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Proactive struck-by risk detection with movement patterns and randomness

Chao Dong[a,b,c], Heng Li[c,*], Xiaochun Luo[c], Lieyun Ding[a,b], Joanna Siebert[d], Hanbin Luo[a,b]

[a] School of Civil Engineering & Mechanics, Huazhong University of Science & Technology, Wuhan, China
[b] Hubei Engineering Research Center for Virtual, Safe and Automated Construction (ViSAC), HUST, China
[c] Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong
[d] Department of Computing, The Hong Kong Polytechnic University, Hong Kong

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ABSTRACT

This study proposes a proactive struck-by risk detection method for workers proximal to the laydown area. This approach regards the laydown area as a radiation source, and proactive struck-by risk detection is formulated as a location-based estimate of radiation quantity received by the worker. The position probability grid is adopted to track the worker and model their movement. The movement pattern model, which is learned from the trajectory records of the workers in the same trade, reflects the movement preferences of different trades, and the randomness model represents the randomness of worker movement. The worker's next location can be predicted by using the tracked location and movement model, and the struck-by risk can then be estimated. The method's potential for integration into currently available proximity warning systems is also demonstrated.

1. Introduction

Construction sites are typically cluttered with different kinds of resources and are characterized by a constantly changing environment. Continuous and dynamic interactions between various entities in such a chaotic and dynamic place can easily lead to construction accidents and work-related injuries and deaths. Workers on-foot who move excessively close to hazard sources (e.g., equipment) are a distinct safety issue on construction job sites [1]. Struck-by hazards are the second leading cause of construction fatalities, in which approximately 42% of fatalities result from being struck by falling objects [2].

The dynamic nature of laydown areas on construction sites poses considerable challenges to traditional safety monitoring. Usually the safety precautions, which protect workers proximal to laydown areas from struck-by hazards, are provided through walkie-talkie communication between the crane driver and the signal worker who manipulates the lifting operation [3]. Such an unreliable and time-consuming task raises the need for an objective and efficient means to provide proximity warnings during ongoing construction operations.

Several studies have been proposed to deal with struck-by hazards. They focused on the use of remote locating and tracking techniques to provide simple equipment-worker proximity alerts [4]. Thus, equipment and workers on the site could be located and tracked. Advances in technology have been utilized to improve safety management on construction projects [5,6]. Nevertheless, the timely prediction or the advanced warning of hazards remains problematic [7]. Warning systems can raise 59% false or negative alarms over a seven-day test [8]; therefore, operators are prone to lose confidence in such systems and ignore alarms hereafter [9]. The frequent false alarms generated by currently available proximity warning systems impede their practical applications [10]. The rate of false alarms can be lowered by integrating additional information (worker movement information) in proximity warning systems [11].

Therefore, this research addresses the need for proactive and objective means to detect the struck-by risk posed by lifting materials in the laydown area. The laydown area is analogized as a radiation source, and struck-by risk is referred to as the radiation quantity received. Given that radiation quantity is a space-related factor, we adopt the position probability grid to model the worker movement. The proactive struck-by risk is modeled as the estimate of the radiation quantity that the worker received at his next location.

The remainder of this paper is organized as follows. The research background, which includes the current states of proximity warning systems and the identified research gap, are presented in Section 2. The proactive struck-by risk detection method is described in Section 3. An illustration of the proposed method is generated by experimenting on location tracking data obtained from a construction job site and is presented in Section 4. Research limitations and future work are discussed in Section 5. The conclusion is presented in Section 6.

* Corresponding author.
E-mail addresses: chao.dong@polyu.edu.hk (C. Dong), heng.li@polyu.edu.hk (H. Li), eric.xiaochun.luo@polyu.edu.hk (X. Luo), dly@hust.edu.cn (L. Ding), joanna.siebert@polyu.edu.hk (J. Siebert).

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2. Background

The Infrastructure Health and Safety Association showed that contact collision remains a major cause of injuries and fatalities in the construction industry [12]. Considering the high number and severe consequences of contact accidents on construction job sites, the state of construction entities should be properly monitored, and warnings should be issued to prevent potential collisions in a timely manner. The monitoring and issuing of warnings have been done manually, wherein managers would assess hazard risks and verbally warn approaching workers. Many researchers [2,11,13] have adopted information technology to provide real-time proximity information to the on-site safety manager or to workers approaching hazards. The most popular approach is the proximity warning system, which monitors worker proximity to safety hazards and issues warnings.

2.1. Proximity warning systems for construction safety

The advancements in tracking/sensing technologies have greatly promoted the development of proximity warning systems. Studies in this field have attracted extensive interest, and numerous proximity warning systems have been developed and evaluated in the past few decades. Based on the proximity detection method, these systems can be divided into two groups: distance-based and location-based [3].

Distance-based systems detect dangerous proximity by measuring only the distance between hazards and workers to be protected. These systems are often installed with signal transmitters at the hazard source (e.g., dangerous location and heavy equipment) and receivers carried by workers. The distance between the worker and the hazard source is measured on the basis of the signal strength received by the receiver from the transmitter. Schiffbauer [14] developed a proximity warning system with a transmitter mounted on equipment and receivers worn by workers. It detects equipment proximity by the strength of the magnetic field signal received by the receivers. Lee et al. [15] reported the development of a hybrid sensing device, which integrates ultrasonic and infrared technologies to sense the proximity of a worker to dangerous sites (e.g., an unprotected floor edge for lifting construction materials). Teizer et al. [10] adopted radio frequency remote-sensing technology to detect the risk of contact between a worker and heavy equipment. Given that these systems focus solely on the distance between the worker and hazard at the current moment, they use limited information to detect hazard proximity.

Additional information is used in location-based systems, which are more complicated than distance-based ones. They adopt technologies, i.e. Global Position Systems (GPS) or Chirp Spread Spectrum (CSS), to estimate locations of workers and danger sources, and then evaluate proximities by a central location data-processing unit. Most location-based systems detect proximity risks through calculating the current relative distance between the hazard source and the workers [13,16–19]. Vega [18] and Ruff and Holden [19] developed proximity warning systems based on GPS and communication technologies for preventing collisions between equipment and workers during mining tasks. A real-time location-based construction worker safety management system was introduced by Lee et al. [16], within which the locations of workers are tracked and visualized in real-time, early warnings are sent directly to workers in dangerous situations. Li et al. [13,17] developed CSS-based real-time location system for proactive construction safety management, which detects the workers proximity to hazardous areas through comparing workers positions with hazardous areas.

Wang et al. [11] considered the current location of the worker, the direction of the worker and equipment, the reaction time of the worker and equipment operator, and the brake time of the equipment. They used such information to expand the hazard proximity detection area. The warning should be triggered when the worker enters the warning area with speed and direction falls below a predefined threshold.

2.2. Research gap

Existing proximity warning systems have greatly improved safety practices [8,10,11,20,21]. However, most systems only use worker's location at the current moment for proximity calculation. Thus, these systems may generate a high frequency of false alarms. In [11], considering the movement of the worker contributes to low frequencies of false alarms. Distinguishing between workers and estimating their near-future state could further improve the avoidance of contact collision, such as struck-by accidents.

Workers can be distinguished from each other on the basis of their movement patterns. Workers in the same trade share similar movement patterns. Learning movement patterns from the past trajectories of workers would provide information that will help predicting the workers' next locations. The randomness of the on-site movements of workers cannot be ignored, and slow movement increases the probabilities of changes in heading direction [22]. We adopted the heading direction change model to reflect the randomness of worker movement. The next location and struck-by risk of workers can be predicted on the basis of their movement patterns and randomness.

3. Proactive struck-by risk detection for workers

Luo et al. [3] has analogized a hazard as a radiation source, and considered the laydown area as an area radiation source. In the present research, the proactive struck-by risk detection is achieved through a location-based estimate of the radiation quantity that a worker receives from the laydown area. This estimate can be achieved by quantifying struck-by risk based on the worker's next location, as illustrated in Section 3.1, and by predicting the worker's next location based on their movement patterns and randomness, as described in Section 3.2.

To mathematically model the worker's location and movement, we borrow the concept of position probability grids [23] in robot path planning, which is used to track a mobile robot in a two-dimensional (2D) environment. We divided the construction site into 2D grids akin to a chessboard and ignore elevation. For the workplace requirement analysis of labors [24], we set cell size as 0.5 m × 0.5 m.

3.1. Quantitative struck-by risk assessment

In this research, the laydown area is a radiation source that occupies a set of cells in the partitioned grid. The repulsive potential, which keeps the robot away from an obstacle in the robot path-planning algorithm [25], is adopted to calculate the exposure strength (ES) of the laydown area in accordance with a worker's proximity. ES is calculated in terms of distance D between the cell of interest and the cells occupied by the laydown area, see Eq. (1):

$$ES = \begin{cases} \frac{1}{2}\left(\frac{1}{D_{min}} - \frac{1}{D_{max}}\right)^2, & \text{if } D \le D_{min} \\ \frac{1}{2}\left(\frac{1}{D} - \frac{1}{D_{max}}\right)^2, & \text{if } D_{min} < D \le D_{max} \\ 0, & \text{if } D > D_{max} \end{cases} \quad (1)$$

where D_{min} is the set at 0.5 m, which is the minimum distance that allows for the reasonable quantification of ES, and D_{max} is the set at 6 m given that it is the product of the estimated average crane hook movement speed of 2 m/s and 3 s response time (2 s human reaction time and 1 s system response time). D is the minimum distance between the cell of interest and the cells occupied by the laydown area. The relationship between ES and D is shown in Fig. 1.

Therefore, the proactive struck-by risk is the estimate of the quantity of exposure strength that the worker will receive based on his next location. We adopt the exposure amount (EA) to denote the proactive struck-by risk of the worker. Let $m_{i,j}$ denote the cell with index i, j in the 2D grid, and $ES(m_{i,j})$ is the radiation that cell $m_{i,j}$ receives. $P(m_{i,j}|t = T + \Delta t)$ represents the probability that the worker will be in cell