AUTOMATED EVALUATION OF PROXIMITY HAZARDS CAUSED BY WORKERS INTERACTING WITH EQUIPMENT

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ABSTRACT

Previous research and applications in construction resource optimization have focused on tracking the location of material and equipment. There is a lack of studies on automated monitoring of the interaction between workers and equipment for safety purposes. This paper presents a new approach for measuring the safety performance of construction personnel particularly when they work in very close proximity to moving equipment as well as static hazards such as chemical and flammable substances. A method of generating hazardous zones according to the geometric and kinematic characteristics of the considered hazard is introduced. The spatio-temporal relationships between the hazardous zones and workers' positioning data collected by real-time location sensing technology are automatically analyzed. This approach has been validated in a controlled test bed environment that simulates a construction site. Results indicate that worker's safety performance of selected activities can be automatically and reliably measured using the developed approach. Furthermore, a heat map is generated for visualizing proximity related issues in the test bed using the computed results.

KEYWORDS

Safety, Proximity hazards, Equipment, Real-time location tracking, UWB, Spatial-temporal analysis

INTRODUCTION

Bureau of Labor Statistics (BLS, 2010) reported that 3,171 workers suffered fatal injuries from 2003 to 2010 due to contact with objects and equipment, falling from height, exposing to chemicals and flammable substance, and struck by vehicle. These fatalities counted for approximately 40% of the total construction fatalities. Division of Occupational Safety and Health (2011) found constantly changing job site environments and conditions; unskilled laborers; high diversity of work activities occurring simultaneously; and exposure to hazards resulting from own work as well as from nearby activities as factors causing workers to be exposed to hazardous situations. Hazards can be grouped into chemical, physical, biological and ergonomic according to these factors. Alternatively, based on the spatio-temporal characteristics, this research classifies hazardous situations into static and dynamic hazards.

Many hazardous situations occur when dynamic resources such as heavy construction equipment, vehicles and materials operate in close proximity to ground workers. Contact collision between ground workers and these dynamic resources can increase the risk of injuries and fatalities for construction personnel (Marks and Teizer, 2012). The other type of hazard that causes injuries on a construction site is static hazard. Compared to the moving resources, static hazard has relatively constant location and geometry, such as toxic, chemical and flammable substance, high-voltage power line, edge of elevation, and blind space to crane operator.

Control measures including OSHA safety regulations, administrative policies, best practice, and new proactive sensing technologies that have been established and developed to reduce the proximity hazards whenever. However, a deep understanding, evaluation, and measuring of workers' safety performances under proximity hazards is still lacking, which is based on scientific analysis of the spatial and temporal relationship between workers and hazards.

BACKGROUND

Safety performance indicator measures implemented in the construction industry fall into two major categories, lagging and leading Indicators. The lagging indicators for measuring safety performance are based on the fatality and injury statistics. Examples include lost workday/restricted work activity injuries, and Occupational Safety and Health Administration (OSHA) recordable injuries. This type of measure requires an accident to get a data point and cannot be used to prevent occurrence of injuries or their potential severity.(Hinze and Godfrey, 20030.

Leading indicators are able to predict the future safety performance based on selected criteria. They focus on minute analysis of behaviors at the individual level and improvements can be made before injuries actually occur if they show unacceptable result **Error! Reference source not found.**. Several techniques have been studied to measure leading safety indicators, such as Behavior Based Safety (BBS) (Choudhry and Fang, 2008), safety audits (Agnew and Daniels, 2011), and near misses reporting (Gadd and Collins, 2002).

The implementation of leading indicators relies on the data to be collected from on-site inspections. Since data collection is only performed manually in current construction industry (Toole, 2002), the nature of resulting safety measurement is subjective and varies considerably from inspector to inspector (Hinze and Godfrey, 2003). Therefore, a method is required that can measure the construction safety performances in an objective, consistent and reliable manner. Accurate and emerging remote sensing technology provides critical spatio-temporal data that has the potential to automate and advance the safety measurement of construction processes.

Various emerging remote sensing and ranging technologies can be utilized to assess the conditions of a construction site at the operational level for safety purpose. It has been suggested that the Radio Frequency Identification (RFID) based pro-active safety technologies are capable of providing alerts to construction workers and equipment operators in real-time when a hazardous proximity issue is present (Marks and Teizer, 2012). LADAR technology, as an optical remote sensing technology, has been widely utilized for range measurement (Johnson and Hebert, 1999). Algorithms have been developed to automatically measure the blind spots of equipment operators generated by construction site layout (Cheng and Teizer, 2012). Further research developed a user interface to analyze and visualize safety and productivity related information of equipment operations using GPS devices (Pradhananga and Teizer, 2013).

OBJECTIVES AND SCOPE

The goal of this research is to design, test, and validate a new method that can improve construction safety measurement. Several sub-objectives have been defined to achieve this goal. The first objective is to automatically define hazardous areas surrounding the existing static and dynamic hazards on the specific construction site settings. The second objective is to automatically analyze the spatio-temporal conflicts between workers and considered hazards. The last objective is to define an indicator that can be utilized to measure the safety performance of workers.

Several typical proximity hazards are considered, which include but are not limited to:

- Contacting with objects and equipment (machinery and materials)
- Struck by a vehicle
- Working close to chemical, flammable, and toxic substances
- Unauthorized intrusion to access-controlled space

This paper focuses on human-equipment interactions occurring in selected construction activities that the construction personnel are repeatedly exposed to. Automated analysis and a consistent and reliable indicator of their safety performance in terms of their exposure to above mentioned hazardous condition is suggested.

METHODOLOGY

This section presents the method of analyzing the spatio-temporal relationship between personnel and hazards existing on the construction site. The considered hazards are classified into dynamic (mobile ground vehicles and equipment) and static (flammable, chemical, and toxic substance placed at fixed position). Figure 1 show the flowchart for measuring proximity issues between worker and various hazardous conditions based on real-time location sensing data. The technologies and techniques implemented for tracking the spatio-temporal data of construction resources and gathering the geometries of major objects on construction site have been introduced in authors previous researches (Cheng et al., 2011; Cheng and Teizer, 2012). The rest of this section details the development of an approach that utilizes the known tracking data and geometric information to measure the proximity hazards. The developed approach includes three major parts: classifying and generating hazard zones surrounding specific source; analyzing the spatio-temporal relationship between workers and generated hazard zones; computing an indicator that can be used to evaluate the proximity hazard.

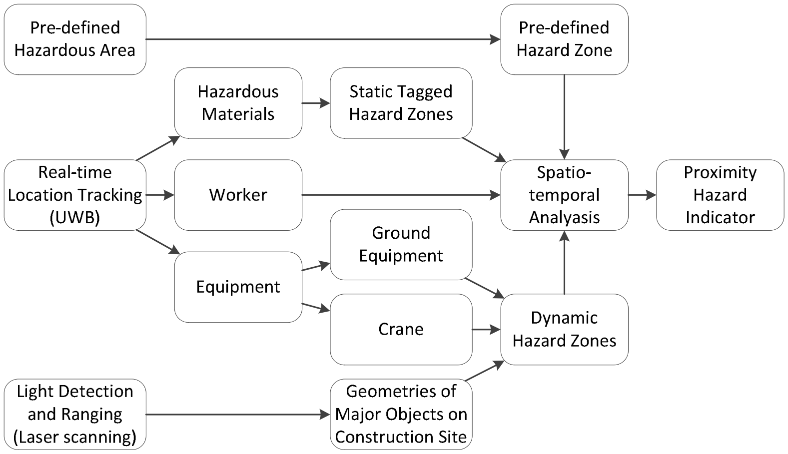

Figure 1 - Flowchart of measuring proximity hazards

Definitions of Hazard zones

In general, a hazard zone is represented as a polygon that is generated based on the location and geometry information of the potential hazards. The characteristics of hazardous sources are classified as static and dynamic. In static case, a hazard is either pre-defined according to the construction environment whose geometry is known (e.g., access-controlled space that only authorized personnel is allowed to enter), or monitored through remote location tracking and sensing technology (e.g., UWB). In dynamic case, the location of a hazard is gathered utilizing real-time location tracking and sensing technology. The following sub-sections introduce the methods of generating hazard zones in difference situations. Algorithms were developed to define these zones and to analyze the movement of workers in such zones.

Pre-defined Hazard Zone

As one type of the static hazard zones, pre-defined hazard zones are formed based on the existing construction site settings and structural components. Examples include but are not limited to the following cases; edge of roof and/or big openings on elevation, high voltage power lines, unstable excavations and trenches and confined and other limited-access space.

Since these components are always maintained on a construction site and do not change frequently, the hazard zones associated to them have fixed locations and geometries. The locations and geometries of site components are achieved by conducting survey using ranging sensing technologies such as Robotic Total Stations and Laser scanning. Such zones can be represented by boundary of its representing polygon and movement of workers into/outside the polygon can be analyzed.

Static Tagged Hazard Zones

Another type of static hazard zones are generated due to the temporary placement of construction materials or substances that have potential and rapid negative impact to human safety, health and productivity. Examples include but are not limited to the following cases; flammable liquids, such as petrol, alcohol and welding gas, chemical and toxic substances, such as acid and alkali solvents and high-voltage power generating unit. Pre-defined hazard zones often times cannot represent the geometry of these zones as they change frequently. These zones are created by tagging the boundary using UWB sensors and defining a hazard zone using a buffer radius around the boundary.

Dynamic Hazard Zone

Besides static hazards, workers on construction site are often continuously exposed to another type of hazardous conditions that keep changing in location, shape, scale and orientation over the time. In this paper, this type of hazards is regarded as dynamic hazards. Examples include but are not limited to the following cases:

- A worker is walking across a traffic road without using the crosswalk while a piece of construction equipment or vehicle is moving toward him
- A worker is performing work tasks behind a piece of equipment or vehicle while it is reversing
- A loaded crane hook swings over a crew of ground workers
- A worker is performing work tasks inside the blind space of ta crane operator while the operator is maneuvering the load

The generation of a dynamic hazard zone requires four parameters, which include: scale, function type, location, and velocity of the considered equipment. The equipment's scale influences the size of the hazard zone. The function type defines whether it is a piece of ground equipment or lifting equipment which consists of carrier and a revolving component. The location of a dynamic hazard determines the position where the corresponding hazard zone is centered. The moving velocity determines the orientation and shape of the generated hazard zone. Taking a piece of ground equipment as an instance, Figure 2 illustrates how a dynamic hazard zone is generated.

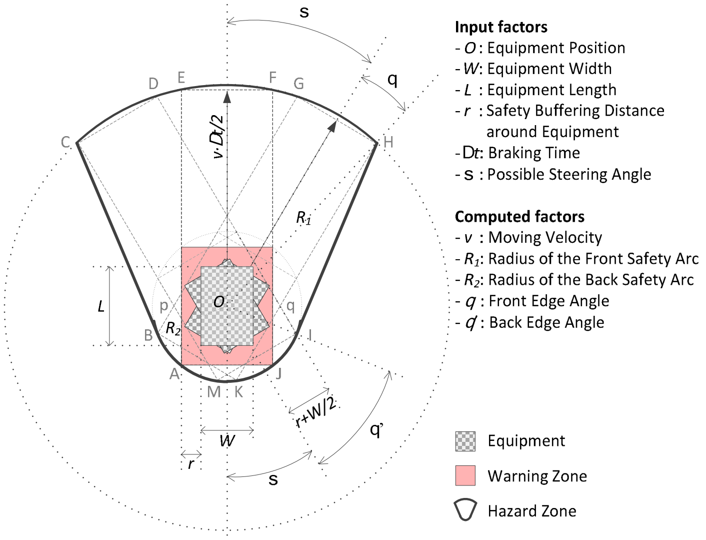

Figure 2 - Generation of a dynamic hazard zone surrounding a piece of moving vehicle

Hazard Zones with Blind Spaces

Besides static dynamic and static hazards, a construction site generally consists of numerous multi-sized objects which represent obstacles in the field-of-view (FOV) of an equipment operator and create significant large blind spaces. Detailed investigation on blind spaces can be found in Cheng and Teizer (2012) and Ray and Teizer (2011). Ground worker working inside the blind spaces when a part of or the entire piece of equipment is operating close to the same area is considered as a dangerous situation. In this case, a new hazard zone combining equipment movement and blind spaces has to be generated. The new hazard zone is generated through Boolean Operations of the blind spaces and dynamic hazard zones.

Proximity Hazard Indicator

The spatio-temporal analysis has been used to sample the worker's activities and performances into safe and unsafe when the worker(s) is close to considered hazards. Therefore, the worker(s)' safety performance is measured by introducing the Proximity Hazard Indicator (PHI), which is achieved by using the following equation:

$$Proximity\ Hazard\ Indicator\ (PHI) = \frac{\sum_i \kappa_i \times Counts\ in\ Hazardous\ Zone\ i}{Total\ Observing\ Time\ [min]} \qquad (1)$$

where i is the index of a hazard zone defined in the previous section and κ_i is the safety factor of each hazard zone. The PHI represents how often the observed target is exposed to various defined hazards within the observing period. The observed target could be a single individual, or a crew of workers.

Compared to traditional work sampling technique and safety inspection which relies on random observation, PHI is achieved based on continues monitoring of the working progress. User can choose appropriate length of observation periods. Within each period, a unique PHI for a specific target can be computed. As the work and monitoring progresses, a series of PHI can be achieved. The distribution of the PHI over the time can be utilized in statistical analyses to find out the target has significantly high rate of unsafe performances. An example on computing and using PHI is given in the following section.

EXPERIMENT AND RESULTS

This section demonstrates an experiment conducted in a controlled environment to validate the accuracy and efficiency of the developed algorithm on detecting proximity cases when the subject is continuously exposed to various hazards. The participants including personnel and vehicles performed various safe and unsafe tasks by following pre-scripted scenarios. By comparing the results of the algorithm to manual observation, the accuracy was measured by the percentage of successfully detected proximity hazards, and the efficiency was measured by the time that was required to achieve the results. The experiment was conducted on the top floor of a parking deck, which occupied a $50m \times 110m$ rectangular area (Figure 3). The UWB system with multiple tags was deployed to collect the spatio-temporal data from the participants. The Robotic Total Station (RTS) system was utilized to set up the UWB infrastructure as well as to collect ground truth tracking data and measure the tracking errors. In this experiment, the tracking error of UWB system had mean as 0.27m and standard deviation as 0.31m 0. In addition, three video cameras were set up to monitor the entire site when the experiment progressed.

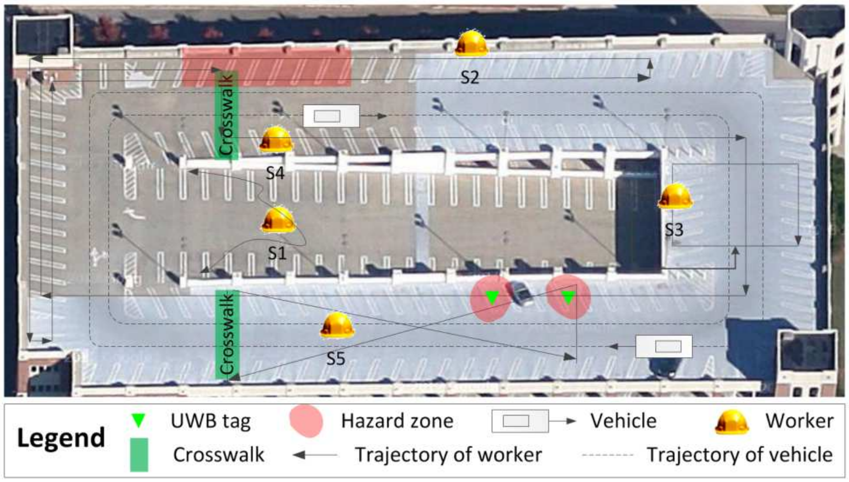

Figure 3 - Layout of the controlled experiment with scripted scenarios

Figure 3 shows a plan view of the site. Two static hazard zones (red polygons) were designed for this experiment, one of which was measured by RTS and the other was defined by a static UWB tag (green triangle). Two crosswalks were planned on both sides. The experiment involved two vehicles (dash lines) and five people (solid lines). The two vehicles drove following the lanes in clockwise and counterclockwise direction, respectively. The five participants were instructed to perform the following scripts during the experiment. The experiment was performed in five sessions each lasting 20 minutes. The participants switched the scenarios in each session.

- Scenario #1 (S1) always walked off the traffic, which is considered safe
- Scenario #2 (S2) moved parallel to the traffic lane by keeping a safe distance to the moving vehicles. W2 had to walked across a static hazard zone
- Scenario #3 (S3) regularly crossed the traffic lanes
- Scenario #4 (S4) walked inside the parking area, and cross the traffic lanes using the cross walk. W3 also temporally walked on the traffic lane
- Scenario #5 (S5) crossed the traffic lanes with and without using the crosswalk, and randomly approached to the moving vehicle from arbitrary directions. W4 also entered the UWB tag defined hazard zone

The participants' trajectories, the locations of the proximity cases detected by the algorithm are plotted in Figure 4. The background color of the grid represents a heat map and indicates the number of proximity cases occurred in each grid cell. The color bar to the right of the figure shows the scale of color to number of proximity cases.

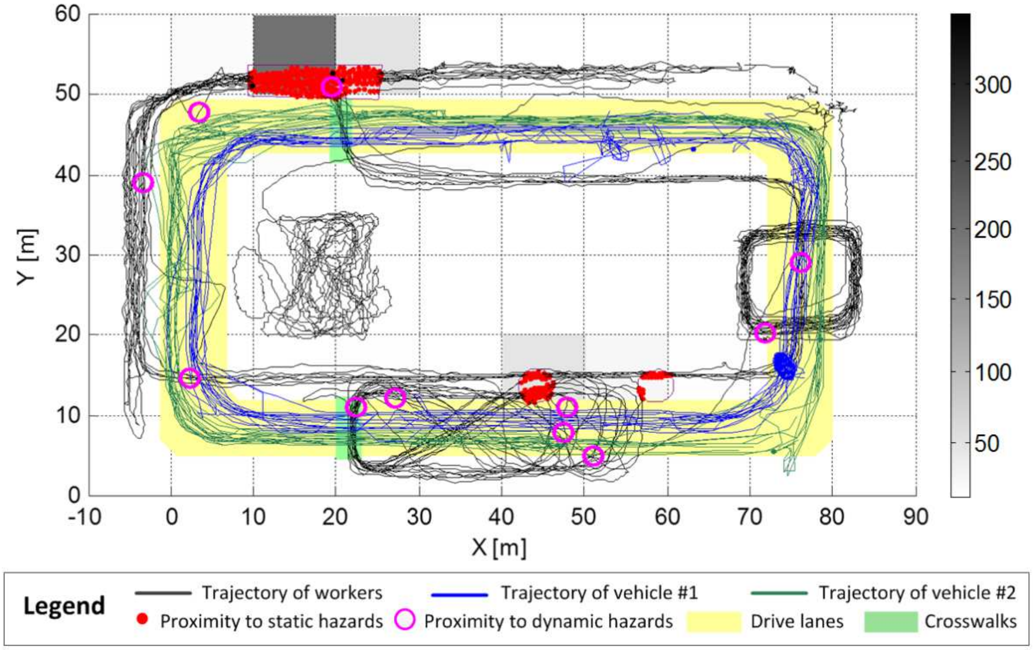

Figure 4 – Trajectories, detected proximity cases, and a "heat map" in the controlled experiment

Figure 5 showed that the algorithm always detected greater number of proximity cases than the analysis of video clips. Considering the manual video clips as ground truth of detecting unsafe proximity cases, comparisons between the results achieved by these two approaches were detailed in Figure 5**Error! Reference source not found.**. The comparison was performed on the cases of static and dynamic hazards separately.

Total		Algorithm detection	
		Safe	Unsafe
Manual video analysis	Safe	N/a	25 (Improve: 21 Wrong: 4)
	Unsafe	4	235

Precision = 98.3% Recall = 90.3%

Static case		Algorithm detection	
		Safe	Unsafe
Manual video analysis	Safe	N/a	14 (Improve: 14 Wrong: 0)
	Unsafe	0	174

Precision = 100% Recall = 92.5%

Dynamic case		Algorithm detection	
		Safe	Unsafe
Manual video analysis	Safe	N/a	11 (Improve: 7 Wrong: 4)
	Unsafe	4	61

Precision = 93.8% Recall = 84.7%

Figure 5 - Results validation by comparing to the video analysis

The Proximity Hazard Index (PHI) of each participant was calculated for every 2 minutes interval using Equation (1), and the results were plotted in Figure 6. It can be noticed that any participant who performed scenario 4 and 5 had significantly high PHI value, which indicated that these two scenarios requires the workers to be regularly exposed to various hazards.

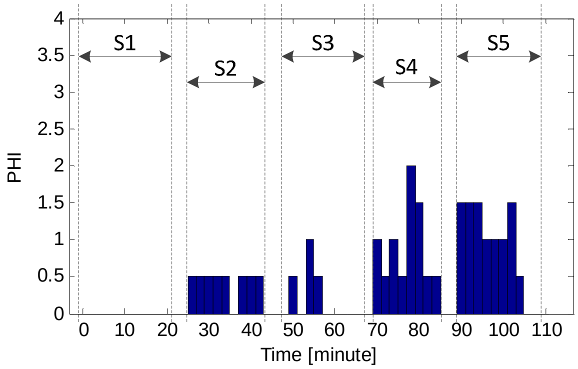

Figure 6 - Distribution of the Proximity Hazard Index of all the participants

CONCLUSIONS

This paper detailed a method for measuring workers' safety performance based on spatio-temporal data, site geometry and kinematic characteristics of construction resources. A new model has been developed for detecting proximity hazards and was validated by comparing to video recording. The results demonstrate that the model can accurately, consistently and reliably detect and measure the workers' safety performance under proximity hazards. PHI indicator introduced in the developed measure can be used for rating the safety performance of each individual or crew and can assist the safety manager to identify frequently occurring proximity hazards before any incident occur. The index can also be used as a measure for assessing the requirement of preventive measures like change in site layout, schedule or additional instruction or training to the workers. The use of real-time tracking data automated the entire process and also overcome the drawbacks of manual safety inspection by providing consistent and reliable results which is not subjected to human judgement.

The parameters used in this analysis can affect the results to a great extent. Detailed studies need to be done on safety distance requirements from equipment, material and fall hazards and blind spaces. Furthermore, equipment braking time, steering angle and probability of equipment motion in certain zone also need to be carefully chosen. The parameters have been arbitrarily chosen in this paper for demonstration of the method. Inappropriate parameter setting can result to unreliable and unrealistic output. A thorough study of construction resources traffic inside the site should be done before implementing this method. The method does not include equipment movement in non-linear trajectory like performing pure rotary motion. Such specific cases have their own set of proximity requirements and algorithms need to be developed to address these cases. Last but not the least, the spatio-temporal analysis method developed in this paper has the potential to be extended to other domains like workers' health monitoring and labor productivity analysis if the parameters required for these analysis are determined carefully.

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