Detecting Falls-from-Height with Wearable Sensors and Reducing Consequences of Occupational Fall Accidents Leveraging IoT

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Abstract

Labor intensive and hazardous nature of the construction activities plays an important role on the increase of the amount of accidents and fatalities on sites. One of the most important sources of fatalities occurring on construction sites is falls-from-height (FFH). Despite the various efforts for the solution over decades, the yearly statistics still indicate high amount of fatalities and severe injuries due to FFH accidents on construction sites. Medical literature emphasize that the time passed after the accident is a critical factor for avoiding preventable deaths and permanent disabilities of trauma patients. The objective of this study is to timely detect FFH accidents on construction sites by using a wearable device and to provide a real-time notification to the emergency medical team (EMT) leveraging Internet-of-Things (IoT). This is expected to maintain the earliest possible medical intervention on site in order to help reducing fatal and severe consequences of FFH accidents for construction workers. Test results of the system evaluation show that the fall is detected correctly and the alert message is sent to the prescribed addresses with 100% sensitivity. The system has shown a good accuracy for true detection of the fall height with an overall error rate of 10.8%. Another metric which shows the detection of the disconnected network time of the system has been surveyed and the results are accurate with an overall error rate of 3.16%.

Keywords

Occupational health and safety • Falls-From-Height • Internet of things (IoT) • Wearable sensors and devices
Data acquisition

25.1 Introduction

Construction industry is known with its labor intensive and hazardous nature among the other industries. The risk-prone working conditions of construction industry lead to frequent accidents and health issues on construction sites. Hence, construction workers are exposed to occupational accident risks, and many of them are subject to lose their physical integrity, have permanent disabilities, or face death correspondingly. According to Bureau of Labor Statistics (BLS) [1], construction industry takes the lead among other sectors with 899 fatal injuries occurred in 2014, where the total number of the fatal occupational injuries was 4821 for all the industries in the US. Having 4386 fatal records for the whole private industry [2], with a share of 20.5%, construction industry seems to possess at least 1 out of 5 fatal injuries occurred in 2014 among the overall private industries in the US.

Risky working conditions on construction sites may result in several occupational accidents. Some of the well-known examples are fall-from-heights (FFH), being struck-by objects, electrocution, and caught in/between objects [3]. Indeed,

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Occupational Safety and Health Administration [4] has declared "*construction's fatal four*" which are responsible for more than half (64.2%) of the fatalities occur on construction sites in year 2015, and accordingly, falls are the leading causes of fatalities among all. Another statistics that prove falls are leading fatal occupational accidents is published by BLS [2], revealing that out of 899 deaths occurred in the US on construction sites in year 2014, 359 of them were due to falls which corresponds to the biggest amount of share. These statistics reveal the serious results of occupational fall accidents in construction industry. Moreover, health and safety countermeasures undertaken in construction sites unfortunately fall short of reducing or eliminating these numbers, apparently.

Conventionally, several safety countermeasures have been undertaken to prevent occupational fall accidents, such as on-site precautionary measures including use of Personal Fall Arrest Systems (PFAS), guardrails, safety nets, etc., educating and training of personnel in accordance with safety regulations, redesigning jobs in order to reduce the impact of FFHs, and promoting safety among workers [5]. However, these precious efforts do not provide satisfying results, and unfortunately, cannot prevent FFHs being the leading cause of deaths in construction sites for many years. Therefore, although construction industry has been implementing health and safety efforts and regulations against FFH accidents; fall accidents still remain as a persistent problem [6], and the available safety measures and techniques are not sufficient yet to decrease the amount of fatalities resulting from FFH [7]. Hence, until every influencing factor behind occupational falls and regarding issues are fully understood and addressed by deploying novel approaches and techniques, it will not be hard to predict that a lot more workers will be subject to FFH accidents and probably be exposed to permanent disabilities or deaths on construction sites.

25.2 Objective and Scope

Taking the fatality rates of occupational fall accidents into consideration, remediation of the results by preventing deaths and reducing the effects of injuries that occur in construction sites, deserves particular attention and vigorous efforts.

In medical emergency domain, time is a critical factor for patients who are exposed to trauma [8]. There is a well-known fact in the medical emergency lexicon called 'golden hour' which is the first hour right after the accident has happened [8]. In this very critical time, it is very important to intervene with the trauma patient as early as possible and give an appropriate definitive care, which may save lives of critical patients or avoid future disabilities [9]. Effective use of this time is expected to reduce the mortality and morbidity rates of trauma patients [8].

Considering abovementioned factors, in case of trauma it is obvious that every minute counts against the trauma patients' benefit, and every possible period of time should be efficiently utilized on behalf of the patient. Therefore, faster and true detection of the accidents gains much higher importance in order to provide an agile response to prevent deaths, disabilities and/or serious consequences. Hence, the accident has to be accurately detected and immediately reported to the emergency personnel in order to support them intervening with the trauma patient as fast as possible.

This study investigates a solution within this scope for occupational fall accidents occurring at construction sites. This solution will use a dedicated wearable sensor for true detection of the accident, by leveraging Internet-of-Things (IoT) to provide a connection and communication with emergency medical teams (EMT) immediately after the accident happens. Thus, workers that are subject to accident trauma would find a chance to meet early medical treatment while there is still an opportunity to recover unwanted consequences of the accident.

25.3 Background Review

25.3.1 Technology

IoT

IoT proposes an approach to connect things together to communicate within a network by leveraging emerging technologies which offer affordable low-cost solutions that are widely applicable. Gubbi et al. [10] defined IoT as an integrated framework which is enabling cross-platform innovative applications to share information through connected sensors and actuators. Sensors do the abstraction of data from the physical world and communication facilities provide connection between the things. Corresponding applications can be exemplified as smart grid and energy metering, smart homes/offices/cities, intelligent transportation and smart logistics [10, 11].

IoT based technological applications might offer a great potential for real-time tracking of progress and construction resources on site [12]. This may lower the costs of monitoring activities at construction sites when compared to the traditional operation handling, where responsible site personnel periodically collect and report the required information about the resources on construction sites. Efforts and resources required for the monitoring of the resources can be minimized by taking the advantage of reliable information obtained from the use of IoT implementations. In order to have better understanding about IoT concept and its applications, definitions, relevant technologies and exemplary use cases as well as challenges and its future directions, the reader is kindly referred to [13–15].

Wearable technology

With the technological advances in electronic products manufacturing industry components to any electronic device are getting much smaller in size. The compaction of these devices due to this development enables new approaches to facilitate them on a body as part of the wearable technology for different purposes such as monitoring and tracking of humans and animals. These systems typically consist of components such as sensors to gather data from the physical world, processors to interface and interpret the data and communication units to transmit the output of the system wirelessly to their correspondents. Several use cases of these devices can be exemplified as remote patient monitoring, health tracking, wellness applications, wireless activity monitoring, performance tracking in sports and fitness, and proximity warning systems in mining industry [16]. Devices that are facilitated as hardware platforms during these activities can be smart watches, wristband sensors, disposable sensing patches, augmented reality eyewear, brain-computer interfaces and smartphones with their peripherals [13].

Wearable technology is generally favored against other systems such as ambient type sensing using external sensors and vision-based type of sensing using camera and images with regard to its low-cost hardware configuration and ease of installation. The use of wearable technology provides relatively practical and cost effective solutions [17], whereas, obtrusiveness of the wearable devices is regarded as a drawback compared to aforementioned methods [17, 18].

25.3.2 Safety Related Technology Based Studies in Construction

As being one of the most important sub-disciplines in construction domain, researchers and practitioners of occupational health and safety (OHS) management sub-discipline have been seeking solutions against safety issues using various methods and technologies at construction sites. In a review study involving advanced technological applications conducted in construction safety management field between years 1986 and 2012, Zhou et al. [19] pointed out that real-time flow of information is a crucial factor to solve safety relevant issues on construction sites and technologies such that radio frequency identification (RFID) systems, sensors, global positioning system (GPS), and wireless systems have been used in this domain and gaining more attraction towards achieving effective safety management goals. Skibniewski [20] reviewed studies that were published between 2000 and 2014 regarding deployment of information technologies (IT) applications in construction safety engineering and management and similarly reported that researchers are seeking solutions to the safety issues on construction sites like proximity detection and early warning systems that are aimed to prevent collision of on-site resources and real-time positioning of workers to track their safety status indoors and outdoors.

Another study conducted by Marks and Teizer [21] investigated the usability, effectiveness and reliability of radio frequency (RF) based proximity and warning technologies in eliminating being struck by objects which is another significant source of fatalities on construction sites. Teizer [22] presented another study including an implementation named “SmartHat” in which sensors are attached to personal protective equipment (hardhat) and the system tracks RFID tags on workers using readers for proximity detection that triggers a sound warning system during alert situations. Zhong et al. [23] proposed an IoT solution to prevent the collisions of tower crane groups on construction sites by producing position data of the crane parts using sensors where it is able to make the cranes stop if the maximum acceptable level of proximity limit is reached during any operation.

With technological advances in recent years, technology based solutions are finding much more chance to be implemented into the studies regarding safety related problems of construction industry. In this study, an IoT based approach has been implemented by deploying a cost-effective wearable device. This study aims to contribute to the literature by detecting occupational falls on construction sites with relating key attributes such as fall height and fall time and providing EMT with corresponding information.

25.4 Detection of Occupational Falls

Existing methods of fall detection can be classified into three different approaches such as (a) using ambient sensors, (b) using vision based systems such as cameras and (c) using wearable devices [24]. Ambient sensing refers to the use of several external sensors deployed around the place of interest. These sensors provide data of the physical setting in order to capture the prospecting behavior of the corresponding phenomenon such as human activity recognition. Sensors used in this type of sensing method can be RFID tags that can help to identify the user and detect the proximity of the subjects, pressure sensors that detect the presence of a subject, thermal infrared (IR) sensors to detect presence, etc. As being unobtrusive to the user on one side, ambient type sensing requires too many sensors to be deployed all around the place of interest in order to increase the accuracy of fall detection. This will inflate the cost of installation as well as computational costs regarding a consistent fall detection system.

Another approach used in fall detection studies is computer-vision-based sensing. Computer-vision type of sensing uses camera-based solutions to capture streaming images for detecting anomalies or intended behavioral patterns using image recognition techniques. Useful information is extracted by deploying computational analysis on imagery data using computer-vision methods such as object detection, object tracking and action recognition [25]. Computer-vision approach needs to have a line-of-sight with the subject of interest in order to perform these methods. Therefore, the obstructions are one of the biggest problems in vision-based techniques since analysis regarding the subject will not be performed [26]. That is, construction sites will need particular attention due to possible interferences of different subjects within the sight when it is required to track multiple workers at the same time. Considering the dynamic nature of construction sites, progressive work environment limits the use of ambient-sensing and vision-based approaches and makes them unattractive.

Establishing a trade-off of selecting the best option among these alternatives, wearable device based approach is adopted in this study to detect occupational fall accidents on construction sites. Several studies [27, 28] have also used wearable devices in their fall related studies. With using wearable devices on workers connected to wireless networks, real-time tracking of multiple workers would be viable to accomplish as soon as they remain connected.

In several studies [27–30], smartphones are promoted for being used as a wearable device. However, owners of these devices are much likely to use them for their calls, messages and schedules, and most frequently as an entertaining medium connected to the internet. Therefore, people might want to put their smartphone into their pockets for easy access. These have a potential to interrupt the working conditions of the wearable device and when the designated position of the wearable device is changed it will not function properly for its intended use in detection systems. Habib et al. [31] reported that adequacy of the built-in sensors such as the dynamic reading range of accelerometers remains as a doubtful issue for most of the smartphones. It has also been denoted that typical acceleration limits of these built-in sensors fall short during fall detection. Another technical issue is the capacity of the batteries used in smartphones. Lifetime of a fully charged battery will depend upon the energy consumption and a smartphone battery will last only about a few hours with heavy usage [31].

Accounting these, smartphones as well as smart watches are not feasible alternatives of continuous safety monitoring devices. In these cases, selection process should favor dedicated wearable devices which are designed to fit specific requirements of the corresponding problem. With this study, a dedicated wearable device is used as a data acquisition and fall detection mechanism.

25.4.1 Proposed System

Method of study

A wearable device is developed to record the acceleration data of the workers during their jobsite activities which runs a threshold based algorithm at the background and processes the data to detect occupational fall accidents instantaneously in real-time. In order to develop an algorithm that detects FFH accidents on construction sites, physics of fall behavior is studied. According to Risser et al. [32], falls from height is defined as unrestricted drop of a body from a specific position to another crushing position. From this point of view, a subject that is exposed to a fall from height will initially show a free-fall behavior. Thus, free-fall due to gravity is decided to be investigated as a first matter to determine the fall pattern of the workers during an accident. An object that is exposed to free-fall is subject to the gravity acceleration towards earth's center of gravity is a well-known fact. As can be seen from Eq. 25.1, the velocity of this falling object will increase proportional to the time passed starting from the beginning of free-fall until the collision of the object with the ground.

$$a = \partial v/\partial t \quad (25.1)$$

The gained velocity right before the collapse will be decelerated to zero in a very short amount of time during the collision of the subject with the ground. Thus, the kinetic energy of the falling human body will be damped by the body itself to return to a static position during the collapse. This is the main reason behind the major trauma happened to the human body. While the height of fall (see Eq. 25.2) increases, the time spent during the fall increases which then will increase the instant velocity of the body right before the collision.

$$h = 1/2 * g * t^2 \quad (25.2)$$

Using accelerometer sensor integrated into the wearable device, acceleration data is collected and interpreted by the developed algorithm in real-time and in case of any accident, the detection of the FFH is realized.

System architecture

According to the system architecture, as can be seen in Fig. 25.1, the wearable system is attached to the worker's body and collects real-time acceleration values which are trained in the microcontroller by the developed algorithm at the background. If the algorithm detects any FFH accident, an instant notification is sent to the main control unit wirelessly. The control unit immediately generates an alert message through the custom terminal software including information about the actual accident time, fall height, and accident address and sends it to the EMT and corresponding prescribed personnel on the construction site in no time. Thus, prior to intervention with the patient, EMT can be provided with the information indicating that the emergency situation relates to an occupational fall accident. This could enable the opportunity for a definitive care with early preparation to the intervention with the patient at accident scene which might minimize the risks of fatality and permanent losses during the most critical time period (i.e. 'golden hour') of the accident.

In brief, the approach of the system architecture involves two major steps as one of them is true and timely detection of the fall accident using a wearable device, and the other is transmitting the alert message instantaneously to the control unit in order to contact with the EMT and corresponding personnel on site. The reliability of the system exactly depends upon the output of the first step. In the next section, the developed algorithm of this study for true detection of FFH accidents on construction sites is explained.

Fall detection algorithm

This study refers to a multi-phase threshold based fall detection algorithm that trains the real-time streaming acceleration data generated due to the movements of the workers on construction sites. In order to distinguish the fall behavior from the normal work activity patterns of the worker and eliminate false positives, three successive interrogation and verification steps are applied.

Accordingly, as a first step, the first query of this algorithm surveys the continuous real-time acceleration data that is produced as a result of magnitude value of each axis to detect and verify 'free fall' behavior which is the acceleration towards earth's gravity center with gravitational force—zero g.

When free fall is detected, the next interrogation as a second step comes into play and surveys the data stream for 'collision' to the ground which yields a peak acceleration value (i.e. 4 g) as threshold in this study. In case the collision is detected, third interrogation looks for the 'steadiness' detection of the subject who is anticipated to stay motionless due to

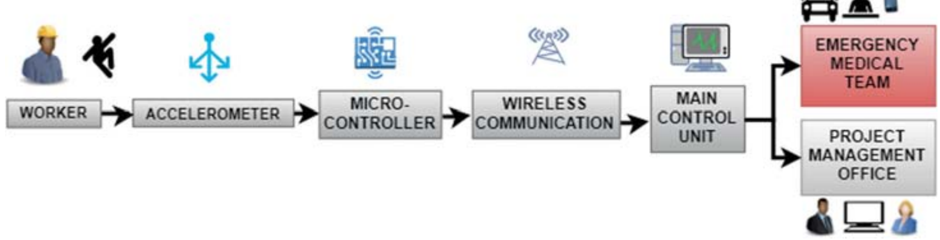

Fig. 25.1 System architecture

being exposed to major trauma. Between the second and third steps, delay timing (i.e. 1 s) is required to prevent erroneous results such as exiting the algorithm due to possible fluctuations in acceleration data during the crash with the ground. After observing dedicated amount of steadiness of the subject, the algorithm decides upon occupational fall accident and generates an alert notification indicating the details of the accident. In order to obtain reliable results, acceleration and time values are being used as threshold parameters which are based upon findings of pre-evaluation fall tests.

25.4.2 Implementation of the System

While using on a human body, the use of wearable devices should satisfy several considerations in order to facilitate their ultimate goal. Some of these required characteristics of a wearable device are size and weight of the device, location and mounting of the sensor, power supply, processing capabilities, wireless transmission range and storage of the device [16].

The wearable device should not interfere with the worker's activities for getting a desired performance. Moreover, size and weight of the device should be as small as possible. Having out-to-out dimensions of 11.4 cm by 8.2 cm by 3.2 cm, the wearable device developed for this study consists of a tri-axial accelerometer sensor (i.e. ADXL345 ± 16 g), microcontroller unit (i.e. Arduino Nano with Atmel ATmega328), wireless communication module (i.e. XBee Series2 radio with uFL antenna), storage module (i.e. MicroSD card module), a step-down voltage regulator and a power supply module containing 2600 mAh Li-ion rechargeable batteries inside. It should be noted that the power demand of any system determines the number and size of the batteries to be used and therefore, the most influential part which controls the size and weight of a wearable device is the power supply module.

Aiming higher accuracy for detecting occupational falls, the wearable device is planned to be positioned on the waist of the worker with a fastener belt tape. In similar studies, waist is used as the most common location for positioning of the wearable device [17]. The main reason for this is collecting the overall acceleration of the worker body as much as possible instead of being deceived by the free motion of body extensions during activities and to prevent false positives of the system outputs due to job activities performed using these extensions.

As mentioned above, the system uses XBee radio modules to communicate with the main control unit over a proprietary Zigbee network protocol. The system records acceleration data to a Micro SD card in order to provide data for further feature extractions regarding the accident and/or worker movements. The system is installed with a mesh networking configuration using XBee Series2 radios. The coordinator radio, installed on the main control unit side, expects alert notifications from the router nodes which are installed on the wearable devices. The system is configured to maintain the connection between nodes as much as possible. In case of any accident, alert notification can be sent to the coordinator using every node in the coverage area of the victim node.

25.4.3 Test Results

The developed system has been tested in a controlled office environment in order to obtain the preliminary results from the system in terms of fall detection sensitivity and fall height accuracy. Corresponding results are shown in Table 25.1. The results shown in the table reveal that the system is able to detect the falls from a predetermined height with 100% sensitivity. The height data output that the system calculates and sends via alert message is also obtained with good accuracy indicating an overall error rate of 10.8%. Additional tests are also planned to be performed on construction sites to emulate FFH accidents.

In case of accident detection, the system stamps time on the main control unit. However, if any connectivity issues occur between the victim node and the main control unit, the wearable system logs the duration of disconnected time in order to provide EMT with the actual accident time and reports it whenever the system provides a connection again. In Table 25.2 delay results revealed from a controlled test are shown. Connection between the wearable device and main control unit was disconnected from the network on purpose for the amount of times indicated in the second row, and then the reported delay duration from the alert message for each case was noted. The disconnection time is detected accurately with an overall error rate of 3.16%.

Table 25.1 Test results

Test case	Drop height (m)	Fall detection	Reported height (m)	Average (m)	Error %	Overall error %	Fall detection sensitivity %
1	1.50	Yes	1.251	1.341	10.6	10.8	100
2	1.50	Yes	1.266				
3	1.50	Yes	1.286				
4	1.50	Yes	1.538				
5	1.50	Yes	1.362				
6	2.00	Yes	2.028	1.779	11.1		
7	2.00	Yes	1.754				
8	2.00	Yes	1.736				
9	2.00	Yes	1.650				
10	2.00	Yes	1.725				

Table 25.2 Delay results

Test case	1	2	3	4	5
Disconnected duration (s)	30	60	90	120	180
Reported delay (s)	33	60	93	123	180
% Error	10.0	0.0	3.3	2.5	0.0
Overall error %	3.16				

25.5 Conclusions

Despite many valuable prevention strategies and efforts implemented against occupational fall accidents on construction sites, the fatality rate records do not indicate a significant decrease. Using this wearable system, physiological status of workers will be monitored using a wearable device using a tri-axial accelerometer that is developed for detecting occupational fall accidents on construction sites within the scope of safety monitoring on construction sites leveraging IoT. The ultimate expectation is to detect inevitable FFH accidents and provide an opportunity for notifying EMT in-time, in order to save lives and eliminate permanent disabilities of construction workers who are subject to FFH accidents. Another main contribution would be the information about the key attributes of the accident that is provided to the EMT such as fall height and true accident time, which might supply EMT with the crucial information for providing a true definitive care to the patient. Indeed, Locker and Morris [9] suggest that the height of fall can give information about the injury mechanism and trauma situation.

The developed system and its data can be used in forensic analysis against any possible fraud attempts that hide the accident information. As offering an imperative solution, it is designed to prevent delays that may occur due to poor site organizations. Also in case of any unfortunate events resulting with death, this data might be a useful source for further analysis that will be performed by the authorities to discover the fall pattern.

As an ethical issue, tracking of workers might be a source of concern for their privacy. In order to address this, in the proposed system the device has got its own ID rather than having an assigned personal information. Also, the location information is not monitored continuously but only automatically reported to EMT services as soon as the fall detection occurs. Thus, personal privacy of the users is taken into account during the development of the system.

The initial tests on the system have been performed by dropping the device from designated heights. The results are satisfying as findings ensure that the fall is detected correctly (100%) and the message with true fall detection time and height is sent to the prescribed addresses. The corresponding fall test heights are detected with an overall error rate of 10.8%. Another metric that shows the detection of the disconnected network time of the system has been surveyed and the results are accurate with an error rate of 3.16%. As future work, additional tests to emulate FFH accidents are planned to be performed on construction sites using dummies in order to optimize the threshold values in the algorithm and improve the outputs of the system and present an applicable and reliable solution to the problem. These test case results are expected to be discussed as part of a further study paper.

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