Algorithms for Automated Monitoring and Control of Fall Hazards

R. Navon, M.ASCE1; and O. Kolton2

Abstract: Most lethal accidents in construction are caused by falling from heights. Researchers point out the importance of safety control, carried out systematically and based on real-time data collection, as the most important element of accident prevention. An automated model to monitor and control fall hazard was developed. The model identifies the activities associated with risk of fall from heights and the areas where these activities are scheduled to be performed and plans the protective measures—guardrails in the present case. The model is designed to follow up the existing guardrails and constantly compare their locations and lengths to the planned ones. Based on this comparison, the model issues warnings whenever guardrails are missing, or temporarily removed. The model provides reports and warnings—the reports are used for planning the materials, or workers, needed to erect the protective measures. Warnings are given when a dangerous activity is performed without appropriate protective measures, or when the latter were removed before the dangerous activity was completed. The model’s main algorithms—dangerous activities and areas identification—were implemented and evaluated on site. Whereas the proposed model was developed to improve safety during the construction stage, it can be used as a useful tool during the design stage too. Including safety in the design stage, typically absent, can meaningfully improve safety during the actual construction.


CE Database subject headings: Automation; Data collection; Feedback control; Control methods; Monitoring; Safety.

Introduction

Fall from heights is the number one risk factor in lethal accidents in construction (Hinze et al. 2005). Out of the total of 2,798 fatalities caused by fall from heights in the United States between 1980 and 1989, 50% were in construction (Cattledge et al. 1996). The authors specify that in 41% of the falls, workers fell from slabs and roofs, 19% fell from scaffolding and work surfaces, and 11% fell from ladders. Many of the fall accidents could have been prevented if the right preventive measures had been taken in time. These measures are guardrails—the most common and the best measure. All other measures do not prevent the fall, but rather intercept the fallen worker and prevent injury—they include: safety nets, personal measures, protective partitions, or surfaces, and others.

Many factors affect dangerous situations in construction projects. Therefore, it is important to identify and map the existing risk factors and constantly monitor and control them. This has to be done systematically and to be based on real-time data collection so that the dangerous situations can be monitored and prevented and unanticipated dangerous situations can be dealt with as soon as they occur (Bernold 1997; Cox et al. 2003; Hinze and Wilson 2000; Hinze and Pannullo 1978; Rasmussen and Whetton 1997; Stanton and Willenbrock 1990; Tarrants 1980; Widner 1973).

Researchers point out that protective measures alone are not enough to prevent accidents due to the dynamic nature of the construction site. The aim of our research was, therefore, to develop an automated model that monitors guardrails in buildings under construction. The model identifies the activities associated with risk of fall from heights and the areas where these activities are scheduled to be performed. Accordingly, the model plans the protective measures, namely the guardrails, follows up the existing guardrails, and constantly compares their locations and lengths to the planned ones. Based on this comparison, the model issues warnings whenever guardrails are missing, or temporarily removed.

Monitoring and Control Model

The model identifies activities which expose workers to fall hazards and the areas of work where these activities are scheduled to take place. The model alerts the construction management team, in real time, when and where these hazards are not treated by appropriate protective measures—continuous guardrails—or when the protective measures have been removed.

The input to the model includes five databases (Fig. 1), as follows:

• The project model (PM) provides the monitoring and control model (MCM) with data relating to the geometrical variables of the building elements; to schedule related data—list of activities including start and finish times and the logical relation-
ship between them; to the association between building elements and the activities required to construct them; and to the required inputs needed to construct the guardrails. The PM is a dynamic database and all the data in it are, therefore, up-to-date (Bjork 2002; Eastman 1999; Faraj et al. 1999; Han et al. 1999; Tolman et al. 2000). The MCM updates the PM regarding the dangerous activities, the preventive activities, the planned locations of guardrails, and the actual locations of existing guardrails.

- The risk factors database is needed to define the level of hazard such as the height the activity is performed at, type of construction, period of the year, day of the week, etc. These are additional factors which intensify the level of hazard (Hinze et al. 2002).
- The Safety Regulations database contains the safety regulations relevant to the model, which define the situations considered as dangerous and, hence, require protective measures.
- The activity characteristics (AC) database classifies the activities according to predefined characteristics which permit the model to identify them as dangerous (e.g., type of activity, the constructed building element, and the location of the building element). The pending activities (PA)—all the activities whose predecessors are completed and the ones whose early start falls within a specified time duration—are analyzed based on the characteristics in this database. The analysis determines if the activity creates a fall hazard, or is performed in an area where a fall hazard exists.
- The general data database is built once by the project management team. It includes general characteristics of the project such as the project’s name and location, the construction method, number of floors, height of a typical floor, and the building’s intended use (e.g., residential, commercial). Some of these characteristics were identified as patterns of fall from heights (Hinze et al. 2002).

The model is divided into four modules:
- **Module I: Dangerous activities identification (DActID)**, which identifies activities creating fall hazards, or ones performed where a fall hazard exists; classifies them; and identifies the types and the level of the hazards.
- **Module II: Dangerous areas identification (DArID)**, which identifies dangerous areas, determines where and when protective measures have to be taken, and designs the guardrails.
- **Module III: Guardrail actual location (GAL)** is designed to dynamically determine where the guardrails are actually installed and whether they are continuous. This is done in order to compare the planned guardrails’ locations to the ones actually installed and used, at all times.
- **Module IV: Processing, monitoring and output generation (PMOG)**, which handles the data processing to generate the reports, and compares the planned timing and location of guardrails to the actual location of currently installed guardrails. It also checks if all the guardrails are continuous and ascertains that none of their elements have been removed.

There are three types of outputs:
- **Warnings**—issued to alert about deviations between planned and actual timings and locations of guardrails.
- **Written reports** regarding all aspects of fall hazards and the protective measures.
- **Graphical outputs**: The latter are used to illustrate the warnings and reports, and as a general means for monitoring and managing fall hazard safety.

The model starts by identifying the dangerous activities and is followed by the identification of the dangerous areas for each of the dangerous activities. The other two modules operate continuously in parallel.

### Detailed Algorithms

**Dangerous Activities Identification**

This is the main module of the control model. The module scans the PA to identify the dangerous ones enabling the project management team to prepare the preventive measures and monitor them. The activity description has three characteristics: type (e.g., formwork erection, painting), the constructed element (e.g., slab, wall), and the location type (e.g., perimeter, internal). These characteristics are compared to the ones in the AC database to determine if the activity is dangerous and subsequently to define the required preventive measure, to calculate the duration of the preventive activity (the activity needed to erect the preventive measure), and specify how it is to be integrated in the project’s schedule.
Principles
The AC database is organized as a tabular model (Neuman 2001)—it has three tables, as shown in Fig. 2: Activities, Preventive Activities, and Risk Classification—all linked via common coding. The Activities table has main and subclasses and is detailed in the following. For each dangerous activity, the Preventive Activities table lists the preventive activity (e.g., Install Guardrails, Use Safety Nets), to be automatically integrated in the project’s schedule, its duration, the logical relationship between this activity and the dangerous activity, and the type of preventive measure (e.g., guardrails, safety net). The Risk Classification table helps in determining if the dangerous activity creates the fall hazard (e.g., formwork erection, which creates a new hazard—preventive actions have to be taken before such activities are performed), or is performed in a dangerous area (an activity which has a predecessor that either creates a fall hazard or is, itself, performed in a dangerous area—e.g., install rebar in formwork—the existence of adequate preventive actions has to be monitored while these activities are performed).

Since any sequence of elements in tabular format can be represented as a simple branching binary tree (Chan and Franklin 2003), the Activity table is described in that way (Fig. 3). At the root of the tree (left) is the main class, which divides the building into the Structural Frame and the Finishes. There are five subclasses: the first defines the construction method (e.g., conventional, industrialized), the second defines the activity type (e.g., formwork erection, concrete pouring), the third defines the constructed elements (e.g., wall, slab), the fourth determines the location where the activity is performed (e.g., internal, external) and the fifth defines the code of the activity. The latter helps linking among the three tables.

Algorithm
The algorithm identifies the dangerous activities out of a list of the PA (extracted by the PM Interface), classifies them, defines the type and level of hazard and, accordingly, determines the required preventive activities (Fig. 4).

Activity Classification. The classification is performed in order to identify the dangerous activities; to determine if the ac-
Activity creates a new fall hazard, or is performed in an area where such a hazard already exists; to determine the type of hazard and the level of hazard as well as to decide about the preventive measures and the activities needed to install them. The module’s main inputs are the Project Model, from where it receives data regarding the up-to-date schedule, the General Data, Risk Factors, and the Activity Characteristics databases.

At the beginning of its operation, the PM Interface extracts the PA. Then, the activity classification process performs the following:

1. Breaks the activity description (or its code) into its basic subclass components as shown in Fig. 3. For example, the activity “external walls formwork erection, B8S3F8” is broken into the following three components: “formwork erection,” “walls,” and “external.”

2. Compares these components with the ones specified in the Activity Type, Element and Location fields of the subclasses in the Activity Characteristics database.

3. Classifies the activity according to the certainty of it creating a fall from height hazard, or being performed in such a situation. There are three classification possibilities, as follows:
   a. If there is, at the most, one component identical to these subclass characteristics, it does not classify the activity as dangerous.
   b. If there are two identical components, the activity is defined as “potentially dangerous.” This situation normally occurs if the activity is not fully defined, e.g., (using the previous example) “walls formwork erection, B8S3F8.” In this case, the definition misses the location where the activity is performed, hence the user is prompted to manually determine if the activity is dangerous, or not. If the case is not very specific to the conditions of the current project, the user also decides whether to update the activity characteristics database accordingly so that in the future the model will run more smoothly.
   c. If all three components are identical to the subclass characteristics, the activity is defined as dangerous.

The dangerous activities are subject to a determination of the type of the hazard, as explained in the following.

Hazard Type. The hazard type refers to the question whether the activity in question itself creates the hazard, or is performed in an area where a hazard already exists. In the first case, the project management team has to make sure that the materials for the guardrails are available at the right time in the correct quantity and to give instructions to install them—which means that an activity (“Install Guardrail”) has to be added to the project’s schedule. If, on the other hand, the activity is performed in an existing dangerous area, the project management team’s role is to monitor the existing guardrails.

The determination of the hazard type is done based on the characteristics of the PA and on the logical relationship with its predecessors extracted by the PM Interface. Resorting to the activity sequence depicted in Fig. 5, “formwork Erection” as the first activity of a specific floor clearly creates a new hazard. “Rebar Installation,” on the other hand, whose predecessor created the new fall hazard is, therefore, performed in an existing dangerous area. Its successor—“Concrete Pouring”—is consequently also performed in an existing dangerous area.

Hazard Level. The determination of the level of the hazard permits the project management team to prioritize its safety-related activities and give its attention to the most critical ones first. The level of hazard is added to the activity record (Fig. 2) and then the activity is finally recorded in the Dangerous Activities file, which is used by the Dangerous Areas Identification module as an input. The hazard level determination is done based on data in the Risk Factors (RF) database and extracted by the RF Interface. The RF database contains data gathered from the company’s experience and research regarding factors which intensify the level of hazard. Such factors are the first day of the week, the height the activity is performed at, etc. (Hinze et al. 2002).

Preventive Activity Determination. Finally, the module determines the activities needed to reduce, or remove, the identified hazard. This process determines the preventive activities, their duration, and the logical relationship between the preventive and the dangerous activities, and feeds these data back to the PM to be integrated with the project’s schedule. The process uses data regarding the type and level of the activity from the Dangerous Activities file, and other data from the PM via the PM Interface. Additional data are used from the Preventive Activities table in the Activity Characteristics database, extracted by the GD Interface.

If the dangerous area is created while the dangerous activity which creates it is performed, such as in the case of formwork erection, a concurrent preventive activity is needed. Therefore the appropriate preventive activity is “Install Guardrail” and the logical relationship between the dangerous and the preventive activities is “Start-Start.” Another dangerous activity such as “External Wall Masonry,” on the other hand, requires the same preventive activity, but with a different logical relationship. Because, in most cases, the guardrails of the formwork are removed when the formwork is stripped, new guardrails have to be installed before the masonry activity commences. Therefore the logical relationship in this case is “Finish-Start.”

Dangerous Areas Identification

This module can be used during the design phase, or during the planning and the construction of the building. The module identifies the areas where the dangerous activity is (or will be) performed and calculates the physical variables of the required protective measures. The module deals with the following fall hazards: fall from openings—in slabs, roofs, and external walls; fall from openings in shafts and open ends of slabs—the following description refers to the latter.

The process starts by extracting the geometrical properties of all the building elements associated with the dangerous activities.
identified by the DActID module (Fig. 6). The extracted data are stored in the Building Element file, which includes the element type (e.g., wall, slab), its geometrical properties, its location in a local coordinate system, and the time this element is scheduled to be erected. Each element is divided into a large number of small rectangular subelements (this number can be determined by the user).

The algorithm is based on a count of the number—"n"—of subelements which have the same local coordinates for any vertex within the plane of the top surface of the element. The next step of the process is to list the vertices of all the subelements and to determine n for each vertex. Each vertex whose n = 4 is “internal,” thus when n = 3 the vertex is part of an edge. The next stage of the algorithm is to identify the “dangerous edges” of each subelement, which is done on the basis of risk area definitions extracted from the Safety Regulations database. These definitions (e.g., “each employee walking, or working, on surfaces shall be protected from falling through holes or edges more than 2 meters above lower levels by guardrails systems erected around each dangerous area”) are translated to geometric and numeric terms and stored in the Risk Area Definition file. Therefore, the algorithm of the dangerous edge identification is based on an arbitrary selection of a vertex, moving to the next one whose n = 3 (when applicable), calculating the (shortest) distance (when n = 3) and drawing a line between the vertices, thus marking all the dangerous areas.

The required guardrails for each building element are determined and the Guardrail Details file is generated. This file includes the dangerous coordinates and edges; the length of the guardrails, broken down to sections; the date and the duration that the guardrails are needed. This file is transferred to the Guardrail Actual Location and the Processing and Monitoring modules.

**Guardrail Actual Location**

The purpose of this module is to dynamically determine, at all times, where the guardrails are installed and whether they are continuous, in order to compare the planned guardrails’ locations to the ones actually installed and used. The module has not yet been implemented, but to ensure its feasibility a conceptual technological solution for a system that determines the locations, the lengths, and the continuity of the guardrails was considered. The system will have three components: sensors which determine if the rails are attached to the posts, transmitters, and a central receiver.

The sensors are installed between the post and the rail and they have open, or closed, positions. As long as the rail is attached to the post, the sensor and the electrical circuit are closed. The sensors are wired to the transmitters, which send the status of the sensors to the central receiver. Data regarding each sensor include its status (open or closed), the identification of the sensor, the identification of the rail, and physical parameters of the rail, e.g., its length. In addition, the transmitter also sends its own identification to enable more precise determination of the locations.

Based on the above-mentioned data, the module first associates the guardrails to the corresponding building elements. Then, based on additional data provided by the people who installed the guardrails, it can calculate the locations and length of the installed guardrails and determine if they are continuous.

**Processing, Monitoring, and Output Generation**

This module handles the data processing for the generation of the output and monitors the existence and the completion of the guardrails at all times. The input to this module is supplied by the other three modules and by the PM. The process starts with data extraction by the PM Interface (Fig. 7), which extracts two types of activities: (1) future dangerous activities (for a time span specified by the user) for the generation of reports for planning purposes, (2) ongoing dangerous activities for the generation of warnings and reports.

For each of the ongoing activities, the process retrieves all its associated building elements and the planned timings, locations, and lengths of the guardrails from the DActID and DARID modules. Next, based on online data from the GAL module, at each given time, the module compares between the actual location and length of the guardrails to the planned ones at the time of comparison. It also checks if the guardrails are continuous. Based on this comparison, the module generates the relevant warnings and reports.

There are three types of output: warnings, reports, and graphical outputs. The warnings alert the management of problems related to fall hazard and preventive measures, which include (1) a notification given before a dangerous activity is about to be performed. The notification can be given in various ways, e.g., a popup message in the scheduling software, or a periodic warning.
The user can determine how long before the performance of a dangerous activity s/he wants to be notified. The message window also includes the model’s recommended protective measure.

(2) A warning when a dangerous activity is performed without a protective measures. This is done when the model identifies a deviation between the planned timing and locations of the guardrails and the existing ones. These warnings are also issued when existing guardrails, or part of them, are temporarily removed for duration longer than a specified time defined by the user.

The reports are comprehensive lists of all aspects of fall hazard and the recommended preventive measures and activities. They serve both for ongoing management and monitoring as well as for historical data recording purposes. The reports can be given to different time horizons and some of them are also available graphically. The reports include (1) a list of dangerous areas, in terms of time and location for different time horizons, or for various sections of the project. For each dangerous area, it also gives the building element, which terminates the hazard (if applicable). For example, a concrete slab: the hazard begins after it has been cast and the railing of the formwork, which was part of it, removed with the formwork stripping. This fall hazard terminates once the external walls are built. The report helps the project management team for general risk management of fall hazards.

(2) Dangerous activities and protective measures. The report lists the dangerous activities, for each it gives the start date and then duration. It also lists the activities recommended to erect the guardrails and the recommended logical relationship between this activity and the dangerous activity. It helps the project management team to prepare for the hazard and order materials, labor, and other resources needed to erect the guardrails. (3) Planned versus actual protective measures. This report gives the project management team comprehensive information about the planned guardrails and the ones actually erected. The report details (1) the exact locations of the guardrails, (2) the date to be installed, (3) the duration that the guardrails will be needed in this location, and (4) their total length in that location. The report also details similar parameters for the guardrails actually erected and compares them to the planned ones.

The graphical outputs are used as a powerful managerial tool, which facilitates the monitoring and management of the protective measures. The project management team that is always short of time can see at a glance where preventive measures will be
needed at any given time, or where there are problems, such as guardrail removal. Thus, after seeing the complete picture of all fall hazard aspects, the management can prioritize and give its precious attention to the most burning issues. There are two types of graphical outputs: (1) dangerous areas. This is the parallel output to the report under the same name, but is easier and faster to understand. Figure 8 depicts the dangerous edges for Floor 4 for a given time (today). (2) Planned versus actual protective measures. This, too, is the parallel output to the report under the same name. Apart from the warnings, this output shows, at a glance, where guardrails are missing. These outputs can be viewed anywhere (at the site, or even the main, offices), which makes them a very powerful monitoring tool.

Model Implementation and Evaluation

The algorithms of the model were implemented in a computer program ("prototype") written in VISUAL BASIC (VB), AUTOCAD, and MS PROJECT—the algorithms which identify the dangerous areas and the processing were written in VB. MS PROJECT was used as the database of the up-to-date schedule, from which the PA were extracted and to write the algorithms that identify the dangerous activities. AUTOCAD was used to model the building, to extract data about the building elements in question—these data were used by the algorithms which identify the dangerous areas. The AUTOCAD was also used as a means of visualization for the warnings and reports. At this stage the technological system for the measurement of the actual location of guardrails was not implemented.

The prototype was used in a demonstration project—a nine story apartment building with a total built area of 4,400 m² and a total cost of $2,500,000 in Netanya. The experiment checked if the prototype

- identifies all the dangerous activities,
- identifies all the dangerous areas, and

• recommends the right protective measures—guardrails—at the right times and in the correct locations.

Fourteen experts were asked to evaluate the model during the on-site experiment. The experts included: five resident engineers, four safety consultants, three foremen, and two academics. The prototype was used in the demonstration project in parallel to an evaluation of the same project by the experts. The experts were asked to identify the dangerous activities and to recommend suitable protective measures. The prototype was run for the same period of time that the experts related to and outputs were generate—the experts were then asked to evaluate the output.

A sample output generated with AUTOCAD, which was used for the experts’ evaluation, is shown in Fig. 8. The main conclusions from the comparison between the output of the prototype and the analysis of the experts are:

- The model is accurate—it identifies the dangerous activities and the locations of the hazard (dangerous areas) and recommends the appropriate protective measures.
- The integration between the safety components (dangerous activities and the activities to erect the protective measures) and the project’s schedule has three advantages: (1) fall hazards can be identified and referred to much earlier than under current practice. This can be done as early as the design stage (Weinstein et al. 2005), during which there is normally no reference to the safety aspects of the construction stage. (2) Identification of hazards that might have been ignored, especially in large projects. (3) The integration permits reference to hazard prevention as one of the activities needed to be carried out during the construction of the project. The equality between the status of the preventive activities and that of the other construction activities increases the weight given to safety issues.
- The ability of the model to provide risk analysis for selected periods, or defined sections of the work, improves the project management team’s ability to prepare itself to prevent accidents.
- The graphical output is very useful to understand the fall hazards and identify them quickly.

The experts expressed their opinion that the model offers an excellent tool for risk management, which enables a daily monitoring of fall from heights hazards. They emphasized its advantage in introducing a methodological component to safety management, on a daily basis, which is a vast improvement to the current practice. The experts added that an additional contribution of the model is increased awareness of safety in general, and fall hazards in particular.

Conclusion and Discussion

The literature emphasizes the importance of identifying and mapping risk factors, as well as monitoring and controlling them, as important elements in accident prevention. Safety control in the context of the present model entails the following steps: identifying and mapping the falls-from-heights hazards, planning and designing the preventive measures, collecting data regarding the existing preventive measures, comparing these data to the planned preventive measures and, when a problem is identified, take corrective measures.

The present model deals with some of the major aspects of safety control, as described earlier—it identifies and maps the hazards in terms of dangerous areas and activities; it proposes preventive activities and integrates them with the project’s sched-
ule (subject to approval of the constructions management team); it collects data in real-time regarding the existing preventive measures, compares them to the plan’s ones and warns when they are missing, or temporarily removed, thus enabling corrective measures to be taken on time. The model focuses on the prevention of falls from slabs, roofs, and scaffolding and on guardrails as preventive measures.

The prototype did not implement two important components of the model: the PM and the actual location measurement of the guardrails (GAL). As shown in the “Monitoring and Control Model” section, the concept of the PM has been extensively researched and reported. The second component—GAL—will have to be implemented and tested in future research. The smooth operation of this model requires that the schedule and other data be searched and reported. The second component—GAL—will have to be implemented and tested in future research. The smooth operation of this model requires that the schedule and other data 

While the proposed model was developed to improve safety during the construction stage, it can be utilized as a useful tool during the design stage, too. By using DAriID, the designer can identify dangerous areas and integrate safety measures in the design. For example, leaving inserts (or holes) in slabs for faster and better installation of guardrails as soon as formwork (with its railing) had been stripped. The model is instrumental in identifying the risks of fall from heights and in evaluating, and monitoring them. The graphical interface helps to easily determine where these hazards are and aids in focusing on the main problems. As the model automatically identifies the hazards, their locations, and the time when they are scheduled to appear, we believe that it is almost impossible to forget to use protective measures. The graphical output is very useful to understand the fall hazards and identify them quickly.

References


