CONSTRUCTION SITE SAFETY CONTROL WITH MEDIUM-ACCURACY LOCATION DATA

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Abstract. A statistical safety control method is presented that utilizes location data from a relatively inaccurate yet cost-effective system to track workers in real time, and prevent unsafe situations at construction sites. In light of the inaccuracy of the tracking system, buffer areas are defined as statistical zones, at some distance from potential workplace hazards. Statistical alerts are created according to predefined rules when the hazard exposure of workers in those zones crosses a certain threshold. The results of tests of the method demonstrate that the model is able to successfully process the location data in order to compensate for its inaccuracy. This is done without necessitating a significant increase in the areas that are defined as being of high risk, and therefore off-limits for most workers on site. The model can thus ensure the efficiency of the construction work by restricting the size of the areas on site that are off-limits for most workers, while at the same time ensuring the safety of workers. The method can also ensure that alerts will not be ignored by using statistical rules to avoid an excessive number of alerts, and by discerning who should be the client of an alert.

Keywords: construction safety, hazard control, real time location systems, statistical process control, buffer areas, Wi-Fi.

Introduction

Various studies indicate that the incidence rate of fatal workplace accidents in the building industry, with an estimated 60,000 fatal casualties a year around the world, is higher than in any other industrial sector (Aires *et al.* 2010). The most common cause for fatal accidents on construction sites is usually falling from heights (Aneziris *et al.* 2012; Wu *et al.* 2010). The customary paper-based and manual methods (e.g., check lists, training, and arbitrary inspection) used by construction companies to ensure that the required safety measures are implemented are often insufficient in preventing accidents (Navon, Kolton 2006). For example, a major cause for falling accidents is a lack of fall protection devices such as guiderails or safety nets (Chi *et al.* 2015). 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 (Zhang *et al.* 2013).

Consequently, a number of studies have been dedicated in recent years to the improvement of safety on construction sites through the application of a Real Time Location System (RTLS) (e.g. Naticchia *et al.* 2013; Maalek, Sadeghpour 2013). A RTLS can be used to track the movement of workers and prevent accidents from occurring, thus enhancing the safety of construction workers. Currently, the main purpose of the RTLS is to facilitate an alert immediately after a worker enters an area that has been defined as being of high risk. Such an approach can be considered deterministic, and requires a highly accurate tracking system in order to be able to detect in real-time when a worker moves from a low hazard area to a high hazard area.

Highly accurate indoor tracking systems such as Ultra Wide Band (UWB) are relatively expensive technologies that require significant time and effort to deploy (Khoury, Kamat 2009). Unlike GPS, indoor tracking systems can also be used inside buildings that are under construction. Other, less expensive technologies such as WLAN-based tracking systems are economical, but provide a much lower accuracy (i.e. 1.5 to 2 m, as opposed to centimeter level positioning accuracy for UWB). Such a low accuracy is not compatible with a deterministic approach, in which any penetration into a high hazard area needs to be immediately identified. Nevertheless, a recent study underlined the importance of cost in preventing automated data collection technologies from being adopted by the construction industry (Sardroud 2015).

One solution for this could be to compensate for the expected inaccuracy of a cost-effective RTLS by signifi-

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cantly enlarging the areas on site that are defined as being of high risk, and therefore off-limits for most workers. This would ensure an alert in any case in which a worker is exposed to a high risk. However, this would also greatly reduce the efficiency of the construction processes, by allowing fewer activities to be carried out simultaneously onsite. This, in turn, is likely to prevent the actual implementation of such a strategy on most construction sites.

The economic rationale for using cost-effective yet inaccurate RTLSs may therefore imply that we might not be able to ensure worker safety by defining adjacent work areas with clear-cut boundaries, and relying solely on deterministic alerts in case these boundaries are crossed. Consequently, the solution that is pursued in this research is to develop a statistical method that can process the data provided by a cost-effective RTLS, in order to compensate for its inaccuracy. Using such a method, the efficiency of the construction work will be achieved by restricting the size of the areas on site that are off-limits for most workers, allowing for different activities to be carried out concurrently. Yet at the same time, the safety of workers will be ensured by alerting when a worker is approaching a location in which he is likely to be exposed to a safety risk. Such a statistical method will stand in contrast to the current deterministic approach for using a RTLS for safety control on construction sites, and the consequent requirement for highly accurate and expensive tracking systems.

The use of a RTLS for the tracking of workers, equipment, materials and construction processes has been the focus of a significant number of studies in construction management. Overviews of research in these technologies can be found in Taneja *et al.* (2011) and Jiang *et al.* (2011, 2012). A number of studies have addressed the question how RTLS data can be processed into useful information for safety control. Among these studies, Navon and Kolton (2006) were the first to propose 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. Carbonari *et al.* (2011) 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. The system includes boundary zones around dangerous areas, within which tracked objects are monitored in order to establish whether it is approaching the edge of the dangerous area. Teizer *et al.* (2010) and Teizer and Reynolds (2011) present 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. Chae and Yoshida (2010) applied RFID technology to prevent collision accidents with heavy equipment such as hydraulic excavators and cranes. Working area information of workers and heavy equipment on the site was used to identify dangerous situations.

The objective of this research is the development of a statistical safety control method that utilizes data from a relatively inaccurate, yet cost-effective RTLS, to alert of unsafe situations at construction sites of multistory buildings. The proposed statistical approach complements the existing deterministic methods reviewed in the previous section. In the present study, an unsafe situation is defined as one that causes workers to be exposed to hazards which were initially created by other teams of workers. While there are many methods and models available to assess the risks that the workers' own activities pose to themselves, few studies have dealt with the hazards derived from the concurrent activities of other workers on site, to which workers are also frequently exposed (Hallowell *et al.* 2011).

1. Proposed statistical method

The input of the proposed method consists of a Preliminary Hazard Analysis (PHA), which is based on the construction site layout and the project's schedule, containing the planned activities. The objective of the PHA is to identify the hazards that might be created by the processes that are planned to be carried out on site. The PHA involves a systematic survey of all the processes in the existing construction plan, and of the activities, resources and site space that these processes require, to identify the hazards that they might consequently involve. The outcomes of the PHA are used to define areas of low and high hazard on the construction site, according to an assessment of the hazards that might occur at different locations on the site in light of the planned activities at those locations.

One aspect of construction projects that differentiates them from most production processes is the fact that they are dynamic, with frequent changes in the activities that are carried out on site. In order to address such changes, the proposed method includes a process of evaluating the expected changes ahead of time, and redefining the hazard areas accordingly. Based on the project schedule and site layout plan, the work area required for the execution of each planned activity is analyzed in terms of the type of space, its location on site and the expected worker movement patterns within this space. The potential hazards that have been identified in the PHA are then associated with their locations and durations in the project. A relevant precedent for the spatial analysis implemented here is the space planning method that was developed by Riley and Sanvido (1997).

For example, when an activity is planned for the installation of curtain walls on the façade of a high-rise building, this activity entails the removal of safety barriers at the edges of the floors where the curtain walls are to be installed. The areas near the edges of the floors are consequently defined as high-hazard areas, which should be off-limits for workers who are not involved in the curtain-wall installation activity, and therefore lack the appropriate Personal Safety Equipment. The RTLS can

ensure that such workers will not stray from their designated work areas into areas in which they will be exposed to safety risks. In order to deal with the inaccuracy of the RTLS data, such hazard areas are translated into statistical zones in the proposed method, as will be explained in the next section.

1.1. Definition of statistical zones

The proposed statistical method is inspired by an existing methodology, called Statistical Process Control (SPC) (Oakland 2007). The research hypothesis was that an approach similar to SPC could be used to accommodate the inaccuracy of the RTLS, while at the same time ensuring efficiency by allowing multiple activities to be carried out simultaneously on the site. SPC is a statistical methodology for process management, which has mainly been used for quality control in manufacturing. SPC uses statistical tools to observe specific measured characteristics of the manufactured product, and identify significant variations in those characteristics. Instead of defining deterministic rules for rejecting a product that does not meet specifications, SPC assumes that some variation in the process is to be expected due to natural "common causes" such as substandard raw materials. Therefore, only a statistically significant variation needs to be addressed, and the factors causing it identified.

The assumption in SPC is that when a process is under control, the measured characteristic of the process has a normal distribution, due to natural sources of variation. This assumption is supported by the Central Limit Theorem. Consequently, the quality measurements are expected to be distributed symmetrically around the Mean (m), and relative to the Standard Deviation (σ):

1. About 68% of the measurements are expected to be up to one standard deviation from the mean ($\mu \pm \sigma$).
2. About 95% of the measurements are expected to be within $\mu \pm 2\sigma$.
3. About 99% of the measurements are expected to be within $\mu \pm 3\sigma$.

Any significant deviation from such a distribution is an indication that the process is "not in control" in terms of quality.

An application of the SPC methodology for safety control on construction sites, instead of for quality control in manufacturing, requires adjustments. In the proposed method, the distribution of worker movements relative to their designated work location is similarly assumed to be normal when under control, given common causes of variation that can be expected in the measurement data. While this assumption is supported by the results of the tests of the method, its implementation in real projects is required to fully confirm it.

Since it may be impossible to define in advance the mean and standard deviation of the workers' movements, statistical zones are defined instead for the location measurements, relative to an Upper Control Limit (UCL) (Fig. 1). All locations that are statistically above
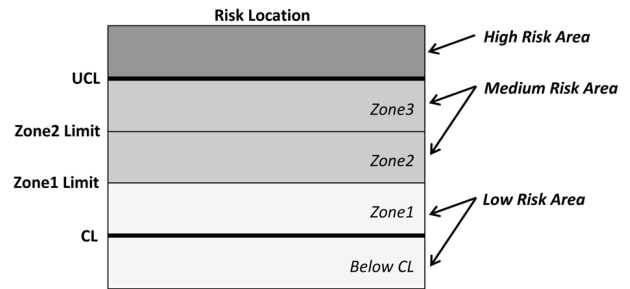

Fig. 1. Definition of statistical zones relative to the location of a workplace hazard

the UCL are related to a high hazard area, in which the safety risk is immediate and unacceptable. The objective of the method is to prevent a worker from penetrating into such a high hazard area. Therefore, each statistical zone is related to an area on the site in which there is an increased exposure to the safety risk, corresponding to its proximity to the UCL. Accordingly, there should be a lower probability that a worker will penetrate a zone with a higher hazard exposure:

1. *Zone 1*, up to a limit expected to contain about 84% of the measurements. It is related to a low hazard area.
2. *Zone 2*, up to a limit containing about 98% of the measurements, and related to a medium hazard area.
3. *Zone 3*, up to the UCL containing over 99% of the measurements, and also related to a medium hazard area.

There is thus a probability of less than 1% that a worker will be located outside Zone 3, in the high hazard area beyond the UCL. On the opposite end, at the lower limit of Zone 1, is the statistical Center Line (CL), or mean, of the worker's movement, which is considered sufficiently safe.

The statistical zones are based on a predefined maximum allowable exposure to the safety risk that has been identified. In other words, the method is a means to control the movement of workers on the site, and to proactively impose certain limits to their hazard exposure, rather than a passive representation of the expected location of workers. For example, the distance from the CL to the upper limit of Zone 2 is defined as the distance for which there should be a probability of no more than 2% that a worker exceeds it. SPC in manufacturing, on the other hand, is based on the preliminary collection and analysis of data which constitutes a statistical sample, and which is then used to define the mean and standard distribution of the data.

The hypothesis of the present research is that the statistical method can deal with the relatively low-level accuracy of a cost effective RTLS, while ensuring the efficiency of the construction processes. The method achieves this objective by providing alerts based on a statistical analysis of locations within the medium hazard areas, in addition to a deterministic alert when a pen-

etrates into a high hazard area. In practice, the medium hazard areas constitute buffers between planned work areas for specific activities, and other areas that have been identified in the PHA as being of high risk to the workers carrying out these activities, and whose location is also being tracked.

1.2. Statistical and deterministic alerts

The proposed method differentiates between three types of hazard areas:

1. *Low hazard areas*, within which the statistical Zone 1 is located.
2. *Medium hazard areas*, translated into Zone 2 and Zone 3 in the statistical method.
3. *High hazard areas*, beyond the UCL in the method.

When a worker is located in a low hazard area, the method will provide no safety alert, since the level of exposure to safety risks in this area is considered to be acceptable. When the worker is located in a high hazard area, an alert will be provided immediately. This alert is deterministic, since the exposure to safety risks in that location is considered unacceptable. The chart in Figure 2 presents the locations of a tag that was tracked in tests. The horizontal axis is the time axis, whereas the vertical axis represents the location of a tag relative to the predefined statistical zones. A black mark indicates a location for which a deterministic alert was provided, when the person carrying the tag entered the high hazard area, beyond the UCL, while not authorized to do so.

The medium hazard areas are treated as buffers, given the inaccuracy of the RTLS. Accordingly, the method

provides an alert regarding the presence of a worker in these areas only under certain circumstances, which are defined according to statistical rules. The application of SPC for quality control is similarly based on certain statistical rules. The rules that are nowadays commonly used in the manufacturing industry were defined in the middle of the 20th century by an American company called Western Electric Company (Western Electric Co. 1958). These rules can be used to detect statistical trends relative to the desired mean, based on the expected normal distribution. For example, measurements that fall within Zone 3 in the proposed method have a low probability (under 1%), and are therefore considered outside the norm.

The statistical rules used in the method are based on sequential measurements related to the predefined zones and their probabilities. They enable the detection of trends of an increasing exposure to hazards, as a worker moves nearer to the UCL, in order to provide a proactive warning of the possibility that a worker will penetrate into a high hazard area. Specifically, the probability of a trend of increasing hazard exposure occurring randomly (P_{trend}) is calculated as:

$$P_{trend} = 1/n!,$$

where n is the number of successive observations of an increase in hazard exposure. For example, the probability that 6 successive measurements will display a consistent increase in hazard exposure is less than 1%, and therefore considered to be statistically significant. An alert is accordingly provided by the method in such cases. Figure 3 presents an example for the implementation of such an
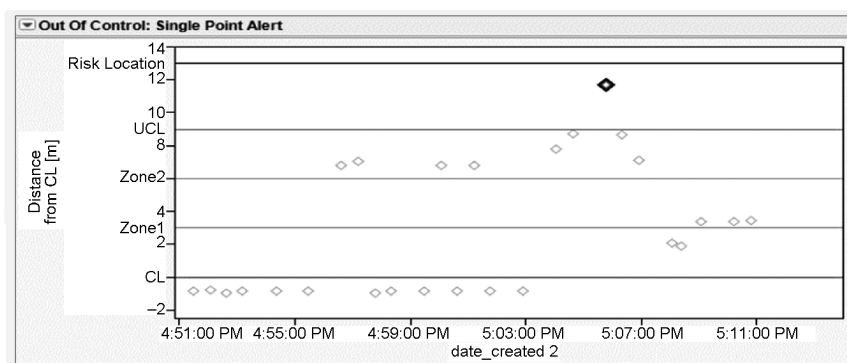

Fig. 2. A deterministic alert of a penetration into the high hazard area beyond the UCL
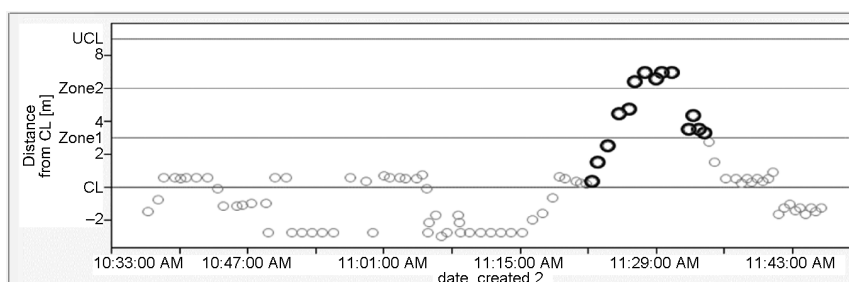

Fig. 3. A statistical alert of a worker approaching the UCL

alert, when the movements of a worker as he approaches the UCL are detected.

The proposed statistical approach thus supports proactive actions in the form of alerts, which are received before a critical exposure takes place. As will be demonstrated with the tests results of the method, this approach can ensure that alerts will not be ignored, by using such statistical rules to avoid an excessive number of alerts. It can thus increase both safety and efficiency, in terms of multiple teams working simultaneously on site. This stands in contrast to the present situation, in which areas with moderate hazard exposure levels are either ignored (therefore increasing safety risks), or included in deterministic no-entry zones (therefore reducing the efficiency of the construction processes).

1.3. Wi-Fi-based RTLS

The implementation and testing of the method was based on laboratory tests that were carried out using a Wi-Fi-based RTLS. Wi-Fi technology was chosen due its relatively low cost, compared to UWB or indoor GPS. Since Wi-Fi does not require line-of-sight between access points, the number of system components that is required is relatively low. Its low cost is expected to increase the likelihood that it will be used in actual construction projects. In fact, this type of RTLS is based on a regular Wi-Fi network that is installed in any case in most buildings, once the structure is in place. The only extra costs would therefore be those of the mobile Wi-Fi devices, which can be reused from one project to another.

The RTLS used in this research is based on active tags that are carried by the workers, and which are identified by Access Points (AP's). Through triangulation of the signals received from a tag at three different AP's, the location of the tag is determined. An advantage of the system that was used was the ability to incorporate additional types of components in the network. These included:

- *Low Frequency Exciters*: these exciters emit a low frequency signal that is identified by the tag, and causes the tag to emit in turn a signal that is identified by the AP's. By installing a Low Frequency Exciter at a narrow "choke point", the precise moment at which the tag passes this point can thus be identified.
- *Ultra Sound Exciters*: these exciters emit an ultra sound signal that that is identified by the tag. Their advantage is that this type of signal does not penetrate walls, and can therefore enable the identification of the precise location of the tag in a specific closed space.

Along with these advantages, an obvious disadvantage of the Wi-Fi-based RTLS is its relative inaccuracy. In the tests that were carried out using the AP's alone (i.e. without the exciters), the accuracy of the RTLS was found to be at a scale of about 2 meters. However, it was assumed that the implementation of the statistical method would make it possible to overcome this relatively low accuracy, which would normally be insufficient for construction safety control purposes.

An additional parameter that was taken into account in order to define the required distances from workplace hazards and the size of the statistical zones in the method was the signal transmission rate of the tags. The tags could be configured to emit a signal at different rates (e.g. every 10 seconds, or every 20 seconds, etc.). A higher rate would lead to a shorter battery life, and higher maintenance costs. On the other hand, a lower rate would have to be taken into account in the implementation of the method, since it would lead to a loss of data. An important factor in the choice of transmission rate is the type of construction site. In a larger site, in which there is less worker congestion, larger buffer areas can be defined to compensate for the loss of data due to a low transmission rate.

2. Testing of the method

The implementation and initial verification of the method was based on laboratory tests that were carried out at a university department. A Wi-Fi-based RTLS was installed in the department, composed of:

- 8 AP's that covered one floor of the department;
- 4 Low Frequency Exciters that were installed at the entrances to that floor;
- 4 Ultra Sound Exciters that were installed in specific rooms;
- 1 server for collecting and processing the location data.

During the tests, teams of participants carrying tags moved around the department and their locations were tracked. These movements were random: no attempt was made to reenact the actual movements of workers on a construction site, since this could have affected the results of the tests, without the ability to verify that the movements matched the actual behavior of construction workers. The tracked locations were converted into their distance from simulated hazard locations, according to a number of predefined scenarios. In the scenario described below, 8 tags were used.

One of the scenarios that were defined concerned the installation of a curtain wall at one of the edges of the department floor (representing the façade of a high-rise building). The tags were divided into 3 simulated teams. The first team, consisting of two workers, was a curtain wall installation team with fall-protection equipment. Two additional teams consisting of three workers each (one installing sprinkler pipes, and one installing electricity cables), did not have the Personal Safety Equipment required for working at heights, although they were carrying out activities on the same floor.

2.1. Definition of hazard areas through a PHA

A PHA was carried out to identify all the processes composing the curtain wall installation activity, and the work-

place hazards involved. One hazard that was identified was a fall-from-heights hazard, when the safety barriers at the edges of the floors where the curtain walls are to be installed are removed. When a curtain wall is installed on a section of the façade, this requires the removal of guardrails that protect workers from falling, according to the following procedure:

1. The area where the guardrails will be removed is cordoned off using a yellow caution tape.
2. The yellow caution tape is tied to the top of guardrails that will remain in place, and around columns or rubber cones inside the building.
3. Warning signs are set up outside the cordoned area.
4. Workers in the vicinity are verbally warned.
5. Workers inside the cordoned area must use a travel restraint system.

In many cases, one or more of these steps in the procedure is not fully implemented: the tape might get detached; other workers might enter the area without proper safety equipment, etc. The danger of workers falling down is exacerbated by the fact that a mast-climbing work platform is often used to install the curtain wall on the façade. This platform is enclosed by guardrails on three sides, but on the fourth side, a fall hazard exists between the platform and the facade of the building. Workers are expected to place wood planks on top of tubes that extended to the facade of the building, thus eliminating the fall hazard. However, these planks need to be removed while the platform is moving up and down the side of the building, causing open holes through which construction workers can fall down.

Consequently, in the scenario of the installation of a curtain wall the area near the floor edge was defined as a high-hazard area for the two teams of workers installing sprinkler pipes and electricity cables, who lacked the equipment necessary to prevent such an accident.

Following the identification of the hazards involved in the scenario, the distance of the high-hazard area from the location of the hazard (i.e. the UCL) was defined as being 4 meters, based on two parameters:

1. The average accuracy of the Wi-Fi based RTLS was approximately 2 meters.
2. An average walking speed of 0.5 meters per second was assumed for the workers' movements (Carbonari *et al.* 2011).

In addition, a distance of 13 meters from the hazard was defined as a safe distance, beyond which the impact of the workplace hazard would be negligible (i.e. the CL). While an alert would be provided on any penetration of a non-authorized worker beyond the UCL and into the high-hazard area, and any movements beyond the CL could be ignored, movements in between those two boundaries would be continuously monitored.

2.2. Definition of statistical zones

Following the definition of hazard areas, the department floor was divided into three different statistical zones, ad-

jacent to the high hazard area that lies beyond the UCL. While the high hazard area was off limits for all workers apart from those involved in the curtain wall installation activity, their movements within the statistical zones were monitored in order to provide an appropriate alert, in case a worker would come too close to the location of the hazard. Given that the size of the three zones is identical, the upper limit (UL_i) of each zone was defined as:

$$UL_i = CL - i \cdot \frac{CL - UCL}{3},$$

where i is the number of the statistical zone. For example, the distance of the upper limit of Zone 2 from the hazard was calculated as:

$$UL_2 = CL - 2 \cdot \frac{CL - UCL}{3} = 13 - 2 \cdot \frac{13 - 4}{3} = 7.$$

The resultant limits of the zones are specified in Table 1.

Table 1. Statistical zone division

Zone division	Distance form CL [m]	Distance form hazard [m]
CL	0	13
Zone1	0–3	10–13
Zone2	6–3	7–10
Zone3	6–9	4–7
UCL<	9–13	0–4

2.3. Simulations

According to the scenario, a simulation was carried out, in which the movements of the 8 tags throughout the department were monitored. Each one of the tags was assigned to one of the three teams in the scenario, and appropriate restrictions were defined in the method regarding the locations in which it would be permitted to reside. The duration of the simulation was 45 minutes.

The simulation was held in accordance with the definition of the previously described statistical zones. However, it was divided into two parts, each of which required an adjustment in the location of the zones in the department:

1. The first part of the simulation relied solely on the use of AP's for locating the tags. It was assumed that interior partitions had not yet been constructed on the floor at the stage at which the curtain wall was to be installed. Therefore, a worker could theoretically walk in a straight line from any point on the floor towards the hazard, without an obstruction standing in his way. The hazard was assumed to be located at the east (right) edge of the floor, and the statistical zones were defined accordingly (Fig. 4a).
2. In the second part of the simulation, Ultra-Sound Exciters were used in addition to the AP's, to locate the tags. In this part, it was assumed that interior partitions had already been constructed on the floor
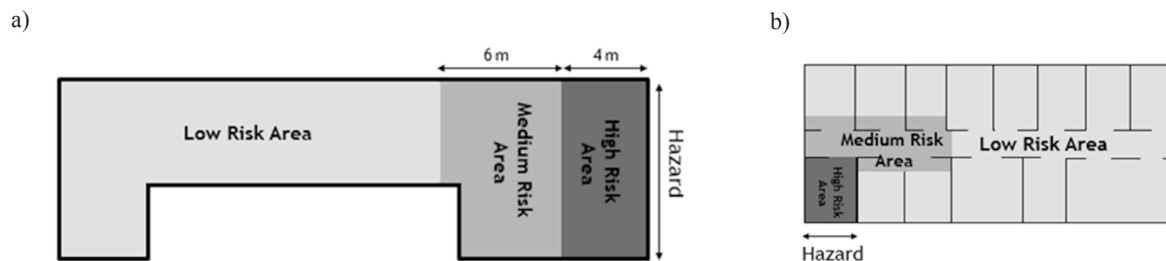
a)

b)

Fig. 4. Definition of hazard areas in the simulation

at the stage prior to the installation of the curtain wall. These partitions restricted the movements of workers, and would require them to walk along certain paths in order to approach the hazard. Furthermore, since the section of the façade on which the curtain wall was installed was enclosed by walls, and the Ultra-Sound Exciter could provide an immediate identification when a tag entered that room, a smaller high-hazard area could be defined within the perimeters of that room. The hazard was assumed to be located at the south (bottom) edge of a room, and the statistical zones were defined accordingly (Fig. 4b).

These two different variations of the same scenario underline the fact that the definition of the statistical zones on the site depend on the specific layout of the site, and that different site elements need to be taken into account, in addition to the location of the hazards themselves.

3. Method validation

The validation of the method was carried out through a comparison of the alerts produced by the method in the laboratory tests, with a manual measurement of the duration of time in which each tag in the tests was actually located in a specific statistical zone. To enable these manual measurements, the location of the boundaries of the statistical zones were marked on the floors of the department in which the tests were carried out.

In the analysis of the tests' results, and the validation of the method's success, the following two criteria were taken into account:
- The method provided an alert for every critically dangerous hazard exposure;
- The method did not provide an excessive number of incorrect alerts (i.e. "false positives").

The comparison yielded the following general results: 11% of the results obtained from the RTLS, regarding the location of a tag within a statistical zone, were found to be erroneous when compared with the correct manual measurement (Table 2). These erroneous results can be divided into a number of types of mismatches, as detailed in Table 3.

One of the criteria defined for the method's validation is that it did not provide an excessive number of incorrect alerts. The results of the comparison reveal that

Table 2. The alerts produced by the method in the laboratory tests

Sample type	Sample count	% of samples
Match	446	89
Mismatch	56	11

Table 3. Comparison of the method's output with manually collected data

Manually identified zone	Identification by model -type of error	% of samples
Low risk	No error	90
Low risk	Medium instead of Low risk	10
Medium risk	No error	87
Medium risk	Low instead of Medium risk	6
Medium risk	**High instead of Medium risk**	**7**
High risk	No error	88
High risk	**Medium instead of High risk**	**12**

7% of the alerts provided by the method regarding instances in the tests, in which a tag was supposedly in a high-hazard area, were incorrect (Table 3). In those cases, the tag was in fact in a medium hazard area – i.e. a "false positive". Nevertheless, no such an alert was provided when a tag was in fact in a low-hazard area.

The second criterion for the method's validation is that it would provide an alert for every critically dangerous hazard exposure. Here, the comparison reveals that in 12% of the instances in the tests, in which a tag was in a high-hazard area, it was incorrectly identified as being in a medium-hazard area. It may appear as if in those cases, the risk potential was high, since there wasn't any deterministic alert of the participant entering a high hazard area. However, all of those cases were in fact detected through the statistical rules in the method, and statistical alerts were accordingly produced. For example, the two encircled tag locations in Figure 5 that are identified by the method as being in Zone 3, are in fact in the high hazard area beyond the UCL (as identified in the manual measurements). However, the method in any case provided an alert concerning an excessive hazard exposure.

Therefore, all of the events in which a worker would have been exposed to a high risk, were either warned of through a deterministic alert of a penetration into a high hazard area alert (~88% of the events), or through
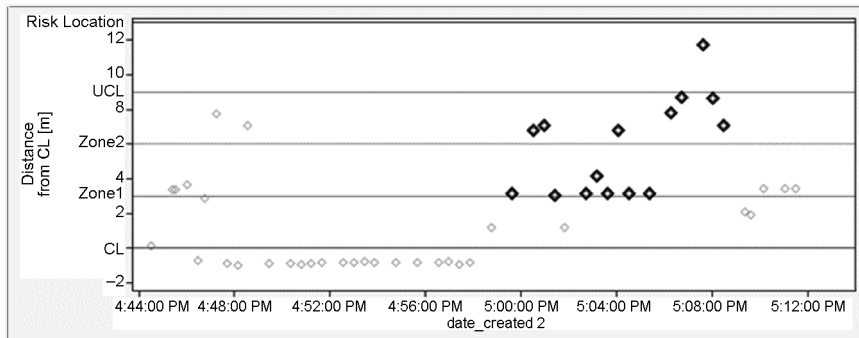
Fig. 5. Statistical alerts ensure that no unsafe situations occur despite inaccurate tracking data

a statistical alert that was produced according to the pre-defined rules in the method (the remaining ~12% of the events). In all the cases in which a deterministic alert was given, it was preceded by a proactive statistical alert. Thus, both criteria for method validation were satisfied. Nevertheless, it should be noted that an implementation of the method in a real project, will of course include an adjustment of the method's parameters in order to improve its accuracy.

Finally, the results for the tests in which Ultra Sound exciters were used, revealed their high accuracy. 100% of the cases in which a tag entered the room in which an Ultra Sound exciter was installed, were correctly identified by the method. This underlines the effectiveness of this technology, when the presence of workers in an enclosed space needs to be identified. The Low Frequency exciters were not used in these tests, but showed a similar high accuracy in other tests that were carried out. Nevertheless, it should be noted that unlike the AP's, Ultra Sound and Low Frequency exciters would not be installed anyway in the building, as part of a standard Wi-Fi network, and would therefore entail extra costs.

Conclusions

The proposed method provides a solution for the use of cost-effective yet relatively inaccurate RTLS to ensure safety on construction sites. Currently, such systems would either require an increase in the size of deterministic no-entry zones on site, reducing the efficiency of the construction processes, or an increase in safety risks. The statistical method that has been developed complements current deterministic approaches, and avoids their limitations. It can ensure an increase in both safety and efficiency, allowing multiple teams to work simultaneously on site, in relative proximity, without creating an excessive exposure to risks. At the same time, it relies on a relatively inexpensive RTLS, increasing the likelihood that it will be implemented by contractors. The results of the tests that were carried out demonstrate that the statistical method can assure that alerts it provides will not be ignored, by using statistical rules to avoid an excessive number of alerts, and by discerning who should be provided with the alert.

Future research can focus on an enhancement of the proposed method by using advanced methods for a more rigorous definition of safety risks, on which the definition of the hazard areas can in turn be based. Studies show that these can be used even in cases of limited available statistical data (Vaidogas, Juocevičius 2007) and that Bayesian updating can be used to take advantage of additional data that is collected during the implementation of the method (Vaidogas 2009).

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