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Proximity hazard indicator for workers-on-foot near miss interactions with construction equipment and geo-referenced hazard areas

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A R T I C L E   I N F O

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A B S T R A C T

Despite the many existing best practices in safety, the construction industry lacks automated safety monitoring and analysis of task-level construction operations. Data to workforce, equipment, and the overall site safety performance are currently observed, measured, and evaluated almost always manually. Such resulting performance information is likely assessed infrequently and due to subjective human interpretation or error. Research in lagging and leading safety indicators shows further that safety knowledge is hardly ever shared among relevant project stakeholders in time to prevent accidents. Since a large number of all construction fatalities are related to struck-by events – for example, workers-on-foot being too close to construction equipment and to other restricted or geo-referenced hazard areas – a novel framework around real-time location tracking technology was designed and tested to collect and study near miss data. The objectives of this article are to automatically identify the areas of static and dynamic hazards on a construction site and to automatically gather and analyze the spatial–temporal conflicts between workers-on-foot and the identified hazards. Automated conversion of raw sensor location data collected to the operation of workers, equipment, and geo-referenced hazard areas into meaningful proximity-related safety information is introduced. Field experiments validate the research based on an a priori created safe site layout information model. Results are in particular useful for practitioners or researchers who would like to enhance their quantitative and visual understanding of operational construction resource activity monitoring and analysis, and in the specific domain of detecting and mapping spatial–temporal proximity relationships of near miss events. Applications of the resulting knowledge are explained in the context of empowering construction safety engineers, managers, and the workforce by enhancing decision making in safe site layout design and planning and providing additional interactive tools in safety education and training.

1. Introduction

Construction sites have unique sizes and settings, but generally are composed of similar types of resources, for example, workers, equipment, and materials. In order to meet construction schedules, highly complex and dynamic construction activities require workers to frequently be in close proximity to potentially hazardous site conditions. Although design for safety (DfS) concepts [1] propose to eliminate safety hazards early in a project's lifecycle, construction planning inherently includes unsafe work conditions that either were overlooked by designers or planners [2] or occur due to late or frequent design change and the dynamic nature of the construction site. Examples of such hazards are poor site layout plans, insufficient site traffic control, frequent heavy equipment operations nearby workers-on-foot, restricted entrance into hazardous or confined areas, or access to uncontrolled hazardous substances [3].

Statistics show that working in proximity to hazards significantly contributed toward the number of construction fatalities. In between the years 2003 and 2010, 3171 workers were killed due to the exposure to various hazardous situations, including (1) contact with objects and equipment, (2) falls from floors to lower levels, (3) exposure to chemicals and flammable substances, and (4) struck by vehicles [4,5]. This large number of fatalities accounted for approximately 40% of all construction fatalities in those years. About one quarter of these relate to struck-by events [4,5].

Research also found the risk factors which cause worker exposure to hazardous situations. Examples are constantly changing construction site environment and conditions, unskilled laborers, high diversity of work activities occurring simultaneously, and exposure to hazards resulting from own work as well as from activities in the same or nearby locations [6]. According to these risk factors, hazards can be categorized as chemical, physical, biological, and ergonomic. Alternatively, this research classifies a hazardous situation into either static or dynamic based on the spatial–temporal characteristics of the hazard.

Frequent hazardous situations occur when dynamic resources, such as heavy construction equipment, operate in close proximity to

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workers-on-foot. Such conditions exist frequently in a congested work environment, for example, during conventional excavation in tunnels and for a high number of workforce at large capital facility projects. The U.S. Bureau of Labor Statistics reported in 2009 that among the 818 construction-related fatalities in the US, 18% (151 fatalities) were caused by workers being struck by an object or a piece of construction equipment [7]. Past research has also shown that being struck by equipment increases significantly the severity of injuries and/or the potential for a fatality of the construction personnel [8–11]. Other types mentioned – which are predominantly static in nature – are hazards such as toxic, chemical, and flammable substances, high-voltage power lines, edges in elevation, and blind spaces, for example, of ground vehicle or crane operators [12,13]. Toxic and chemical substances include dusts, mixtures, and common materials such as paints, fuels, and solvents [14,15]. High-voltage power lines pose hazards to the safe operation of cranes and derricks [12]. Falls from floor openings and leading edges have been a major reason of construction fatalities for the past years [15]. [11,12] and [16–24] stated that equipment operator visibility and specifically operator blind spaces contribute to contact collisions between equipment and workers-on-foot.

Hazard controls following the Occupational Safety and Health Administration's (OSHA) safety rules and regulations and company–individual administrative policies and best practices are vital in preventing proximity-related equipment and worker incidents. Although they have been successfully established and practiced on construction projects for many years, specific understanding, evaluation, and assessment of the interaction between equipment and workers-on-foot have been missing. Furthermore, changing a company's safety culture – which is the likely approach of many safety professionals to achieve a better operational safety performance – highly depends on reliable access to accurate data. Should the problem of struck-by incidents between workers-on-foot and construction equipment in the construction industry be solved, first a scientific method is needed that can study and analyze the spatial–temporal relationship.

Since humans perform existing safety data collection and analysis manually [25], the nature of resulting safety measurement is subjective and varies considerably from inspector to inspector [26]. Concepts focusing on virtual fencing of hazardous areas [27,28] and representing workspaces of equipment [29] have been discussed in several past research articles. The problems of automating the data gathering and processing of proximity events between workers-on-foot and equipment and proving that such methods promise feasible approaches to reduce incidents in the harsh construction environment have yet to be studied in greater detail.

A need still exists for methods at the construction stage that measure the construction safety performances in an objective, consistent, and reliable manner. Accurate and emerging remote sensing technology and data mining algorithms can provide information from such data that are critical in the specific spatial–temporal analysis between construction workers-on-foot and equipment. Such automated methods have high potential to lead to much needed change in construction safety engineering and management practices since more detail to site resource maneuvers and behavior becomes available. Once the data are processed, the resulting information can be used for designing or planning out the hazard in the first place, or for controlling safety more effectively and efficiently during the construction processes in (near) real time.

2. Background on safety data collection and processing methods

There are a variety of safety performance measures that are in use in the construction industry. The most common ones can be categorized into lagging and leading indicators.

Lagging indicators are based on fatality and injury statistics. Examples include lost workday/restricted work activity injuries, and injuries recorded by OSHA. Since the reporting of lagging indicators has been standardized, they are good for benchmarking the own records against others (national or competitor's safety performance). However, such reporting or benchmarking is often voluntary. Many industries apply lagging indicator data reporting as they show trends of past safety performance [30]. Studies have been conducted to demonstrate the effectiveness, efficiency, and reliability of various lagging indicators [31–33]. However, the main disadvantage of lagging indicators, especially in reflecting the safety performance in complex and dynamic construction projects, is it requires an occurrence of a reportable incident in order to count a data point [26]. Lagging indicator data thus can neither be used to prevent the occurrence of an incident, nor can it reflect the potential severity of an event, merely the consequence [34].

On the other hand, leading indicators represent a continuous monitoring of safety in ongoing work processes. Leading indicator data primarily and often focuses at the level and the analysis of small units (e.g., behavior of individuals). Hence, modifications or improvements to existing processes and behavior can be made before an incident actually occurs on a construction site [35]. Leading indicators might as well predict the future safety performance based on selected criteria [35]. Behavior-based safety (BBS), as an example of a leading safety indicator, is the application of behavioral research on human performance to the problems of safety in the workplace [36]. This technique relies on manual site observations and individual feedback after the observation period ends. The data gathered from the observation(s) is matched to a pre-defined checklist. Eventually unsafe trends can be flagged and used for pro-active resolution. Changes to safety engineering and management can be taken as needed to prevent such identified hazards in the first place. Multiple researchers have come up with a reporting scheme that is generated for gathering, analysis, control, and use of leading indicator data [37–42].

Other techniques exist to capture leading indicator data. Safety audits, for example, attempt to assess the safety management and safety culture by measuring whether selected safety performance indicators are present or not [43]. This technique is useful to gauge the extent to which an organization's policies and rules are being followed and how they might be improved. However, the effectiveness of a safety audit can be influenced by the organization's safety culture itself [44]. Investigation of near miss occurrences is another very useful measure of health and safety performance at a project level which enables organizations to learn from such errors [45]. A common industry problem is that the accuracy of reporting, counting, and analysis of near misses largely depends on a voluntary report by workers, supervisors, and management. Often, near misses are not reported due to the lack of a definition what a near miss incident is, the infrastructure reporting an incident, and motivation of organizations sharing feedback with the person that reported the near miss in the first place.

In most of the leading indicator techniques, the data collection process relies heavily on manual reports [25] which cause the safety measurements to be error-prone and subjective, and ultimately considerably incoherent from inspectors [26]. Therefore, a need exists for methods that can measure specific construction safety performances in an objective, consistent, and reliable manner, and preferably in (near) real-time as on-site hazards, which were not mitigated at the design and construction planning phase, might still exist at the operational level (in the field).

Emerging technologies recently have shown to be well-suited in gathering detailed site-specific safety data to construction resources. Since the proposed approach focuses on spatial–temporal proximity-related issues between project resources (workers, equipment, and other static hazards), the following review highlights only potential technologies which are capable of providing real-time location and timestamps to a vast number of resources in the dynamic and complex nature of a construction project.

[46–48] have already reviewed criteria and studied suitability of potential technologies that allow real-time location tracking of resources