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# Stochastic state sequence model to predict construction site safety states through Real-Time Location Systems

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ABSTRACT

This paper addresses the challenge to design an effective method for managers to efficiently process hazardous states via recorded historical data by developing a stochastic state sequence model to predict discrete safety states – represent the hazardous level of a project or individual person over a period of time through a Real-Time Location System (RTLS) on construction sites. This involves a mathematical model for state prediction that is suitable for the big-data environment of modern complex construction projects. Firstly, an algorithm is constructed for extracting incidents from pre-analysis of the walk-paths of site workers based on RTLS. The algorithm builds three categories of hazardous region distribution – certain static, uncertain static and uncertain dynamic – and employs a frequency and duration filter to remove noise and misreads. Key regions are identified as either 'hazardous', 'risky', 'admonitory' or 'safe' depending on the extent of the hazard zone from the object's boundary, and state recognition is established by measuring incidents occurring per day and classifies personal and project states into 'normal', 'incident', 'near-miss' and 'accident'. A Discrete-Time Markov Chain (DTMC) mathematical model, focusing on the interrelationship between states, is developed to predict states on construction sites. Finally, a case study is provided to demonstrate how the system can assist in monitoring discrete states and which indicates it is feasible for the construction industry.



## 1. Introduction

Modern construction industry systems, especially in large and specific projects are highly complex with numerous interrelated processes, workers and hazardous worksites. Real-time monitoring of workers' behavior is necessary for responding to (and preventing) project disruption, accidents and injuries in a timely manner. However, although process innovation and advances in technology have been demonstrated to improve safety management and labor productivity on construction projects (Akinci et al., 2006; Gordon and Akinci, 2005; Jaselskis and El-Misalami, 2003), such timely prediction or advanced warning of accidents remains problematic (Wang and Razavi, 2015; Wu et al., 2010a). It is such a nuisance raising 59% false or negative alarms during a 7-day test (Ruff, 2006) that operators are prone to lose confidence and ignore the alarms hereafter (Bliss et al., 1995).

The development and extensive use of Radio Frequency Identification (RFID), Ultra Wideband (UWB) and Bluetooth Low Energy (BLE) has improved location tracking for allocating labor, materials and equipment resources more effectively and safely (Teizer et al., 2008) and the maturity of Real-Time Location Systems (RTLS) technology has resulted in cost reductions and improved data accuracy and integrity. RTLS and Physiological Status Monitoring (PSM) have also been used as an effective tool to remotely monitor the health (Altini et al., 2014; Wang et al., 2015) and safety of the construction workforce (Bates and Schneider, 2008; Cheng et al., 2013). This integrates data from the construction workers' location and physiological status to automatically identify unsafe work behaviors as accident precursors. However, despite technological improvements in RTLS, construction projects still suffer from unexpected disruptions and delays due to worker injuries. Only major accidents are currently reported amongst the big data stored and do not include the large number of near-misses and minor injuries which constitute the major portion of unreported safety issues

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(Dee et al., 2013; Taylor et al., 2014; Wu et al., 2010b; Yang et al., 2014).

A near-miss is an incident which has the capacity to cause an accident or injury, but fortunately did not happen (Marsh and Kendrick, 2000). If regular near-miss incidents are left unaddressed, they can escalate into serious safety accidents on construction sites. Thus, the identification of near-misses can provide insights into the potential risk of future accidents. Moreover, near-misses and minor injuries on construction sites occur at a much higher rate than more severe accidents (Heinrich et al., 1950; Wu et al., 2010b). As Fig. 1 reveals frequency of accidents is inversely and non-linear proportional to severity. The horizontal axis representing accident severity ranges from 0 (no injuries) to max (fatalities) based on hazard identification index (Carter and Smith, 2006). The band condition around vertical axis of frequency represents near-misses, which have potential to cause serious consequence but fortunately no injuries (severity is almost 0) arises. However, as the circumstances surrounding incident categories are similar, near-misses and minor injuries appear to be of limited use in predicting more serious injuries (Marsh and Kendrick, 2000).

An alternative approach to distinguishing states on construction sites is to utilize the interrelationships between normal incidents, near-misses and accidents instead of their causation. Since 48% of damages are caused by collisions (Pratt et al., 2001) between labor, materials and plants, this approach extracts information from workers' traveling (Teizer et al., 2008). Much of the travel of construction workers is concentrated on moving around the site from one activity to another on walk-paths. From a safety management perspective, therefore, successfully monitoring the walk-path movements of workers provides a significant contribution, especially when technological aids such as RTLS are available.

One of the key challenges in applying RTLS for this purpose is in constructing a reconfigurable rule base to transform the walk-path into incidents then to states. Simple incidents known as the direct observations are built on binary operated rules, including stepping into/out of specific regions, etc., while complex incidents such as issuing a warning or drawing a response are built on simple or other complex ones by a logical operator (Hu et al., 2014), with rule based project progress being integrated with probabilistic reasoning to estimate the probability of project/worker states. However, the relationship between the walk-path and incidents has not yet been taken into consideration in real time, and it is difficult to

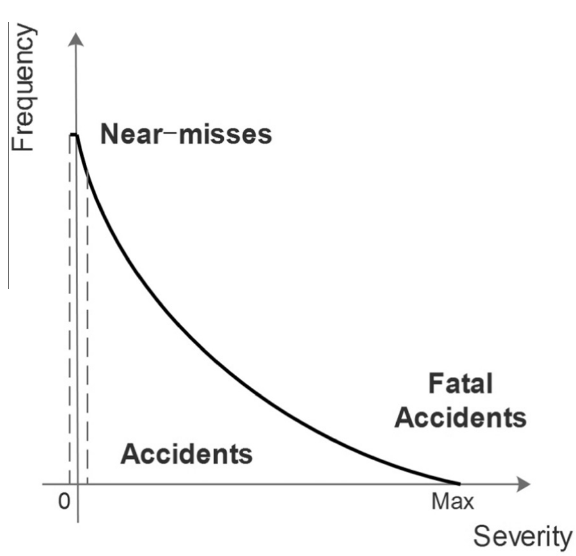


**Fig. 1.** Accident frequency–severity relation trend line.

modify or make a decision when the scale and frequency of data increases. Only by classifying a database containing massive data into separate stored spaces, can the information needed be effectively managed and correlated.

This study aims to process the hazardous states on construction sites through mathematical models based on RTLS records to address the research gap that few researchers have developed prediction models by stochastic analysis based on historical location datasets (Zhou et al., 2013). For this, a monitoring method is developed based on RTLS and capable of predicting project and onsite worker states to provide managers with a more practical and convenient method of implementing RTLS by using a matrix-based stochastic time-series mathematical model suitable for modern complex construction safety management. To achieve this goal, necessary objectives are established:

- Define and classify the hazardous regions and states based on RTLS.
- Formulate the state transition as a stochastic process.
- Simulate and process the hazardous states.

Helmets integrated with sensors designed to capture the location are used to gather the initial data from which walk-path sources are derived. The helmet safety system allows managers to easily control and inspect the system during construction work. BLE is the chosen communication network technology, which can operate for a year without battery replacement and has an accurate communication rate (Omre and Keeping, 2010). The collected data are directly recognized as incidents, which are turned into states in the following steps according to the identified algorithms. Accordingly, a new and feasible approach to process hazardous states on construction sites is proposed, offering a useful reference for future safety management. The scope and applicability of monitoring process from a stochastic perspective clearly indicates that accidents could be addressed with the development of a variety of techniques and algorithms, which assists the managers in proactively preventing accidents. The paper presents details of the methodology, case study and results of testing the use of the Discrete Time Markov Chain (DTMC) algorithm in predicting state sequences. A sequential architecture of system monitoring is designed to construct different levels of incidents. A state recognition and transition equation and a DTMC-based model is then developed for prediction and applied in a case study. Finally, a discussion of the feasibility of using RTLS and DTMC in this application is provided to allow conclusions to be drawn.

## 2. Accident causation models, near-misses and the Hidden Markov Model

The most frequent causes of accidental death and injuries on construction sites are from falls, falling objects and collapses, electrical accidents and the operation of mobile plant (Wu et al., 2010b), and existing studies focus on identifying, analyzing and modeling the causes of safety hazards and risks from an integral accident perspective (Chi et al., 2005; Hinze et al., 1998). Accident causation models can be divided into three categories: (1) models of the accident process, (2) models of human error and unsafe behavior, and (3) models of human injury mechanics (Lehto and Salvendy, 1991). These models fundamentally differ from each other, leading to significantly different inputs, outputs and areas of application. The inputs include narratives, definitions and specifications. The outputs cover hazards, errors, probabilities, causes or solutions. Almost all models explicitly consider the role of human, product, task and accident processes, without a quantitative mathematical or logical structure. Models can be applied