Predictive Analytics for Close Calls in Construction Safety

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Abstract –

Extracting knowledge from data on near hits (aka. close calls) might warrant better understanding on the root causes that lead to such incidents and eliminate them early in the risk mitigation process. While a close call is a subtle event where workers are in close proximity to a hazard, its frequency depends–amongst other factors–on poor site layout, a worker's willingness to take risks, limited safety education, and pure coincidence. While existing predictive analytics research targets change at strategic levels in the hierarchy of organizations, personalized feedback to strengthen an individual worker's hazard recognition and avoidance skill set is yet missing. This study tackles the bottom of Heinrich's safety pyramid by providing an in-depth quantitative analysis of close calls. Modern positioning technology records trajectory data, whereas computational algorithms automatically generate previously unavailable details to close call events. The derived information is embedded in simplified geometric information models that users on a construction site can retrieve, easily understand, and adapt in existing preventative hazard recognition and control processes. Results from scientific and field experiments demonstrate that the developed system works successfully under the constraints of currently available positioning technology.

Keywords –

accident investigation; building information modeling; close call; construction safety; data mining; education and training; hazard identification; location tracking; near miss; predictive analytics.

1 Introduction

Better understanding the root causes that lead to an accident is important to protect construction personnel from similar mishaps in the future. Unfortunately, most of the current accident investigation methods focus on supplying valuable information after the fact, once a person has been injured or killed. Accident investigation reports, as explained in [1], are often (purposely) brief and only a few pages long [2]. Fatality assessment and control evaluation (FACE) reports are one example of a practiced method of an investigation [3]. They typically contain factual information, for example: a description of what happened, the actual results of the event, the persons involved, the equipment or material involved, the activities preceding and during the event, the date, time and place of the event, any emergency actions taken, some pictures of the event situation, and the immediate remedial actions taken.

While the contributions of this study do not substitute any of the existing investigation approaches that are in place, it tackles the topic more pro-actively. In the ideal case, the proposed method will support existing processes with new information to close calls that has not been available before. As [4] has previously outlined, construction safety has to happen at the right-time. Thanks to emerging technology, detailed information on close calls can be recorded and analyzed near real-time. The generated information then can be used for predictive analysis and even immediate mitigation.

This paper first reviews the existing research body on close calls in construction. It explains the proposed algorithm for quantitative analysis of close call events in construction safety. Scientific verification through simulation and validation using real field experiments follow. The results demonstrate the functionality of the developed algorithm and software user interfaces. A discussion and an outlook for future research conclude the paper.

2 Background

2.1 Definition of close calls

Several researches in construction describe a close call as an event that almost resulted in an accident. Too close proximity between a pedestrian worker and a known hazard is one of such events. However, there is no research that provides a scientific definition of the exact characteristics of a close call [5]. According to [6], a close call can be part of a sequence of events that result in anywhere from minor to major accidents. Therefore, close calls should be recorded and followed-up with a close call reporting program. Such programs, in an ideal case, measure safety performance and reduce the probability of accidents. However, the success of close call reporting crucially depends on the participation of persons to report near-misses, which can lead to inconsistent or false results [7]. Due to the often complex contractual organization of projects, construction companies often face difficulties in implementing effective close call reporting and analysis programs.

2.2 Reporting and analyzing close calls

Heinrich's safety pyramid (aka. the accident triangle) provides an early example for separating close calls (called therein near misses) from actual accidents [8]. Fast forward and decades later, the results from a survey by [9] suggest that employees from companies with high health and safety ratings perceive their own safety, zero harm, and continuous improvement in health and safety as very important. In the same study, construction hazard identification, including close call reporting, ranked 10th out of 38 topics which shows the general acceptance of such a system. [10-11] then discussed the strengths and weaknesses for a qualitative (matrix) and quantitative (index) near-miss management system. They focused on how close call reporting and filtering could be implemented to minimize both missed near-miss reports and unnecessary reports. Their design consists of four separate phases: Event identification and reporting, event assessment, prevention measure application and follow-up actions. Among other noteworthy research that followed, [12], for example, established a database consisting of feature vectors (values that represent information on an incident) for close calls, filled with data from common written incident-reports, viewing close calls as events which lead to an accident.

Today, under often self-motivated initiatives for establishing leading indicators for safety, pioneering owner and contractor organizations highly encourage the (voluntary) reporting and analysis of close calls by everyone involved in a project. Databases with restricted access exist where close calls are entered manually or via guided user interfaces (GUI) on mobile devices. Such recent examples from modern construction sites demonstrate the advancements that have been made for reporting and investigating incidents. In brief, the reasons for this change can be summarized twofold: (a) driving organizational change in safety culture by rethinking existing and establishing new processes and (b) taking advantage of sophisticated technologies to record and analyze real data. Our work therefore focuses on low-severity, high frequency injuries. It does not necessarily translate to high-impact, low-frequency events.

Among other research studies, the most closely related previous study was performed by [13]. It describes a method called Proximity Hazard Indicator (PHI). PHI successfully detects spatial-temporal (proximity) conflicts between workers and construction equipment using real-time location sensing (RTLS).

2.3 Summary

Practiced close call reporting and analysis rely on manual data gathering efforts. Using only manual reports as a source of information has several disadvantages. Some of the issues presented in the following help explain the problem:

1. *Size of the problem:* The number of reported close calls is probably smaller than the true number (i.e., personnel may not report close calls fearing retaliation or a drop in productivity).
2. *Standardization:* Accident investigation reports vary by country and are kept general to inform the entire organization and sometimes even the industry. An open-access benchmark which is based on high quality (anonymized), near real-time data and available to every construction site or personnel is missing presently.
3. *Data availability and processing:* Processes depending on manual data lack the necessary level of detail (i.e., unlike the airline industry for the past decades or unmanned autonomous vehicles just recently, trajectories of construction equipment are often neither recorded nor analyzed).
4. *Collaborative planning:* Though BIM offers the construction industry a method to plan, build, and operate infrastructure or buildings, standardized tools for construction safety (and health), site layout or work station planning are missing (i.e., most projects perform modeling efforts with BIM manually at low or moderate detail and only on an as-needed basis).
5. *Safety culture change for labor and management:* Since close call reports may include sensitive information to an incident [14], person(s) reporting them might impact labor-management (i.e., workforce vs. supervisor, management) relations and organizational fairness.

3 Proposed method

The proposed method intends to change the close call reporting and feedback process. As introduced earlier, close calls are typically reported when a human witnesses or participates in an event which compromises or threatens to compromise the health or safety of a person or the environment. If necessary, a person may conduct first efforts to prevent an accident or a further incident. The person notifies their supervisor or safety coordinator on site directly or using a close call reporting application on a mobile device (i.e., if permitted on site: smartphones or tablets) (see Figure 1).

Figure 1: Close call reporting, analysis, and personalized feedback process

Some general information about the event is shared once the case reaches the corresponding safety professional within an organization (a knowledgeable person). Afterwards, a problem-solving peer-review team consisting of workforce (who are trained in operational skills), safety professionals (who are trained in root-cause analysis), and management (who are trained in continuous-process improvement) will heighten the awareness for the seriousness of the case within their own organization. Various means exist to learn more about the risks and how to mitigate them, for example, calling for dedicated close call review meetings, department safety meetings, one-on-ones with workforce or supervisors, or involving a neutral third party. The team, while protecting employees from blame [15], finally recommends corrective actions. At this point, well-working close call reporting processes in practice (should) ensure timely feedback to the person(s) who reported the incident in the first place.

The proposed close call reporting and analysis, and personalized feedback process takes advantage of remote sensing and information modeling to automatically record the circumstances that lead to close calls. By attaching a RTLS device on every resource (pedestrian workers, equipment, and material that was a-priori declared hazardous), their then available trajectory data will be analyzed in BIM to locate close calls.

The proposed methods used in the new workflow are explained next in more detail. It is followed by a detailed investigation into the theoretical verification of the proposed methods using first a simulated data set in a fictional construction setting and thereafter (after ensuring the methods work successfully) several realistic data sets for experimental validation on live construction sites. As a note, the initial selection of simulated over realistic data permitted the verification of the proposed method under ideal (repeatable) conditions. In the simulated setting, a fictional building information model and trajectory information was assumed for the artificial pedestrian workers' and equipment travel paths.

3.1 Trajectory data to construction resources

Construction resources are physical objects and spaces that are required to finish a construction process. In this research, the term construction resource refers to (a) the pedestrian workforce, (b) construction equipment, and (c) objects or structures of temporal or final state. The number of any of these resources in the scene under investigation can be one or many. They can also be static or dynamic in nature. Pedestrian workers as well as equipment are moving frequently, while temporary objects, such as scaffolds or hazardous materials like gas bottles, are mostly static and stay in one position. Other examples of static or as-built structures which can be hazardous are unprotected edges in elevator shafts or leading edges in high-rises.

Construction resource data is defined as a term to summarize boundary data from building information modeling and trajectory data from trajectory logging files. Trajectory or position logging devices frequently store a resource's relative position and the current time, namely timestamps, inside a log-file [16-17]. The logging frequency and additional logging information like battery status both depend on the type of device. In this research, a frequency of one event per second (1 Hz) is assumed to simplify the following calculations.

3.2 Protective envelopes

To automatically detect and analyze close call events between *resources*, additional descriptive information for each individual resource involved in a close call event is necessary. For example, its precise position and *boundary* information define a *protective envelope*. For the reason of simplicity, all data presented in this study is kept to two-dimensions (2D, plan view). As a result, the protective envelopes come in shapes of circles or polygons. The number of the involved resources as well as their parameters, i.e. the size of the protective envelope called the *safety distance*, are set in advance based on the previous research findings by [18]. Trajectory information and building information model complement this chosen approach. The size of its safety distance and its shape are based on the following assumptions:

- *Pedestrian workforce:* A circle with a radius of 1.5 m is selected. This value is based on the average distance a human walks in one second, reacts, and comes to a complete stop [18].
- *Construction equipment:* A protective envelope for equipment must be wisely chosen considering several of its operating parameters. These include, but are not limited to: operating speed, angle of operation, and articulation. Even external factors, such as ground conditions, might be included into calculating a machine's breaking distance. While [19] has shown that multiple hazard zones for equipment are advisable to avoid a hit, generally a fixed value decided by a user is added around the equipment's known bounding box.
- *Temporary object:* The size of a protective envelope for temporary objects (e.g., safe storage of gas bottle) is determined according to rules and regulations set

by governments and local authorities [20]. The resulting shape is a resized version of the existing boundary.

- *As-built structure:* Many structures, once they are erected and remain on site, might also require protection. Guardrails, for example, preventing workforce or equipment from falling to lower levels typically have protective envelopes associated to them. Their safe installation is also regulated by official regulations or company best practices [20].

3.3 Close call event and analysis

Currently, there exists no common definition for close calls [5-6]. A close call, as defined in this research, is a proximity event between one or several pedestrian workers and a hazard, leading to an endangerment of the workers. Also, a close call as it relates to a too close proximity event between two resources A and B is defined as an overlap of their protective envelopes at positions $P(A,t)$ and $P(B,t)$. When using trajectory data, there are two possible approaches towards categorizing close call events: (a) to categorize every proximity event as a separate close call or (b) to combine consecutive occurring proximity events to a single close call. The latter is the more sensible choice for this study.

For each proximity event, a proximity event buffer is created to store information for later processing. This information includes timestamp a [yy:dd:hh:mm:ss], position [m], velocity [m/s], and orientation [°]. Information on the distance [m] and facing direction [°] towards the other resource is also stored. In the example shown in Figure 2, a piece of equipment has been traversing too close to a gas bottle.

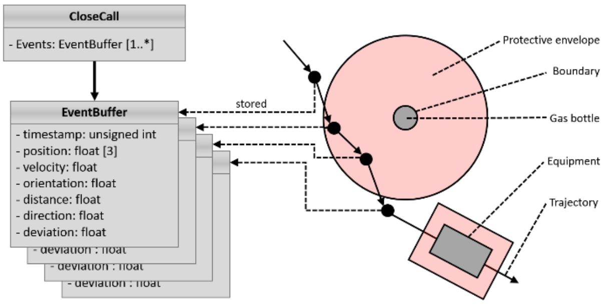


Figure 2: Close call EventBuffer class diagram

For two resources A and B, a close call detection algorithm (1) analyses their trajectories and (2) checks for each *timestamp* $t \in T(A), T(B)$ if their protective envelopes overlap. If an overlap is found, a new close call gets created and a proximity event buffer is assigned to it. Every consecutive proximity creates a new event buffer which is added to the same close call. If no further overlap is detected, the close call is completed and the next proximity will create a new close call. As the trajectory data only consists of coordinates and timestamps, *velocity, facing direction, distance, and orientation* must be calculated separately.

For each close call a radar plot is computed showing the weight values for velocity, duration, deviation, distance, and orientation. Values to these weights visualize the severity of the different aspects that contributed to the close call event. The higher the value points in the radar plot, the more the aspect contributed to the endangerment of the resource. Velocity and length during the close call event (see Figure 3) give a user a brief overview of a resource's safety performance. As suggested by [16] personalized feedback or other change (i.e., selection of other equipment or type, modification to site layout plans) can be issued and future performance monitored until the issue is resolved.

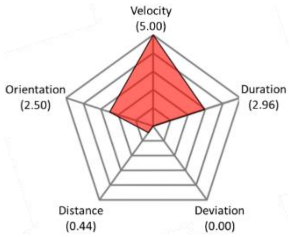


Figure 3: Factors leading to a close call

3.4 Close call visualization

The computational analysis of the gathered data starts with the examination of all single event buffers. From there, it abstracts and combines these information into more general statistics. As the level of detail drops with this generalization, a Guided User Interface (GUI) displays the construction site layout on a map, general construction site statistics and an overview to all construction resources, separated by type. A heatmap, if selected by the user, shows the location of close calls (see Figure 4). It covers statistical data as well as a brief overview on all resources being present at the construction site and involved in close calls. This GUI might be used by management to derive a quick performance overview on close calls for one construction site.

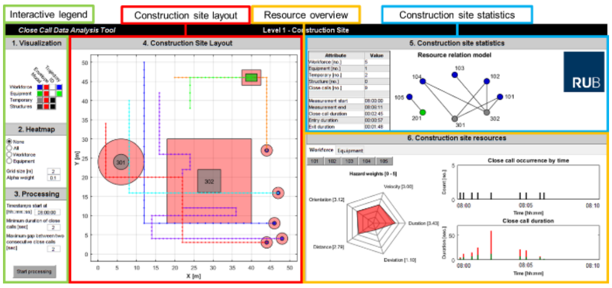


Figure 4: Guided user interface for close calls

4 Verification of method

To verify the method, close calls among few resources were artificially generated. Details were discovered, for example: the course of close calls, individual resource- and hazard-statistics, a heatmap as well as comprehensive construction site safety statistics.

Industry expert input asked to find intuitive answers to typical safety-performance-related questions:

- Which are the areas where close calls occur frequently?
- Which workers or pieces of equipment are involved in a close call and are there any particular differences in the safety performance among them?
- How does a worker react on entering a hazard zone, when might the worker recognize to be at risk, and how will the worker react upon detecting it?
- Which ways exist to leverage the newly generated information for continuous safety performance improvement, e.g. in safety education and training?

The artificially generated data set (called scenario) is based on known trajectories (straight lines) where the ground truth is known and evidence available is used to verify the close call analysis algorithm. This scenario included five workers that traverse a construction site in a continuous manner, facing two temporary static hazards and one dynamic vehicle. Each worker simulates a behavior which addresses one of the different hazard weights. To raise the orientation weight value for a worker, for example, the vehicle creates a close call in a workers' blind space. All trajectories are straight lines. This permits simplicity in the verifying process of the algorithm. A heatmap displayed in the GUI further allows the evaluator to spot the close calls.

Some more specifics to the scenario: one pedestrian worker (A) traversed the site at a speed of 2 m/s (at a maximum allowable speed limit of 1 m/s). A second pedestrian worker (B) was a too short distance towards the hazards (301 and 302). A third pedestrian worker (C) simulated a behavior which should result in a high deviation weight. The duration weight was tested by pedestrian worker (D). Pedestrian worker (E) was confronted with a traversing vehicle (F) to verify the orientation weight function. The heatmap functionality was verified by comparing the trajectories with the hazard locations on the map (see Figure 5).

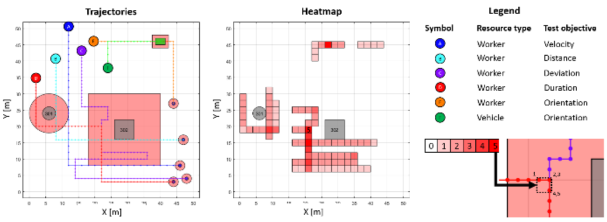
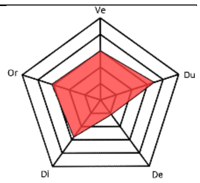


Figure 5: Guided user interface for close calls

The weight radar plots for all resources (team) are displayed in Table 1. The data can be explained as: velocity (high), duration (long), and orientation (vehicle approached from the rear) of the observed close calls in the artificially generated data set were high. The other criteria played a lesser role.

Table 1. Results to close calls from artificial data set

Criteria	Performance
Radar Plot	
Velocity (Ve)	3,00
Duration (Du)	3,43
Deviation (De)	1,10
Distance (Di)	2,79
Orientation (Or)	3,12

5 Experiments and results

To validate the close call data analysis algorithm, datasets from a construction sites were analyzed. The following sections cover the pedestrian workers' individual performances and the overall construction site safety performance. Discussions including future work follow.

5.1 Data from building construction site

A dataset was gathered on a real building construction site where several pedestrian workers were present at an elevated work level. A restricted workspace was located inside the work area. Although the protective guardrails around the leading edges met the required safety standards, the present supervisor estimated it as insufficient (asking his and subcontracted personnel "to stay away from the edges"). The close call analysis algorithm aimed at analyzing the trajectories of 4 workers for potential close calls near the leading edge and/or unauthorized entry into the restricted work space.

As shown in Figure 6 (see the grey areas in plan view) the restricted space and the leading edges were modelled as individual objects using BIM. UWB served as the sensing technology for recording the trajectories of the personnel. UWB allowed to allocate a specific ID to every worker. The information in Figure 6 displays the individual trajectories (in blue color) and, by applying the developed close call algorithm, the resulting heatmap (in a range of red colors) for every worker. The images indicate several close calls, mostly towards the southern and eastern sides of the work environment.

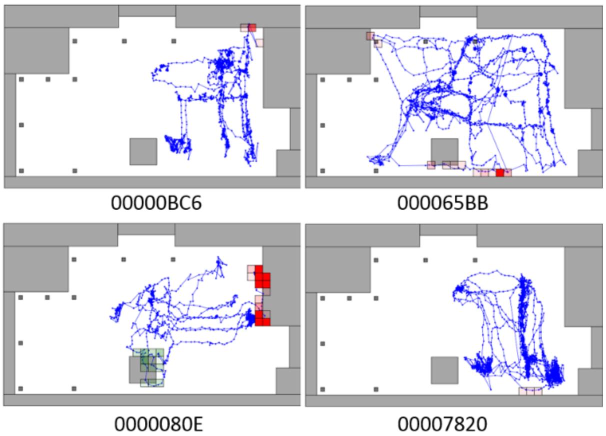


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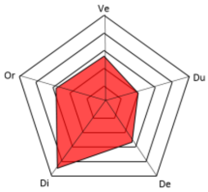
Figure 6: Individual close call performance

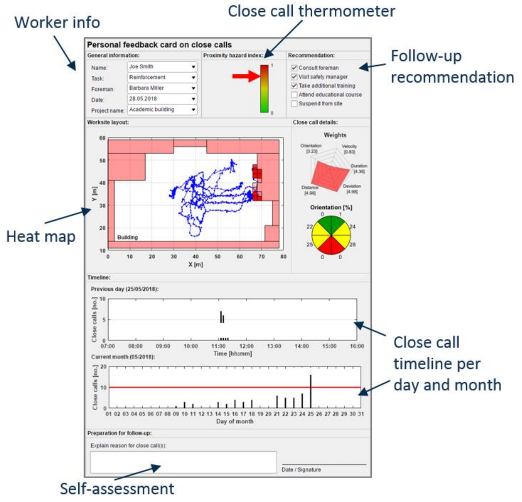
The analysis the generated hazard weight radar plot for the pedestrian workers' team performance gives further insights into the observed close calls (Table 2). Many of them were related to very close distances to the leading edges.

Table 2. Results to experimental validation

Criteria	Performance
Radar Plot	
Velocity (Ve)	2.69
Duration (Du)	2.00
Deviation (De)	2.64
Distance (Di)	**4.46**
Orientation (Or)	2.83

5.2 Personalized feedback

The data generated in this research might be used to give safety professionals the required facts to take corrective actions that protect the human workforce. While multi-lingual manual reporting cards for close calls may still exist in the future, they have–as outlined before–shortcomings in practice (e.g., incentives, collection, and feedback cycle). A successful transformation to digital recording and feedback is possible and yet has to be investigated in the future in much more detail. A conceptual digital feedback card would, for example, need to be tested for simplicity and acceptance by the workforce (Figure 7). While intrinsically safe mobile devices are required for industrial construction applications, recording and analysis via Internet-of-Things solutions like [21] exist to reduce the time needed in the feedback cycle. The foreman would then have new information in toolbox meetings available for use in safety awareness training.



Personal feedback card on close calls

General information:

Name: Joe Smith

Task: Reinforcement

Foreman: Barbara Miller

Date: 28.05.2018

Project name: Academic building

Recommendation:

- ☑ Consult foreman
- ☑ Visit safety manager
- ☑ Take additional training
- ☐ Attend educational course
- ☐ Suspend from site

Preparation for follow-up:

Explain reason for close call(s):

Date / Signature

Figure 7: Conceptual display of digital close call reporting and feedback card

6 Conclusions

This study presented an algorithm for the quantitative analysis of close call events in construction. A process of collecting trajectory data as a valuable construction resource was introduced and a graphical user interface was presented that provides safety personnel with automatically generated safety information on close calls. The proposed algorithm was successfully verified first in a simulated and later in a field realistic work environment.

Although the developed method provides useful information on both artificial and real trajectories that cause close calls, the performed calculations are based on several assumptions. They rely in particular on the performance of RTLS. While many type of sensors provide RTLS data (i.e. computer vision, wireless), existing measurement errors may not qualify these (yet) for commercial application in the harsh construction environment. Though [18] demonstrated that errors with UWB can be below 1 m for each positional data log, RTLS technology must also withstand ethical concerns of tracking workforce and be effective in acquisition, use, and maintenance. The latter issue could be solved by targeting worthwhile business applications at the same time, e.g. logistics for indoor work environments. However, most of the existing RTLS still faces major hurdles and demand new sophisticated solutions to operate successfully in such complex work environments.

On a similar note, the developed algorithm considers trajectory-related information only. Although it tackles a complex question, when are workers safe/unsafe based upon their location and the situation, it uses fixed safety distances. Their current size relies on empiric findings.

Though all of these assumptions made still add new functionality to existing close call management processes, additional research is necessary. For example, the presented hazard weight calculations are based on simplified values. Field-based observations are likely necessary to complement the definition of terms and calibrate the weights accordingly. This then may solve whether a close call was a true close call. Options to expand the dataset for such purpose exist. For example, data fusion including new data points from proximity alert sensors that are able to automatically record close calls between pedestrian workers and heavy construction equipment [22-25] could serve future research agendas well. To enhance personal awareness of every worker, a port to safe test bed environments within mixed reality environments would enhance more realistic education and training scenarios, providing users with much needed personalized feedback [26].

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