions between ground workers and heavy construction equipment cause a significant amount of fatalities in the construction industry. The purpose of this research was to utilize location tracking sensors for data gathering of the locations of workers and equipment and to create and test a computational algorithm that extracts hazardous proximity information of events that relate to interactions between ground workers and heavy construction equipment. The developed methods are explained and preliminary results to a field trial are shown and discussed. Mitigation measures such as enhanced safety education and training can be taken to improve the safety performance of workers and equipment on a job site. Although the presented work shows preliminary results, its potential to impact existing site layout and safety measurement best practices is high. Further testing and linking to other previous research efforts is necessary.

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