An Integrated INS-GPS-Raspberry Pi System Using the Time-Sphere Model for Real-Time Identification of Struck-by-Equipment Hazard

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Abstract

Struck-by-equipment hazard, i.e, contact collision between worker-on-foot and construction equipment or between equipment and equipment, is a major cause of injuries and fatalities in construction. A variety of smart technologies and systems have been developed and utilized to alleviate the risks of this type of hazard. However, most of the existing technologies and systems perform with a high rate of false alarms which have critically impeded their implementations on real construction sites. Therefore, a system performing more accurately and in real-time needs to be developed to enhance construction safety. In this context, a real-time system integrating with the 4D Time-Sphere model is developed to timely identify and alarm struck-by-equipment hazards with reduced false alarms. This system is comprised of Global Positioning System (GPS), Inertial Navigation System (INS), Raspberry Pi micro-processor and the developed Time-Sphere model. Corresponding actuation will be triggered if an unsafe situation is identified, i.e., struck-by-equipment hazard(s) are or to be presented. A controlled field experiment was conducted to evaluate the feasibility of the integrated system and the effectiveness of the Time-Sphere model in reducing false alarms. The obtained results show that average 53% of the alarms generated by the prevalent method can be reduced by the Time-Sphere model. All of the reduced alarms are false positives. The average false positive rate of the prevalent method is 29%. Moreover, it is demonstrated that the developed system is feasible and effective in identifying struck-by-equipment hazards in real time and potentially enhancing construction safety.

Keywords

Real-Time Hazard Identification; Construction Safety; Technological Innovation; Raspberry Pi; Struck by; False Alarm; 4D Model; Inertial Navigation System

1 Introduction

Construction industry has the largest number of fatal occupational injuries against to all of other sectors in many countries such as the U.S., Canada and others [1,2]. The Construction Focus Four Training program initiated by the OSHA provides safety training particularly on the top four types of hazards, i.e., falls, struck by, caught in or between, and electrocution. The largest proportion (38%) of fatal injuries in the category of struck by occurred as workers struck by equipment or falling objects [3]. Therefore, exploring an effective approach to avoid struck-by-equipment hazards has attracted attention of both industry and academia.

In recent years, a variety of smart technologies and proximity detection systems have been developed for construction to prevent struck-by-equipment hazards [4-6]. However, only a limited of them have been indeed adopted and implemented on real-world jobsites. One major reason restricting their wide adoptions in construction is the high number of false alarms (false positive and false negative) generated [7].

As thus, a more accurate and effective hazard identification method, i.e., with reduced false alarms, needs to be proposed and developed. At the same time, a capable platform which supports real-time data collection, transmission and analysis/calculation also needs to be established to enable the implementation of the developed hazard identification method in construction jobsites. Therefore, a formalized system having all of the above mentioned functions needs to be developed to enhance construction safety.

This paper introduces the feasibility of an integrated micro-processor system for real-time struck-by-equipment hazard identification. The developed integrated system uses (i) a GPS aided Inertial Navigation System (INS-GPS) for construction entities' state information collection (3D position, velocity and orientation), (ii) a Raspberry Pi coded with the developed Time-Sphere model for real-time and more accurate data analysis/calculation, i.e., reduced false alarms, (iii) ZigBee modules for real-time data transmission, and (iv) the function of notifying the involved entities of the potential safety risks. The feasibility of the developed integrated system and the effectiveness of the Time-Sphere model in reducing false alarms have been evaluated through a controlled field experiment.

2 Literature Review

Technologies such as radio-frequency identification (RFID), ultrasonic, radar, infrared and others have been utilized and developed as proximity warning systems for construction to prevent collisions. For instance, ultrasonic and pulsed radar were adopted specifically for back-over safety practices in construction work zones. The performances of the developed sensing systems (ultrasonic and pulsed radar respectively) were evaluated under different conditions including sensor installation, static test, dynamic test, and dirty sensor test [4]. In another work, Bluetooth based wireless sensing technology (iBeacon) was utilized for the detection of workers who breached into hazardous areas around equipment, along with auxiliary components to support sound alert, vibration and visualization. A wheel loader and a dump truck were used to assess the system detection distance which was the horizontal distance between beacons and receiver [5]. Magnetic field sensing and actuation technology was also applied to alert workers from being too close to heavy equipment in real time [6].

In the application of unsafe proximity identification, the measurement and determination of the hazardous areas around equipment is essential [8]. A framework integrated with six major steps for creating the hazard zones around construction equipment was presented in the work [9]. A user interface was also developed to generate the hazard zone automatically for a specific piece of equipment. However, the implementation of the developed framework is limited to the jobsites and equipment that are at a horizontal grade. In a study of Teizer [10], by analyzing the point cloud data collected from a laser scan, the equipment blind spots can be detected and determined automatically. In addition, an autonomous pro-active real-time proximity safety alert system was developed by Teizer et al. for construction equipment and workers [11].

Wireless systems have attracted extensive interests and been broadly developed and used in multiple fields in civil engineering. Crane safety and efficiency can be controlled and improved by using a wireless communication prototype that encompassed RFID, GPS, the Electronic Construction Kiosk (eCKiosk), wireless IP camera and Bluetooth intercom [12]. A wireless sensor network was established to acquire both environmental and energy data in real time for monitoring the state of a metro station [13]. In conclusion, a robust, reliable and capable wireless system plays a critical role to promote the effective management of civil projects.

It is noteworthy that most of the current solutions to unsafe proximity detection problem have a major and common shortcoming, i.e., focusing on mere distance between entities. Moreover, generally the hazardous distance or zone (i.e., the threshold) around equipment is defined in 2D space [4,9]. Also in some studies, the thresholds were defined as constant values without updating over time [4]. A dynamic workspace generation method was developed and employed to construction equipment by Vahdatikhaki and Hammad [14]. Nonetheless, not all of the detected collisions were real safety threats as the method did not consider equipment's motion and geometry along with the vertical axis. The identified drawbacks cause such prevalent sensing systems to generate a high rate of false alarms which greatly impedes their real implementations in the real world [7]. In chorus, a capable and robust wireless platform that supports the execution of a more accurate hazard identification method in a real-time manner is needed. Therefore, this paper focuses on proposing and developing effective and timely solutions to the identified gaps and needs elaborated above.

3 Research Objectives

Developing a real-time and reliable struck-by-equipment hazard identification system is the main goal of this study. Therefore, the following three objectives are included: (1) developing a more effective proximity detection method which can detect hazards and reduce false alarms; (2) establishing an integrated platform for real-time data collection, communication and analysis; and (3) conducting a field experiment to check the feasibility and effectiveness of the integrated system developed herein.

4 Methodology

4.1 Integrated INS-GPS-Raspberry Pi System

An integrated INS-GPS-Raspberry Pi system using the Time-Sphere model for real-time identification of struck-by-equipment hazard is proposed and developed in this paper. It is worth mentioning that selection and utilization of Raspberry Pi in the development of this application is attributed to its computation capabilities, small size, high integration and low cost. Raspberry Pi which acts as a micro-processor can achieve real-time sensor data acquisition, entity state analysis and system actuation.

The framework of the integrated system is illustrated in Figure 1 and the major components ((a)-(f)) are explained as below:

(a) Each entity (construction equipment and workers-on-foot) is equipped with an integrated INS-GPS module, a ZigBee module and a Raspberry Pi;

(b) The INS-GPS module [36mm(L), 49mm(W), and 25mm(H)] is used to collect entities' 3D position, orientation and velocity;

(c) The collected state information is input into the Time-Sphere model for hazard identification with a low false alarm rate;

(d) The Time-Sphere model is embedded in the Raspberry Pi in the data processing unit to analyze the gathered state information from multiple entities by taking advantage of the processing capabilities of Raspberry Pi;

(e) Corresponding actuations will be triggered if an unsafe situation is identified, i.e., struck-by-equipment hazard(s) are or to be presented, e.g., the LED lights on respective Raspberry Pi will turn on (more reliable and advanced actuation mechanisms will be explored in the next step of this study);

(f) ZigBee modules are responsible for wireless data transmission between multiple Raspberry Pis.

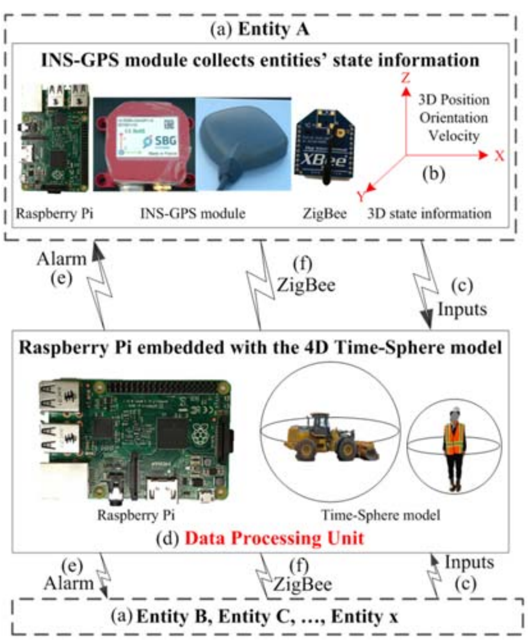

Figure 1. The framework of the integrated INS-GPS-Raspberry Pi system (images by authors)

For workers-on-foot, the developed integrated system needs to be mounted at the elevation of workers knee (e.g. on knee pads) or slightly higher. In the next step of this study, the authors will endeavor to make the device further compacted in order to be more comfortably used by workers-on-foot.

4.2 4D Model: Time-Sphere Model

As identified in the Literature Review section, generation of high false alarms is a major limitation of most of current proximity sensing systems. Therefore, the Time-Sphere model is developed and specialized to reduce false alarms through providing comprehensive solutions [15]. The hazard identification process of the Time-Sphere model is illustrated in Figure 2. The Time-Sphere model can be applied to multiple construction entities to prevent collisions. In this paper, only two entities are used to explain the model's development and evaluation.

The distinctions of the Time-Sphere model are summarized as follow:

- Along with 3D distance between entities, entities' velocity and orientation are also taken into consideration;
- Two thresholds, i.e., alert distance and warning distance, are used for hazard justifications. Alert zone around equipment and workers-on-foot is defined as a sphere in 3D space which will be used to quantify alert distance; Warning distance is dynamically adjusted over time fully in accordance with entities' moving characteristics and personnel reaction and execution time;
- The unsafe proximity query rules developed in the Time-Sphere model not only can detect the actual intersections of 3D alert zones, but also can identify the impending collisions in 3D space in a proactive manner;
- Entities' movements are not limited on a horizontal plane. Vertical motion, different altitudes, site terrain and others are also taken into account in the Time-Sphere model.

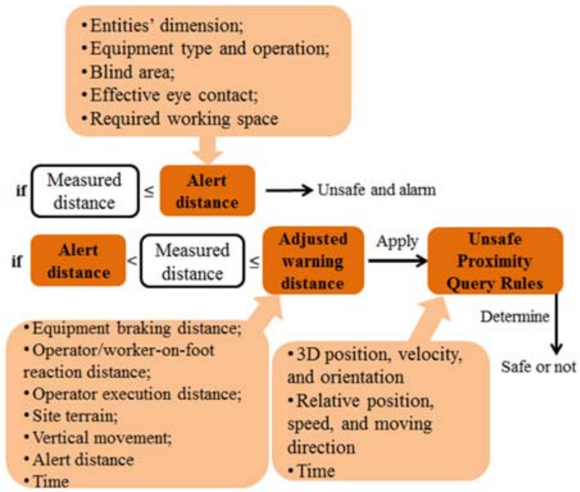

Figure 2. Illustration of the Time-Sphere model

The distance between entities is measured by mounting a sensing module on individual entities. The sensing module will collect entities' state information. Generally the distance between two sensing modules can be approximated as the distance between entities in real-world applications. To be more accurate, the distance between two sphere centers is the distance between entities. The state information of the sphere center can be calculated by using the sensor's state information with the geometry of the sensor's installation position in the sphere. Linear and angular velocity along with entities' orientation need to be considered in the calculation of the sphere center's velocity.

As the Time-Sphere model is established by considering construction entities' 3D kinematics with time, thus it can also be extended and utilized to prevent several types of collisions including materials transported in air, temporal and permanent site facilities and other dynamic elements on sites.

The three major parts involved in the development of the Time-Sphere model (see Figure 2) are explained in detail in the sections 4.2.1-4.2.3.

4.2.1 Identification of Alert Zone

Alert zone is the hazardous zone around a construction entity and is represented using a sphere in this paper. The definition is fairly self-explanatory, i.e., no entities can enter hazardous zones without authorizations. Diverse 2D or 3D shapes such as circle, cylinder and others have been used to denote the hazardous area around a construction element depending on their applications [16].

It is worth pointing out that in the study of struck by hazard prevention, the definition of a situation that is truly unsafe (true positive) or safe (true negative) is crucial. Even though the overwhelming majority of existing studies defined an unsafe situation as the collision of the 2D or 3D zones around the objects. However, no studies conclude a certain 2D or 3D shape that can represent the hazardous zone for all or one specific object. For different objects and applications, the shape that is the closest to the abstraction of the object's hazardous zone is different.

In this study sphere is adopted (see Figure 1) for three reasons: (i) the scope of this paper is to identify and predict collisions in 3D space; (ii) the unsafe proximity query rules which can reduce the generation of false alarms will use the 3D alert zone's 3D position, velocity and orientation (described in section 4.2.3); and (iii) the computational efficiency of sphere contributes to implementing the proposed system in real time. More 3D shapes with corresponding unsafe proximity query rules for reducing false alarms will be studied in the future.

The radius of the sphere for one specific piece of equipment is determined by Equation (1). The quantification of the buffer distance Δ needs to consider equipment type and operation, equipment blind spots, and effective eye contacts between operator and workers-on-foot [17].

$$\text{sphere radius(equipment)} = 0.5 \times \text{equipment length} + \Delta \tag{1}$$

For workers-on-foot, the diameter of the sphere is determined as 2 meters which is slightly higher than the average height of an adult male for safety reasons [18].

Therefore, alert distance is the sum of the radius of the involved spheres. If the distance between entities is smaller than the corresponding alert distance, the situation will be identified as unsafe.

4.2.2 Quantification of Warning Distance

Warning distance is another threshold used in the Time-Sphere model and is dynamically adjusted over time based on entities' kinematics and personnel execution and reaction time. Due to the multiple uncertainties and dynamics on jobsites, it is difficult to calculate the exact warning distance needed by the entities to avoid collisions when they come to a complete stop. The existing methods were endeavoring to quantify it as close to the needed distance as possible by taking more factors into account [9,14].

In this paper, the major factors considered in the quantification include equipment braking distance, operator reaction distance, workers-on-foot reaction distance, alert distance, site terrain (e.g., slopes and different altitudes), entities' orientation and vertical motion (see Equations (2)-(4)). Accurate quantification of warning distance helps to reduce false alarms. The Equations (2) and (3) depict situations without vertical motions. The Equation (4) represents the situation in which the worker has vertical movement.

$$\text{Warning Distance} = \text{sqrt}\{[[(\text{sphere raduis} + \text{reaction distance} + \text{braking distance})\text{of E1} \times \cos(\text{Pitch1})] + [(\text{sphere raduis} + \text{reaction distance} + \text{braking distance})\text{of E2} \times \cos(\text{Pitch2})]]^{2} + [[(\text{sphere raduis} + \text{reaction distance} + \text{braking distance})\text{of E1} \times \sin(\text{Pitch1})] + [(\text{sphere raduis} + \text{reaction distance} + \text{braking distance})\text{of E2} \times \sin(\text{Pitch2})]]^{2}\} \quad (2)$$

$$\text{Warning Distance} = \text{sqrt}\{[[(\text{sphere raduis} + \text{reaction distance})\text{of W} \times \cos(\text{Pitch1})] + [(\text{sphere raduis} + \text{reaction distance} + \text{braking distance})\text{of E} \times \cos(\text{Pitch2})]]^{2} + [[(\text{sphere raduis} + \text{reaction distance})\text{of W} \times \sin(\text{Pitch1})] + [(\text{sphere raduis} + \text{reaction distance} + \text{braking distance})\text{of E} \times \sin(\text{Pitch2})]]^{2}\} \quad (3)$$

$$\text{Warning Distance} = \text{sqrt}\{\big[[\text{sphere raduis of W}] + [(\text{sphere raduis} + \text{reaction distance} + \text{braking distance})\text{of E} \times \cos(\text{Pitch2})]\big]^{2} + [(\text{sphere raduis} + \text{reaction distance})\text{of W} + (\text{sphere raduis} + \text{reaction distance} + \text{braking distance})\text{of E} \times \sin(\text{Pitch2})]^{2}\} \quad (4)$$

Where: E means moving equipment and W is worker-on-foot; Pitch is one dimension of entities' orientation; the detailed calculations of equipment reaction distance and braking distance, and workers-on-foot reaction distance are explained in the work [15]. Equation (2) expresses the distance for two pieces of equipment and Equation (3) and (4) are for one piece of equipment and one worker-on-foot.

Based on the collected 3D velocity, the system can determine whether the studied entity has vertical movement or not. Different from the prevalent methods in which an alarm will be triggered once the warning distance is violated, the Time-Sphere model will apply the unsafe proximity query rules to further confirm whether a real safety threat exists.

4.2.3 Unsafe Proximity Query Rules

The unsafe proximity query rules are developed especially for the use in struck by hazards identification and are another effective solution to reduce false alarms. When the distance between entities is smaller than the updated warning distance, the rules will be applied to further confirm whether an alarm is needed. The unsafe proximity query rules use relative position, speed and moving direction to identify (i) the occurred collisions of spheres and (ii) the imminent collisions. The identification of the occurred and upcoming intersections between spheres is a three-dimensional problem which is converted to three two-dimensional problems. The 3D coordinate system adopted is the geographic east-north-up (E-N-U) system. The overall process of the unsafe proximity query rules is presented in Figure 3. As shown in Figure 3, a situation can be concluded as hazardous only when all three 2D planes are identified as unsafe. A 2D plane is identified as unsafe if the circles projected from spheres are overlapped or to be overlapped in the future. The approach developed to judge whether two circles will overlap in the future is illustrated in Figure 4 and is explained in detail at the end of this section. Execution of spheres collision identification by implementing the developed unsafe proximity query rules on 2D planes has two major advantages:

(1) Speed up the spheres collision detection as the computations on a 2D plane is effortless and the judgment process will stop as long as one 2D plane is confirmed as safe. In addition, consideration of the real operations on jobsites and the scope of this study, if the minimum altitude of sphere A is lower than the maximum altitude of sphere B and the maximum altitude of sphere A is higher than the minimum altitude of sphere B, only the calculation on the geographic east-north plane needs to be conducted. Therefore, whether the situation presents struck by risks or not depends on whether the geographic east-north plane is hazardous.

(2) Detect the upcoming collisions by analyzing entities' relative position, speed and moving direction, without assuming a forecast time interval and generating the corresponding 3D shapes within the time interval. Predicting the 3D shapes within an assumed time interval to check clashes is commonly used in current studies [19,20]. Taking the east-north plane as an example, the identification of two circles that are to overlap is displayed in Figure 4.

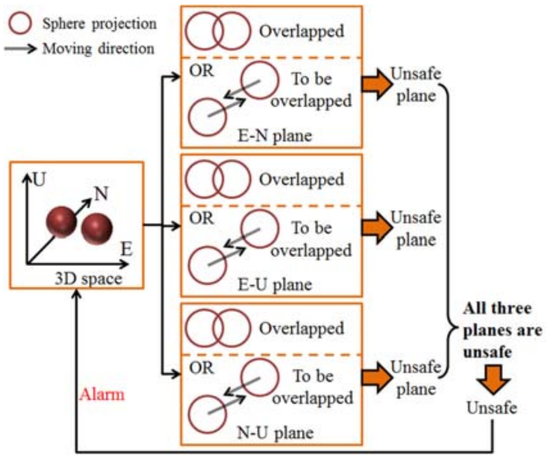

Figure 3. Unsafe proximity query rules

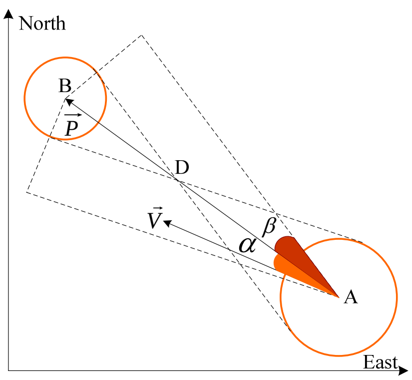

Figure 4. Identification of two circles (sphere projections) which are to overlap

In Figure 4, D is the distance between two circle centers; $\vec{P}$ is the relative position of B with respect to A; $\vec{V}$ is the relative velocity of A with respect to B; α is the angle between the vectors $\vec{P}$ and $\vec{V}$; 2β is the movement range within which two circles will overlap. Therefore, the two circles will intersect with each other if α is smaller than β.

5 Experiment and Results Analysis

A controlled field experiment was conducted to assess the feasibility of the developed integrated INS-GPS-Raspberry Pi System and the effectiveness of the Time-Sphere model in reducing false alarms.

5.1 Experiment Setting

The controlled field experiment was completed on a parking lot by using a vehicle [4.3m(L), 1.8m(W), 1.5(H)] as equipment and a person as worker-on-foot (see Figure 5(a)). Five scenarios were designed and conducted to test the integrated INS-GPS-Raspberry Pi System. It should be noted that at the current stage the developed system was only applied to two entities in each scenario to check the system's feasibility and evaluate its effectiveness. Implementation of the integrated system to multiple entities on real construction jobsites is the next step of this study.

Three out of the five scenarios were designed as "equipment struck by equipment" and the remaining two scenarios on "worker-on-foot struck by equipment". The trajectory of each entity in each scenario was roughly planned by researchers in advance. The trajectories in one scenario ("equipment struck by equipment") are shown in Figure 5(b) by uploading the collected 3D positions to the *Google Earth*.

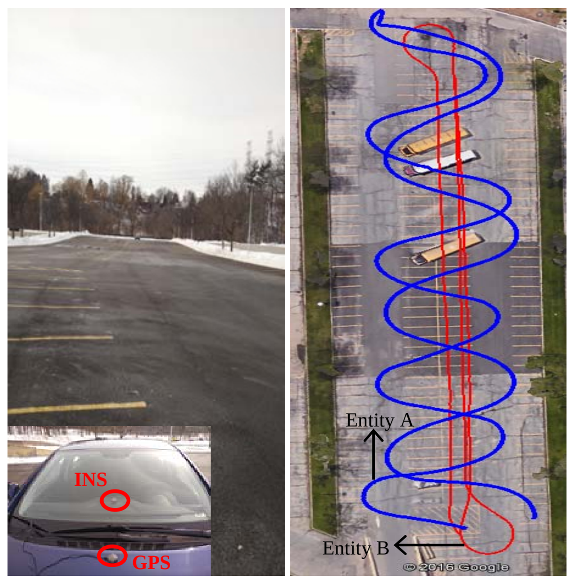

Figure 5. (a) Experiment site and the vehicle installed with the INS-GPS module; and (b) obtained trajectories in one scenario

5.2 Results Analysis and Discussion

In each scenario, entities' state information was collected by the INS-GPS module and analyzed using the Time-Sphere model which was embedded in the Raspberry Pi, i.e., the data processing unit in Figure 1. The accuracy of the INS-GPS module in localization was also assessed in advance on the parking lot. The average localization error obtained is less than 0.5m.

If the situation at any given time was identified as unsafe by the Time-Sphere model, the LED lights on the corresponding entities would turn on. As discussed, in the future work of this study, more reliable and advanced actuations will be developed and implemented to alarm entities of the potential safety risks, such as, flashing of large LEDs mounted on equipment, audible alarms and others.

During the experiment, all of the entities' state information with corresponding hazard identification result (i.e., generation of alarm or not at each moment) was recorded for further evaluations. In addition, a numerical model of the current prevalent unsafe proximity warning method (i.e., merely relying on the distance between entities to identify hazards) was also applied to the state information collected at each moment. The hazard identification results obtained by the prevalent method were also recorded. All of the saved information was used for the assessment of the Time-Sphere model's performance through two major types of analysis:

(1) Verification of the Time-Sphere model by simulation:

- For the collected state information that the prevalent method identified the situation as unsafe while the Time-Sphere model identified it as safe, the results show that the involved spheres neither intersected at the moment nor being intersected in the future (checked through simulation), even though the distance between them appeared to be smaller than the warning distance;
- For the collected state information that the Time-Sphere model identified the situation as unsafe, the results show that the involved spheres either intersected at the moment or being intersected in the future (checked through simulation), indicating that the generated alarms are rightly needed.

(2) Evaluation of the effectiveness of the Time-Sphere model in reducing false alarms

As explained earlier in the section 4.2.1, the definitions of the true positive and true negative vary depending on the application. As the Time-Sphere model was verified, it can be concluded that the alarms reduced by the Time-Sphere model are all false positives generated by the prevalent method. The obtained false positive rates (FPR) of the prevalent method are shown in Table 1.

Another indicator, i.e., reduced alarm percentage (RAP), also is used to specifically evaluate the effectiveness of the developed Time-Sphere unsafe proximity query rules in reducing alarms (Equation (5)). RAP denotes the percentage of alarms generated by the prevalent method can be avoided by the Time-Sphere model. All of the reduced alarms are false positives.

$$\text{RAP} = \frac{a_P - a_{TS}}{a_P} \tag{5}$$

Where: a_P and a_{TS} is the total number of alarms triggered by the prevalent method and Time-Sphere model respectively.

Table 1. Results of the five scenarios in experiment

Scenario	Total scans	False positives	FPR	RAP
Equip.-Equip. 1	1252	196	0.23	0.33
Equip.-Equip. 2	1138	154	0.13	0.58
Equip.-Equip. 3	1245	418	0.41	0.64
Equip.-Worker 1	1272	156	0.14	0.51
Equip.-Worker 2	1076	421	0.53	0.60
Average			0.29	0.53

According to Table 1, (1) the average FPR of the prevalent method is 29%, and (2) average 53% of the alarms generated by the prevalent method can be reduced by the Time-Sphere model.

6 Limitations and Future Work

In the conducted experiment, only two entities without vertical movements were included in each scenario. Applying the developed integrated INS-GPS-Raspberry Pi system to multiple entities for more types of struck by hazards identification on real construction jobsites is left for the future work. Performance evaluation on real-world construction jobsites is another area of future research. As such, the performance of the developed system (e.g., robustness, timeliness and accuracy) in dealing with different types of movement and altitudes will be checked. In addition, more reliable and advanced actuation mechanisms will be explored and tested on jobsites.

An accurate abstraction of the hazardous zone around entities can improve the efficiency of using the limited jobsite space and further reduce the generation of false alarms. In this way, more comprehensive analysis on false positive rate, false negative rate, sensitivity and specificity can be performed. Therefore, using other 3D shapes to develop more accurate hazard identification models also is a perspective research direction.

As the integrated system can collect entities' state information and perform hazard identification in real time, it serves as a potentially valuable platform to provide data and information for the risk analysis of struck by hazards.

7 Concluding Remarks

To detect struck-by-equipment hazards in a timely and more accurate (i.e., a low false alarm rate) manner, an integrated INS-GPS-Raspberry Pi system with Time-Sphere model was proposed and developed in this paper. The feasibility of the system and the effectiveness of the Time-Sphere model in reducing false alarms have been evaluated through a controlled field experiment. The obtained results positively indicate that the developed integrated system has the potential to be employed to multiple types of struck by hazards on jobsites. The study presented in this paper lays a foundation for the safety and risk analysis of struck by hazard and further enhancing construction safety.

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