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REAL-TIME ACCIDENT DETECTION USING UWB TRACKING

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Abstract: Construction industry has one of the highest numbers of fatalities among Canadian industries. Despite ongoing efforts to improve safety through trainings and promoting personal protective equipment (PPE), the number of construction fatalities in Canada is actually on the rise. Studies show that systematically monitoring construction sites and providing immediate feedback to workers are instrumental in improving safety. In particular, close monitoring of the real-time status of moving objects has been shown to improve the safety, productivity and performance on construction sites. Information and Communication Technologies (ICT) and automation techniques have shown strong potentials for identifying hazards. As a result, automated data collection to monitor the status of the construction sites has received researchers' attention in recent decades. The objective of this study is to develop a model that prevents the accidents on construction sites using automated real-time location estimations. A model is developed to detect situations that can lead to fall or colliding with moving objects based on proximity of workers to these situations. The system will use the readings from UWB tracking and generates a visualization of the moving objects on the job site in real time. When the possibility of an accident is detected, the system will send an alarm to warn the involved personnel. The functionality and efficiency of the model in detecting accidents is examined. The results of these experiments shed light on the importance of addressing the time delays caused by UWB tracking in actual real-time applications.

1 INTRODUCTION

The high number of accidents in the construction industry compared to most other industries (AWCBC, 2014a) makes a construction site one of the most complex working environments. One of the main causes of accidents on construction sites has been identified as collision of the on-foot workers with moving objects, due to workers' proximity to heavy construction equipment (Teizer et al., 2008). For example, crane operators have difficulty in relating their own position to that of the load they are moving, and this creates hazardous situations that might lead to accidents and injuries (Cheng et al., 2011). The limited spatial awareness is also the main factor of a second typical cause of accidents: falls from heights. In the United States alone, falls from heights cause the highest number of fatalities in the construction industry – almost 37% of workplace life losses in constructions in 2013 (OSHA, 2014).

Standard policies used to reduce the risk of accidents focus on increasing the training of the workers and their education about potential risks, consequences, and precautions they should take. In addition, measures that reduce hazards and provide collective protection, as well as the use of Personal Protective Equipment (PPE) are commonly required by the law. However, despite these efforts to improve safety through planning, training, and the use of protective equipment, the number of construction fatalities in Canada is actually on the rise, with a growth of about 17% since 2011 (AWCBC, 2014-b). This shows that managing safety issues only through standard safe work practices is not sufficient to avoid accidents.

This is mainly due to the dynamic nature of construction sites. The constant changes of the site during the construction phase create new hazards, and a rapid modification of the safety strategies is not always feasible. Recent studies show that systematically monitoring the work in progress and providing immediate feedback to workers are instrumental in improving the effectiveness of any safety strategy (Skibniewski, 2014). In particular, close monitoring of the real-time status of moving objects has been shown to improve the safety (Teizer et al., 2010), productivity and performance (Cheng et al., 2011 and Song et al., 2006). However, the effectiveness of manual methods is strongly affected by the safety awareness of front-line supervisors. Since the automation technologies have shown strong potential for identifying hazards and decreasing the time required for corrective actions, the development and implementation of an automatic system is receiving an increasing attention in recent years.

This paper presents part of a larger research work on improving safety on construction sites. The long-term goal of this research is to develop an accident *prediction* model that *predicts* potential accidents on construction sites ahead of time, long enough to provide perception and reaction time to the parties involved. This paper focuses only on the first step of this larger research, which is on real-time accident *detection*. Unlike *prediction*, in real-time *detection* an accident is detected only shortly before it occurs. An Accident Detection Model (ADM) is developed to analyze the estimated location of moving objects on the site (workers and equipment) provided by an UWB Real-Time Locating System (RTLS), and send a warning signal when a worker is getting too close to a hazardous situation. The ADM presented in this paper will be the basis for the development of an accident *prediction* model in the next steps of this research.

2 BACKGROUND AND LITERATURE REVIEW

Alerting workers when they are approaching a danger zone is an important part of real-time safety management. The preventative models are required for situations where the standard security procedures and PPE fail. Within real-time safety technology, the reactive and proactive safety approaches are differentiated (Teizer et al., 2010). Reactive real-time approaches collect data in real time, but require a post data processing to convert these data into information. On the contrary, proactive approaches collect and analyze data in real time, in order to alert workers of the dangers occurring in that moment.

Due to their efficiency in collecting data, different remote sensing technologies have been proposed to be used for various applications on construction sites. Radio-Frequency Identification (RFID) is one of these remote sensing technologies, largely used for inventory tracking in several industries including construction (Nasir et al., 2010). This technology has been applied also to the construction industry for position tracking, but since in principle it is not a localization technology, it requires to be used in combination with GPS to get information on the position of a tag, or with other tags of known locations dispersed through the area to cover (Saidi et al., 2011). However, previous researches showed that the estimated tags' locations are within few meters of their actual positions; even if it might appear a high accuracy level, it is not enough for preventing potential dangerous situations in a construction site. For this reason, RFID technology can be very useful for estimating the locations of construction components, but not for being applied with a safety purpose in large construction environments (Torrent and Caldas, 2009).

Ultra Wideband (UWB) is another remote sensing technology that has been explored in the literature for applications on construction sites. By using very short pulses (one nanosecond) transmitted by each tag, UWB allows the filtering of reflected signals from the original signal, offering the possibility to measure distances at the decimeter and centimeter level. Due to this accuracy, UWB has been suggested for applications where more accuracy is required, such as monitor the workers' positions on the site. Previous studies have shown that UWB offers an accuracy of less than one meter under conditions that are common on construction sites, such as the presence of metal objects, or tracking a large number of tags simultaneously (Maalek and Sadeghpour, 2013). In addition to accuracy, UWB offers other characteristics that render them suitable for the conditions of construction sites. For example, due to its high penetration ability, UWB tracking does not require line-of-sight. It also does not suffer from multipath distortion and interference (Gu et al., 2009). Furthermore, they have low installation and operational cost.

Ease of use, small and light (wearable) tags, and long range of operation have been identified as favorable characteristics of UWB tracking for construction sites (Teizer et al., 2008). For the aforementioned reasons, UWB seems to be suitable for safety management systems where accuracy is of high importance.

In recent years, a number of studies suggested the use of Real-time Location Systems for safety management on construction sites. Giretti et al. (2009) and Carbonari et al. (2011) proposed a predictive algorithm for the real-time identification of potential overhead hazards using UWB tracking system. They conducted experiments on actual construction sites and concluded that the capability of the system to identify hazards is affected by the time required by system to update the locations of the workers. Lee et al. (2012) developed a similar system that uses RTLS (without specifying which technology is used) to warn endangered workers. The workers' positions are continuously monitored by a safety manager, who manually activates a warning signal when a worker is approaching a danger area. Riaz et al. (2006, 2012) proposed a conceptual model that could avoid possible collisions between equipment and workers. In this conceptual model, it is proposed that the workers who stand in the operational envelope of a specific equipment can be identified using RFID tracking. Finally, Hwang (2012) used UWB to monitor tower crane movements in real time and prevent potential collisions. Cranes' possible movements were modeled and an algorithm was developed to predict the positions of the booms of two adjacent cranes, based only on their axial rotation. Overall, these studies showed s strong potential for the application of RTLS, and specifically UWB tracking for safety management of construction sites. However, most of these models have either not been implemented, or been used for a specific study. The objective of this study is to advance the current status of research and develop a real-time accident warning system that can be implemented in any construction sites. The study will also investigate the effect of time latency in real-time systems on safety management applications that has not been addressed in the literature before.

3 A REAL-TIME ACCIDENT WARNING SYSTEM FOR CONSTRUCTION SAFETY MANAGEMENT

The proposed Accident Warning System is composed of two parts: a Real-Time Locating System and an Accident Detection Model. The RTLS will estimate the positions of workers and equipment by means of small tags installed on moving objects (e.g. workers' safety helmets or construction equipment). The Accident Detection Model detects accidents by continuously comparing the estimated positions of tags with danger zones in real time. When the possibility of either an accident between two moving objects or a fall from heights is detected, the system will generate a warning. Due to its higher accuracy, UWB tracking is used in this study for real-time locating of the objects; however, the developed model can work with any other RTLS. The overall schematic of the system is shown in Figure 1. The aforementioned two parts of the Accident Warning System are described in this section.

3.1 UWB Real-Time Locating System

The UWB RTLS is composed of receivers (or readers), tags, and a location estimation platform (see Figure 1). To estimate the position of the tags, the readers receive the signals transmitted by the tags. One receiver is assigned as a "Master Receiver" and has two-way communications with the tags. This means that in addition to receiving signals from the tags, it can also send commands to them (e.g. activate the sleep mode when they are not moving). The other receivers are considered "Slave Receivers" and can only receive signals from the tags. Receivers are connected to each other by timing cables whose function is to enable time synchronization among them. Each receiver is connected to a Power over Ethernet (POE) switch through an Ethernet cable. Other than providing power to the receivers, this cable transfers the collected data to the platform for location estimation. When the system is activated, the tags send an UWB pulse to the receivers. Each receiver collects two types of data from the received signal: the Angle of Arrival (AOA) of the signal and the time when the signal reaches the receiver. The time difference between the arrivals of a pulse to two different receivers is referred to as Time Difference of Arrival (TDOA). As a result, the system can estimate the location of the tags through two different methods, AOA and TDOA, achieving a higher level of accuracy (Muñoz et al., 2009). When a tag starts transmitting its signal at a specified frequency, the receivers acquire the signal and transfer the data to the platform, which estimates the position of the tag and generates a log file. Each row of the log file represents a single *reading* that, among other information, contains *Date*, *Time*, *Tag ID*, and *x*, *y*, *z* coordinates of the tags at the time of reading.

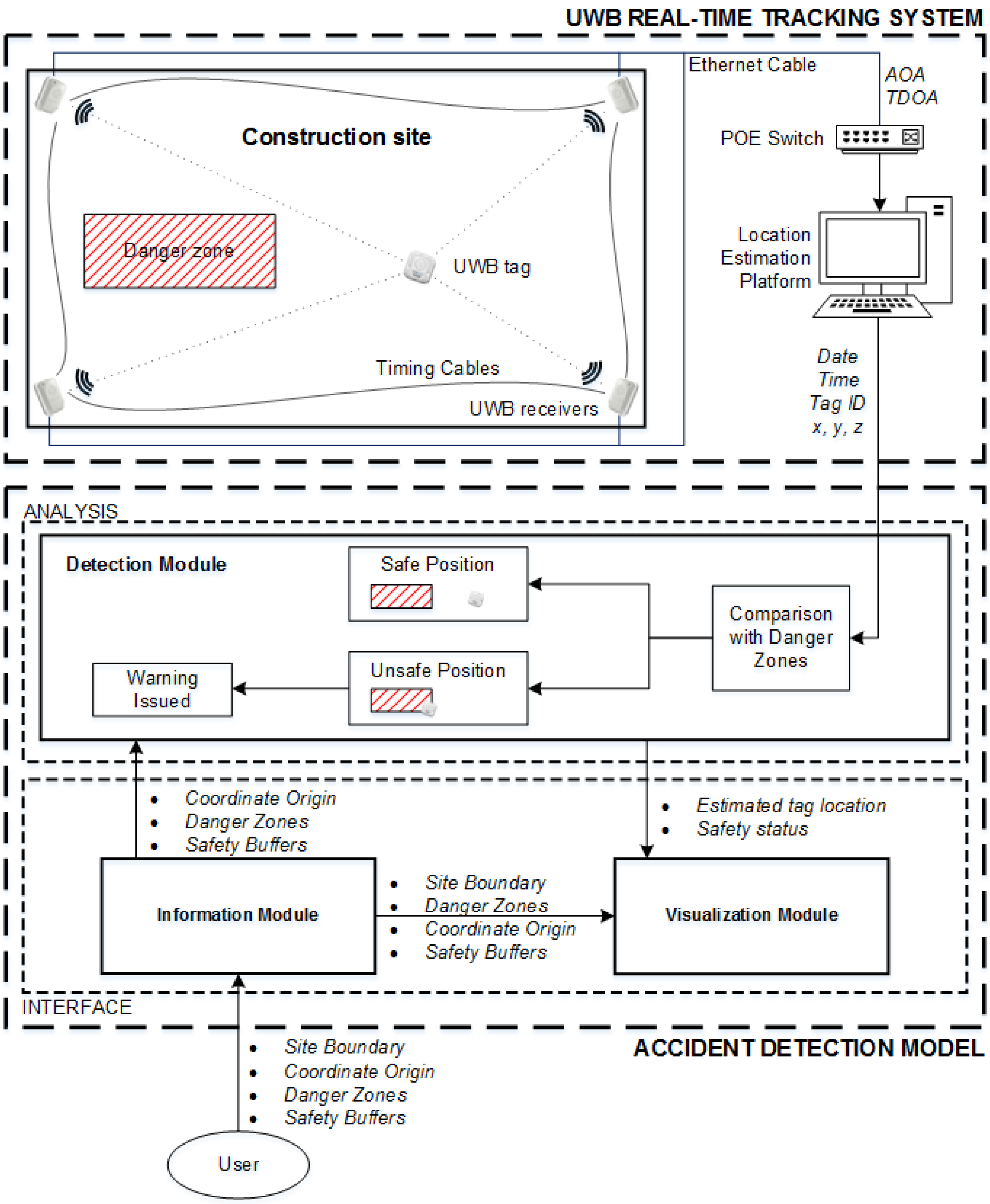

Figure 1: Overview of the Accident Warning System

3.2 The Accident Detection Model (ADM)

The developed Accident Detection Model analyzes the information about the positions of the tags, and determines when an accident is about to happen. To achieve this goal, it utilizes the estimated locations from the UWB platform and compares the positions of the tags with the boundaries of the areas on the site that are defined as danger zones. As shown in Figure 1, ADM consists of three modules, namely Information Module, Detection Module, and Visualization Module. The function of each module is discussed in detail in this section.

The Information Module acquires the project site-specific parameters from the user (e.g. site manager), namely Site Boundary, Coordinate Origin, Danger Zones, and Safety Buffers (see Figure 1). The Site Boundary defines the physical boundaries for where the Real-Time Accident Warning System is activated (i.e. the part of the construction site monitored with the system). Coordinate Origin defines the origin of the coordinate system used by the UWB system on the construction site boundary. Danger Zones defines the location and boundary of the dangerous areas on the site where workers should not approach. Finally, Safety Buffer defines the dimensions of a virtual safety area that is assumed around the moving objects that are tracked on the site (i.e. workers and equipment). In the current status of the model, size of the Safety Buffer is taken as an input from the user. However, it is worthy to mention that the value assigned to it will play a major role in achieving the intended appropriate safety level on the site since the trigger of the warning is determined by the overlap between the Safety Buffers and the Danger Zones. The dimension of the Safety Buffer has been investigated in other studies and depends on a number of factors such as the moving speed, the type of activity conducted and vicinity to danger zones (e.g. Esmaeilnejad and Sadeghpour, 2014).

The Detection Module is the analysis core of the Accident Detection Model and detects potential dangerous and accident-prone situations. The module acquires the information regarding the Site Boundary, the Danger Zones, and the Safety Buffers from the Information Module, and uses the Coordinate Origin to establish these boundaries. The module also acquires the estimated location of tags in real time from the UWB tracking system, and using the Coordinate Origin, it translates the estimated locations from the UWB RTLS coordinate system to that of the Site Boundary. For every new reading received from the UWB tracking (i.e. location estimation), the module checks whether the Safety Buffer of any of the moving objects overlaps with one of the defined Danger Zones on the site, or the Safety Buffer of another object. A detected overlap indicates an unsafe situation, and consequently a warning is issued (see Figure 1).

The Visualization Module acquires the Site Boundary, Coordinate Origin, Danger Zones, and Safety Buffers from the Information Module and generates a visualization of the site. Meanwhile, it receives the results of the analysis from the Detection Module. The translated coordinates of the tags and their safety status (whether their boundary at that instant is overlapping with another tag or a Danger Zone) are transferred from the Detection Module to the Visualization Module at every reading, and the module generates a real-time visualization of the positions of the moving objects on the site. If the status of the tag (moving object) is identified to be safe by the Detection Module, the tag will be represented in green color at the estimated position of the moving object. Red color is used when an overlap is detected to indicate a warning for a potential hazardous situation.

4 IMPLEMENTATION

The described Accident Detection Model was implemented in Processing 2, an open source Java development environment. The flowchart for the implemented tool is shown in Figure 2. At the beginning, the tool requires the parameters of the Information Module as an input (Step1). In this implementation, each worker is visualized as a circle that represents the virtual Safety Buffer surrounding the moving object (i.e. worker or equipment). The user also defines a rectangular Danger Zone through indicating four parameters: x and y of the top-left corner, and width and height of the rectangle. The user is also prompted for the location (x,y) of the origin of the UWB coordinate system on the site. The boundaries of the site can either be drawn in the development environment or loaded from an external file.

Once the tracking is initiated, the tool acquires the location estimations from the UWB tracking system (Step 2). UWB keeps a record of all the readings, including the unsuccessful ones. The developed tool identifies these and filters through the records where the system failed to read the tag, and keeps track of only the successful readings. The x, y, z of the estimated locations represent the position of the moving objects, and they are used as the centers of the circles that represent workers or equipment. The boundaries of these circles are compared with the defined boundaries of the Danger Zones, and the workers are displayed on the site plan as green or red circles, depending on whether they have a safe or unsafe status (Step 3). The tool continuously checks whether a new location estimation is available (Step 4). If this is the case, it reads the new position and repeats steps 3 and 4 (Figure 2).

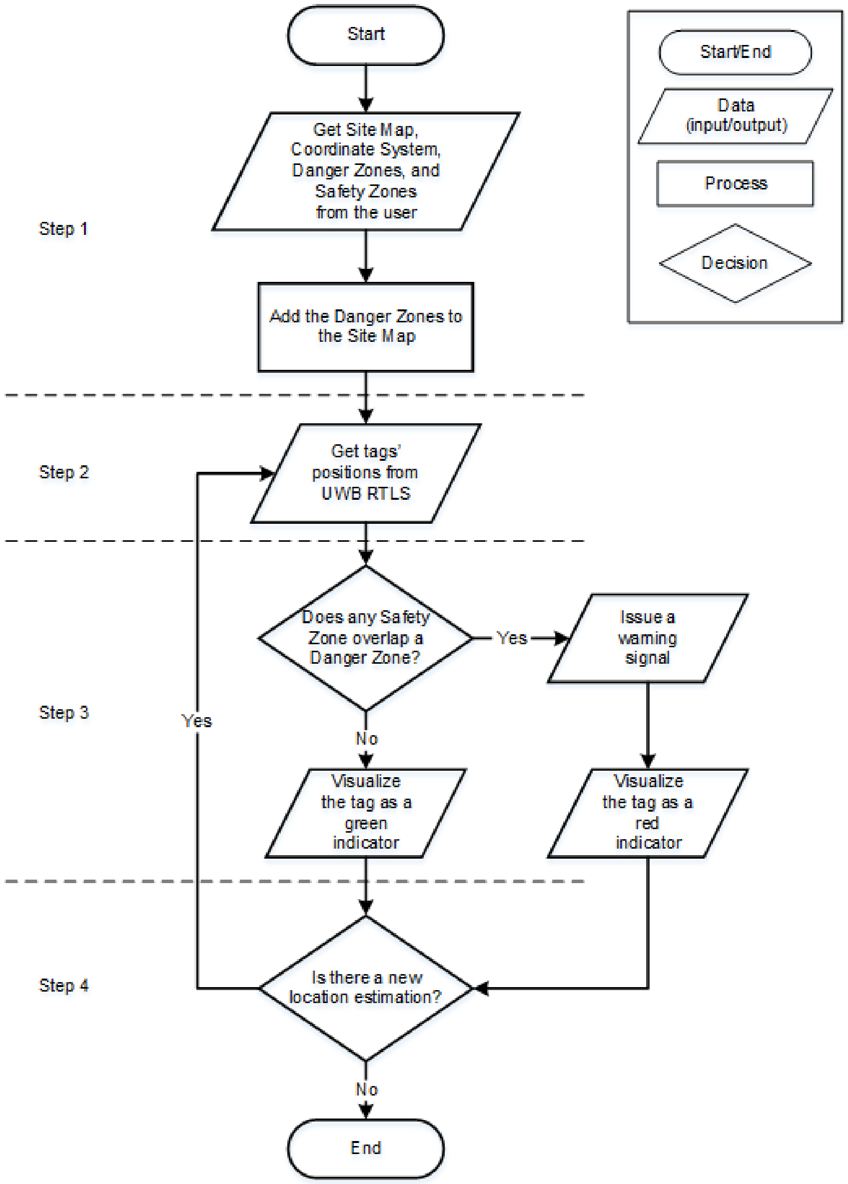

Figure 2: Flowchart for the Accident Detection Model

5 FUNCTIONALITY AND EFFICIENCY OF THE IMPLEMENTED TOOL

The functionality of the implemented tool was tested in the Civil Engineering Concrete Laboratory of the University of Calgary, which is very similar to the work environment of a construction site (see Figure 3). Eight (8) UWB receivers were installed along the edges of the lab. The developed tool was setup for this site by taking in the coordinates of the site boundary. There is a cut in the concrete floor slab of the laboratory that is used for the movement of a lift between floors. This cut is protected by fence on three sides, therefore the fourth side is identified as a falling hazard. Hence, a danger zone was created next to the open edge of this cute. Two workers were initiated in the tool. Their safety helmets were equipped with UWB tags Two different Safety Buffers were assigned to each worker, one with a diameters of 2 meters and the other 3 meters; assuming that based on their movement speed and type of activity they carry the site manager required different Safety Buffers for each. The workers were asked to carry out their normal activities in the lab. The positions of the workers were monitored using the developed tool for two time spans of 10 and 30 minutes. The tool was successfully able to identify when a worker entered the Danger Zone. In other words, every time the Safety Buffer of one of the tags overlapped with the defined Danger Zone, the color of the Safety Buffer of the worker turned into red, and an alarm signal was issued by the tool, indicating an unsafe status for that worker. Otherwise, the tag was represented by a green circle, indicating a safe status for the worker. Figure 3 shows a screenshot of the tool at a moment where Worker 1 is entering the Danger Zone.

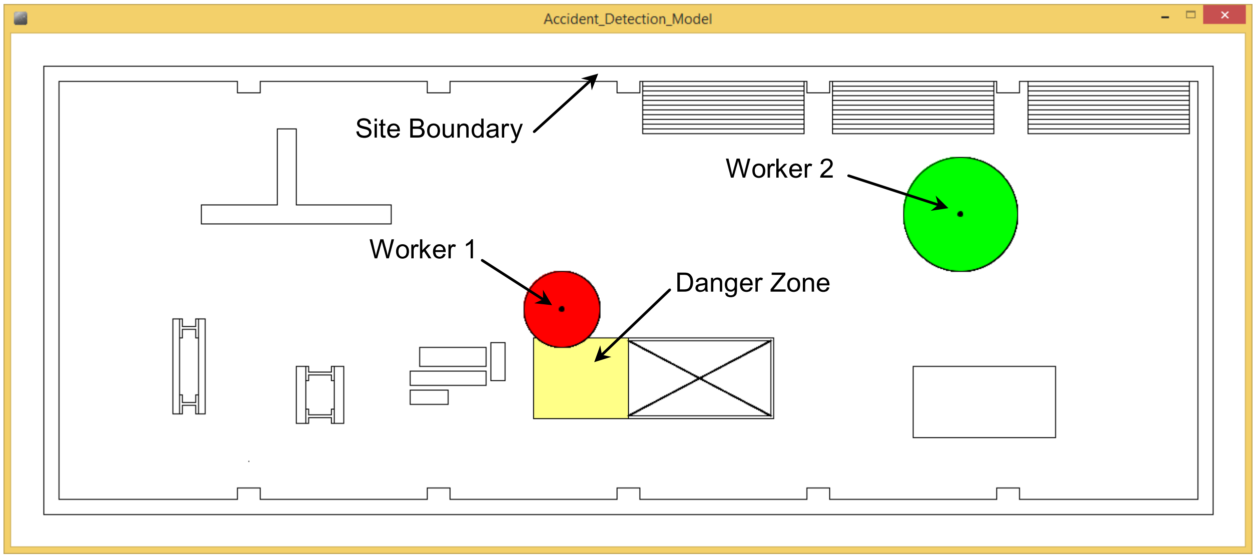

Figure 3: A screenshot of the tool developed based on the Accident Detection Model

The *processing time* of the developed tool was measured to examine its efficiency. This is the time difference between the acquisition of the estimated locations and the visualization of the workers' or equipment's positions on the screen. This time difference is important because it translates into the delay caused by the tool in generating a warning signal when an unsafe position is detected. The two aforementioned scenarios of 10 and 30 minutes were used to measure the efficiency of the developed tool. In the first scenario with the duration of 10 minutes had an acquisition frequency of 3 Hz (i.e. 3 updates per second). In the second scenario, where the duration of the safety monitoring was 30 minutes, an estimation acquisition with a frequency of 8 Hz was used. The location estimation from the UWB system is recorded in a *log* file. Each location estimation (or "reading") of the UWB is recorded in one line in the *log* file. Therefore, the number of lines, and as a result the size of the file, increases with the increase of data acquisition frequency and duration of the monitoring scenario. Table 1 summarizes the information regarding the two scenarios that were used in this study.

Table 1: Information pertaining the two scenarios used in the study

	Duration (min)	Acquisition frequency (Hz)	Number of "readings"	File size (kB)
Scenario 1	10	3	1,752	430
Scenario 2	30	8	14,724	3,696

Each scenario was simulated ten (10) times using the developed Accident Detection tool. In these simulations, for each reading, the processing time - i.e. the rime between when the information is read from the *log* file and when it is processed and a status (safe or unsafe) decision is decided by the tool - was measured. Therefore, there were 1,752 measurements for each simulation in Scenario 1 and 14,724 measurements for each simulation in Scenario 2 (see Table 1). Considering the ten (10) simulations for each scenario, 164,760 instances of the *processing time* were measured in total. The time measurements were conducted on a regular office personal computer (processor Intel Core i7-3537U 2.0 GHz, 8 GB of RAM, and Windows 8.1 64-bit operating system). The average processing times were less than 8 milliseconds for the first, and less than 41 milliseconds for the second scenario, which can be deemed negligible. The details of the processing time measurements are presented in Table 2.

Table 2: Processing time for the implemented tool in milliseconds (ms)

		Simulation Run #										**Overall**
		1	2	3	4	5	6	7	8	9	10	
Scenario 1 (n = 1,752)	Mean (μ)	9.01	8.16	8.03	8.17	8.14	7.69	7.78	5.18	7.80	7.76	7.77
	SD (σ)	2.32	2.03	1.97	2.08	2.08	2.01	1.86	2.16	2.16	2.16	2.29
Scenario 2 (n = 14,724)	Mean (μ)	41.10	39.89	39.28	41.10	41.05	40.93	40.71	40.99	40.70	41.43	40.72
	SD (σ)	3.45	4.81	5.26	3.69	3.45	3.65	3.43	3.64	6.62	4.54	4.41

Discussion: Although the measured processing times were negligible for the defined scenarios in this study, another interesting observation was made from the results. As it can be inferred from Table 2, the average *processing time* for the second scenario is 5 times more than the first scenario (40.72 ms vs. 7.77 ms). As the measurements of processing time were conducted for *individual* data acquisitions from the UWB, it was surprising to notice this time difference. After more investigations, it was realized that this time difference is in fact due to how UWB system operates, and not the efficiency of the developed tool. UWB tracking system saves the readings from one tracking session (i.e. from when system is activated until it is stopped) in a *single log* file. Therefore, and naturally, the size of the file gets larger as the time duration of the observation is longer and as more *readings* are recorded, making it increasingly more time consuming to process the file. From Table 1 it can be seen that the number of readings in Scenario 2 is approximately 8 times larger than the number of files used in Scenario 1 (due to the longer duration of observation and higher frequency used for data acquisition).

Although it is not possible to identify the precise correlation between the number of readings and the *processing time* using only the above two scenarios, some interesting understandings can be derived even with simplistic assumptions. If we conservatively assume a linear relationship, using the two data points from the above two scenarios, the *processing time* $T_{process}$ (ms) can be estimated as (Figure 4):

[1] $T_{process} = 0.0025\ N_{readings} + 3.322$

where $N_{readings}$ represents the number of readings acquired by the UWB system in one session.

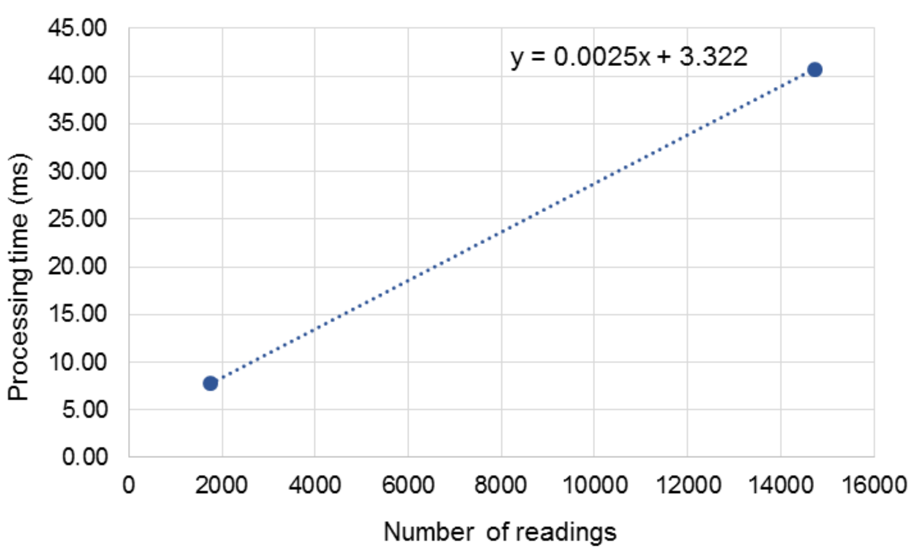

Figure 4: Relationship between *processing time* and number of readings, assuming a linear relationship

This conservative equation demonstrates an interesting point. Even if the regression coefficient in [1] may seem very small, the number of readings increases very quickly with time. For example, assuming an acquisition frequency of 8 Hz, 480 readings are recorded every minute. Consequently, the *processing time (*$T_{process}$) would increase of 1.20 ms every minute.

For a typical 8-hour working day, with an acquisition frequency of 8 Hz, the number of UWB readings by the end of the day would be 230,400. Considering the conservative assumption of linear increase, this means that the *processing time* would be about 590 ms (more than half a second) towards the end of the day. To put the importance in perspective, consider a moving object with a relatively slow speed of 10 km/hr. Half a second of time delay translates into about 1.4 meters of disposition in location of that object. It means that, even if we assume no error in the estimated location provided by the UWB, in case of detecting a dangerous situation, by the time a warning is issued the moving object is 1.4 meters inside the danger zone. It should be reminded that this estimation is conservatively assuming only a linear increase in the processing time. While more experiments are needed to define the actual relationship between $T_{process}$ and $N_{reading}$, the authors speculate that it will be higher than a first degree relationship, resulting in even larger time delays at the end of an 8-hour session. This example demonstrates the importance of time delays caused by the *processing time* for realistic applications of RTLS for safety management systems which has been looked in the past.

6 SUMMARY AND CONCLUDING REMARKS

This paper presented an Accident Detection Model that is developed to detect hazardous situations on construction sites shortly before they occur. The model uses estimations of the positions of moving objects (workers and equipment) provided by an UWB tracking system. It compares the estimated locations for the moving objects with defined danger zones as well as the safety buffers of other objects on construction sites, and when the possibility of an accident is detected, it generates a warning signal. A visualization tool was implemented based on the model using a Java development environment, and its functionality and efficiency were examined.

The results of the experiments in two scenarios demonstrated the model's capability to detect unsafe situations for a monitored moving object. Measurements were also conducted to evaluate the efficiency of the developed model by measuring the *processing time* for each data acquisition (location estimation). The results showed that the processing time for examined scenarios were negligible. However, a more in-depth investigation revealed an interesting finding. The *processing time* for each data acquisition increases gradually with time and the increase in the number of reading. It was identified that this was due to the fact that UWB RTLS records all the readings from a session into a single file. During a tracking session, UWB system adds a line to this file when a new position is acquired. This means that the delay in acquiring the estimated locations of a moving object is less at the beginning of a session, because the log file is smaller, and increases with time as the number of readings, and consequently the size of the file increases. Assuming a very conservative increase in the processing time, at the end of an 8-hour working day, the *processing time* would be more than half a second. Such delays would not be negligible for a real-time application anymore, since it translates in a considerable disposition for the moving objects.

This study shed a light on the importance of time delays in Real-Time Location Systems for safety management systems. While the research until this point has focussed on errors in location estimation caused by the RTLS, the experiments presented in this paper demonstrated the importance of time delays for realistic applications of RTLS in safety management. The future work of this study will include devising methods to acquire location estimation data directly and before it is recorded on the log file. This will not only keep the processing time at their initial negligible values, but more importantly, will mean that the processing time will remain relatively consistent for each data acquisition during a tracking session. Having a consistent *processing time* during a tracking session will facilitate applying corrective measures and as such, objectively accounting for it.

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