Automation in Construction 63 (2016) 66–78

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

# A statistical model for dynamic safety risk control on construction sites

Shabtai Isaac *, Tsah Edrei

*Ben-Gurion University of the Negev, Beer Sheva, Israel*

ARTICLE INFO

*Article history:*
Received 15 May 2015
Received in revised form 23 September 2015
Accepted 5 December 2015
Available online 24 December 2015

*Keywords:*
Construction safety
Dynamic risk control
Statistical Process
Control

ABSTRACT

Existing deterministic approaches to real-time tracking of construction workers for safety purposes provide alerts for specific incidents that are isolated in space and time, once they have occurred. In contrast, this paper presents a statistical model that can support a more dynamic form of safety control, by utilizing real-time tracking data to control the exposure of construction workers to safety risks that accumulate and change over time. The model addresses risks that are the result of concurrent activities on the construction site, and provides proactive alerts in case of an increasing risk exposure for a worker or crew. Statistical zones that are related to medium risk areas on the site are defined in the model. A number of statistical rules are then used to identify deviations from a predefined maximum allowable risk exposure for workers located in the statistical zones. The model can thus prevent potential accidents from occurring, without unnecessarily affecting the efficiency of the activities carried out on site. Laboratory tests of the model were carried out, using a Wi-Fi-based RTLS. The results of the tests demonstrate that the model can identify an excessive exposure to risk for workers, support an initial analysis of the causes for the excessive risk exposure, and compensate for errors in the RTLS measurements.



## 1. Introduction

A large number of studies provide ample evidence that the building industry continues to be plagued by a very high incidence rate of fatal workplace accidents — higher than any other industrial sector [1]. In order to prevent accidents, the management of a construction project should involve both safety *planning* and safety *control* processes. Safety planning processes seek to eliminate potential hazards on the construction site through a structured preliminary hazard analysis (PHA), and subsequent actions such as site layout planning and worker training. Safety risk control processes, on the other hand, seek to reduce the occurrence of accidents by alerting when a worker is exposed to a previously defined safety risk on the construction site, and implementing controlling actions to prevent the accident from occurring.

One solution that has been proposed to enhance and partially automate safety control processes is the application of a real time location system (RTLS) in order to track the movement of workers on construction sites (e.g.) [2,3]. Using the RTLS, accidents can be prevented from occurring by providing an alert when a worker is in an area that is considered to be of high risk. However, the current approach, in which safe work areas with clear-cut boundaries are defined, and deterministic alerts are provided for isolated incidents in which these boundaries are crossed, has two main limitations:

1. It is not fully compatible with the highly complex and uncertain nature of construction projects.
2. It does not take into account the time-related aspects of risk exposure.

Worker locations on construction sites are typically highly uncertain. They depend on activities that tend to deviate in real time from predefined plans, and on unpredictable movements that tend to diverge from expected work envelopes [4]. At the same time, safety risks are often the result of the interaction between different activities that are simultaneously carried out [5]. In this context, a safety accident will typically be the end result of a process in which the uncertain movements of the worker creating a risk, or of the worker exposed to that risk, or of both workers, lead to loss of control. The most effective way to end this process before an accident occurs is to provide a proactive alert.

However, the uncertainty regarding the actual behavior of multiple workers onsite may imply that merely improving the accuracy of RTLS measurements, without providing an appropriate model to process these measurements, will not be sufficient. Transgressions on the site are likely to be frequent — both when workers enter areas with moderate risk exposure levels, and when the location of those areas changes in ways that differ from the plan. There is, therefore, a need to detect when a worker increases his exposure to hazards because he is moving nearer to a high risk area, in order to provide a proactive warning of the possibility that he will penetrate into that area. A model is proposed here that is capable of automatically providing proactive alerts, given that it would be infeasible for the site manager to manually address all such transgressions.

An additional factor that needs to be taken into account, when applying a RTLS for the improvement of worker safety, is the temporal dimension of risk exposure. Since construction projects are highly

* Corresponding author.
*E-mail address:* isaacsh@bgu.ac.il (S. Isaac).

http://dx.doi.org/10.1016/j.autcon.2015.12.006
0926-5805/

complex and uncertain, the process of controlling safety risks in such projects (i.e. assessing, monitoring and responding to risks) should be dynamic and time-related. The level of risk exposure is related both to the intensity of exposure and its duration. Risk control should therefore involve the monitoring of changing trends (i.e. a gradual increase or decrease) in risk exposure, in addition to identifying deterministically isolated incidents in which workers digress from predefined safe work areas. The current fully deterministic approach for applying RTLS systems to enhance worker safety is limited in particular when the cumulative risk exposure is of importance. For example, in case of a hazardous noise exposure, the duration of exposure is an essential factor that has to be taken into account.

The use of a RTLS on construction sites thus has the potential to enhance worker safety. However, safety control on construction sites requires monitoring and controlling the exposure of workers to risks that accumulate and change over time, and that are the result of different interacting factors. To support these tasks, a statistical model is introduced here that utilizes real-time tracking data for dynamic risk control, by providing proactive alerts in cases of an increasing risk exposure, either for a single worker or an entire crew.

## 2. Related research

Current paper-based and manual practices used by construction companies for on-site safety control (such as check lists, training, and arbitrary inspection) are often insufficient to prevent accidents [6]. Failures in hazard identification are often due to the limited expertise or oversight of engineers or safety staff when planning or executing safety practices, indicating that improvements can be gained in construction safety through the use of technology [7]. Consequently, the use of a RTLS to automatically track worker movements on construction sites has been the topic of a number of studies.

### *2.1. RTLS for construction safety*

A significant number of studies in construction management have focused on the use of RTLS for the tracking of workers, equipment, materials and construction progress [8,9]. The technologies that have been tested so far for this purpose include:

- Global Positioning System (GPS) (e.g.) [10] — a commercially available technology that relies on satellite and base station signals, and allows tagged resources to be tracked outdoors.
- Radio Frequency Identification (RFID), wireless local area network (WLAN) and ZigBee (e.g.) [11] — technologies that can locate tagged objects by measuring distances to the tags using radio-waves.
- Ultra-wideband (UWB) (e.g.) [3] — a high-bandwidth radio technology that can track tagged objects with relatively high precision.
- 2D and 3D cameras (e.g.) [12] — produce images that can be processed to track workers and equipment, or generate a model of the construction site.
- Laser detection and ranging (LADAR) and 3D laser scanners (e.g.) [13] — produce data that can be processed into 3D models of scenes, but unlike cameras rely on range (depth) information instead of brightness.

A number of studies have addressed the question how real-time data can be processed into useful information for safety control. Navon and Kolton [6] proposed an automated model that identifies dangerous activities in the project's schedule, as well as the areas in the building where falling-from-heights hazards appear, using real-time data on locations where guardrails are missing. The study provides a useful precedence of a model that takes advantage of preliminary planning data, combined with real-time data on the actual conditions on site, to alert of uncontrolled hazards. It does not, however, address the topic of tracking the locations of workers on site.

Carbonari et al. [14] proposed a proactive safety management system that triggers warning alerts in order to prevent workers from standing in hazardous positions, using real-time tracking data obtained with UWB technology. A 1.5 m wide "warning strip" was defined around a dangerous area in order to send an alarm signal immediately before a worker entered this area. The study thus takes into account the need to warn a worker before he is in danger. However, such a warning is still provided only a very short time in advance.

Teizer et al. [15] presented findings on the use of radio frequency remote sensing for warning or alerting workers and equipment operators once workers get too close to the equipment. They too differentiated between a circular area surrounding a resource in which alerts are given, and a somewhat larger circular area in which warnings are given. Blind spots were determined in order to define the necessary safety zone for each piece of equipment.

### *2.2. Construction safety planning tools and models*

A significant number of studies have also been carried out to develop general tools and models for the planning of safe construction sites. Among them, Jannadi and Almishari [16] developed a risk assessor model for determining the risk associated with a particular activity and the justification factor for a proposed response action. The risk assessment was based on the seriousness of incidents that could happen, the degree of exposure to the hazard, and the likelihood that the hazard event will occur. However, the possibility that workers carrying out another activity will be exposed to the hazard was not explicitly addressed.

Saurin et al. [17] defined a safety planning and control model that includes three hierarchical levels, for long-, medium-, and short-term safety planning. Proactive and reactive performance indicators were defined for safety control and evaluation, based on the percentage of safe work packages and actual accident data. This study provides an example for the successful integration of the preliminary hazard analysis (PHA) technique in a safety control model. However, it too focused on the training of the workers before they started carrying out their tasks, without addressing other tasks carried out concurrently on site.

Mitropoulos et al. [18] presented a model of the factors affecting the likelihood of accidents during a construction activity. The model focuses on the characteristics of a project that generate hazardous situations and shape actual work behaviors, and analyzes the conditions that trigger the release of the hazards. Unlike the previous studies, this model does explicitly address the "threats" generated by surrounding activities, such as falling objects, heavy equipment traffic, debris, etc.

Rozenfeld et al. [19] developed a construction Job Safety Analysis tool, which focused on the identification of potential loss of control events for a detailed planning of construction activities, based on the data collected through interviews. Similar to the present study, this research directly dealt with the fact that at construction sites the physical environment is constantly changing, and workers are often endangered by activities as they move through the site in the course of their work. However, it did not attempt to integrate RTLS data to control these risks.

### *2.3. Summary*

The existing tools and models reviewed in this section can provide valuable information for construction safety planning and control. Previous studies on the use of RTLS for construction safety recognize the need to provide proactive warnings regarding hazards. They do so, however, by providing deterministic warnings for any incident in which a worker has entered a dangerous area. There is an obvious limit to the effectiveness of such a solution, since the areas that are defined as being strictly off-limits for workers can only be enlarged up to a certain extent, without excessively interfering with the construction