DETECTING FALLS-FROM-HEIGHT WITH WEARABLE SENSORS AND REDUCING THE CONSEQUENCES OF OCCUPATIONAL FALL ACCIDENTS LEVERAGING INTERNET-OF-THINGS

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DETECTING FALLS-FROM-HEIGHT WITH WEARABLE SENSORS AND REDUCING THE CONSEQUENCES OF OCCUPATIONAL FALL ACCIDENTS LEVERAGING INTERNET-OF-THINGS

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ABSTRACT

DETECTING FALLS-FROM-HEIGHT WITH WEARABLE SENSORS AND REDUCING THE CONSEQUENCES OF OCCUPATIONAL FALL ACCIDENTS LEVERAGING INTERNET-OF-THINGS

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Hazardous and labor-intensive nature of the construction industry has a prominent impact on increasing the number of occupational accidents and fatalities in construction. Falls-from-height (FFH) is one of the most important sources of these fatalities. 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. In medical literature, the time passed after the accident is critical to avoid preventable deaths and permanent disabilities of trauma patients. By combining these, a novel approach is exhibited to timely detect FFH accidents on construction sites using a wearable device to provide emergency medical team (EMT) with real-time notification including the height of fall and the time of fall information by leveraging Internet-of-Things (IoT). It is aimed to maintain the earliest possible medical intervention to the victim on site to help reducing severe and fatal consequences of FFH accidents for construction workers. A wearable system that can be used by construction workers on site has been developed and tested against FFH on construction sites using dummies. The experiments have shown promising results with 100% successful detection of FFH accidents by having an overall error rate of 5,8% in the calculation of the accident fall height. In order to detect FFH time

correctly, an additional metric that shows the detection of the disconnected network time of the system has been investigated and the results are accurate with an overall error rate of 3.16%. Additional tests have also been conducted for the validation of the system against false positives on construction sites and none of the experiments produced false alarms during tests.

Keywords: Occupational Health and Safety, Falls-From-Height, Internet of Things (IoT), Wearable Sensors, Construction Informatics

ÖZ

YÜKSEKTEN DÜŞME İŞ KAZALARININ GİYİLEBİLİR SENSÖRLER İLE TESPİTİ VE NESNELERİN İNTERNETİ KULLANILARAK KAZA ETKİLERİNİN AZALTILMASI

Dogan, Onur
Yüksek Lisans, İnşaat Mühendisliği
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İnşaat endüstrisinin tehlikeli ve emek-yoğun doğası iş kazalarının ve ölümlerin sayısındaki artışta büyük bir etkiye sahiptir. Yüksekten düşme, bu ölümlerin en başlıca kaynaklarından birisidir. İnşaat sahalarında yüksekten düşme iş kazalarını önlemek adına yapılan kıymetli birçok çalışmaya rağmen ölümlülük oranlarında kaydadeğer bir düşüş gözlenmemiştir. Medikal kaynaklarda, kaza sonrası geçen süre, travmaya maruz kalan kazazedelerde kalıcı sakatlıkların ve önlenebilir ölümlerin önüne geçebilmek için kritik bir faktör olarak belirtilmektedir. Bunlar dikkate alınarak, inşaat sahalarında yaşanan yüksekten düşmelerin giyilebilir sensörler ile anlık tespitini yapacak ve nesnelerin interneti kullanılarak acil yardım ekiplerini gerçek-zamanlı bilgilendirecek bir sistemi içeren özgün bir yaklaşım sergilenmiştir. Bu yolla, kazazedeyi mümkün olan en kısa zamanda tıbbi müdahale ile buluşturarak kazanın ciddi ve ölümcül etkilerinin azaltılması amaçlanmıştır. İnşaat işçilerinin sahada kullanabileceği bir giyilebilir aygıt geliştirilmiş ve geliştirilen bu sistem şantiyede cansız mankenler kullanılarak testlere tabi tutulmuştur. Yapılan deneyler sonucunda, düşmenin tespitini %100 başarıyla yapan sistemin, hesaplanan düşme yüksekliğini de %5,8'lik genel hata payıyla verdiği gözlenmiştir. Düşme zamanını doğru şekilde belirleyebilmek için, yaşanabilecek ağ bağlantısı kopukluğu gibi durumlarda sistemin bu bağlantısızlık süresini doğru tespiti için de ek testler yapılmış ve %3,16 genel hata payıyla hassas sonuçlar elde edilmiştir. Ayrıca, inşaat sahalarında yaşanabilecek yanlış alarm durumları için sistem doğrulama testleri gerçekleştirilmiş ve hiçbir denemede yanlış alarm üretimi gerçekleşmemiştir.

Anahtar Kelimeler: İşçi Sağlığı ve İş Güvenliği, Yüksekten Düşme, Nesnelerin İnterneti, Giyilebilir Sensörler, İnşaat Bilgi Teknolojileri

To my beloved family,

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LIST OF ABBREVIATIONS

ABBREVIATIONS

BLS	Bureau of Labor Statistics
FFH	Falls From Height
OSHA	Occupational Safety and Health Administration
PFAS	Personal Fall Arrest Systems
IoT	Internet of Things
EMT	Emergency Medical Teams
PPE	Personal Protective Equipment
CFR	Code of Federal Regulations
IMIS	Integrated Management Information System
DAFW	Days Away From Work
IT	Information Technologies
RFID	Radio Frequency Identification
WSNs	Wireless Sensor Networks
CC	Cloud Computing
WiFi	Wireless Fidelity
IR	Infrared
GPRS	General Packet Radio Services
IEEE	Institute of Electrical and Electronics Engineers
MEMS	Micro Electro-Mechanical Systems
CPU	Central Processing Unit
PCs	Personal Computers
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
RF	Radio Frequency
LED	Light Emitting Diode

BIM	Building Information Modeling
AR	Augmented Reality
TCP/IP	Transmission Control Protocol / Internet Protocol
UHF	Ultra High Frequency
SHM	Structural Health Monitoring
OHS	Occupational Health and Safety
GPS	Global Positioning System
UWB	Ultra-Wideband
PTD	Prevention Through Design
US	Ultrasound
IMU	Inertial Measurement Unit
ADL	Activities of Daily Living
AAL	Ambient Assisted Living
LDRs	Light Dependent Resistors
SVM	Sum Vector Magnitude
URL	Uniform Resource Locator
METU	Middle East Technical University

CHAPTER 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 Figure 1 released by Bureau of Labor Statistics (BLS, 2016), 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 (BLS, 2014), 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. The fatality rates of construction industry are also not better in Turkey as the numbers indicate that 30.8% out of 1626 deaths due to occupational accidents were in construction industry in 2014 (Bilir 2016).

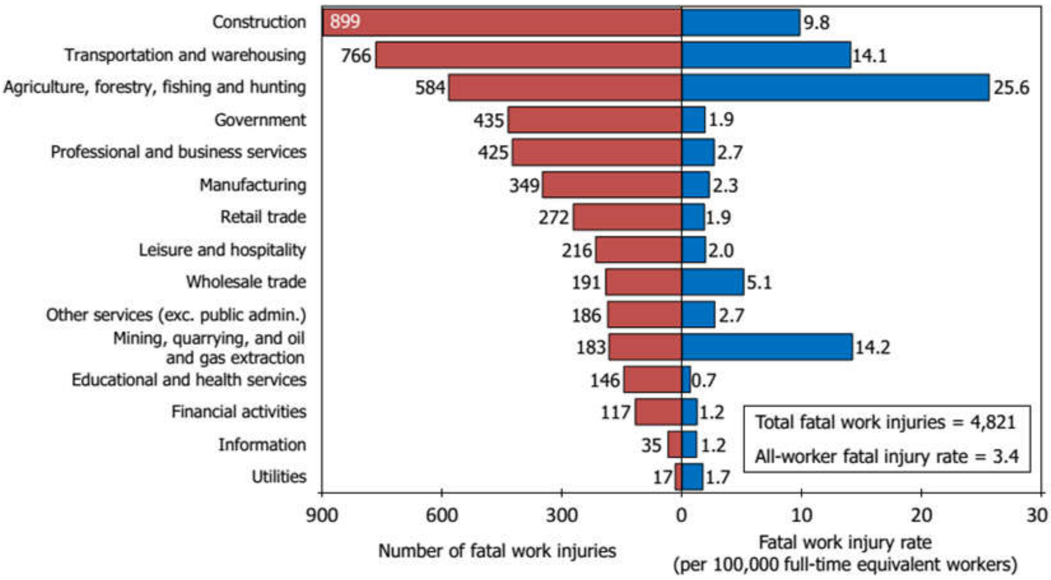


Figure 1 Number and rate of fatal occupational injuries by industry sector, 2014 (BLS, 2016)

Risky working conditions on construction sites may result in several occupational accidents. Some of the well-known examples are falls-from-height (FFH), being struck-by objects, electrocution, and caught in/between objects (Wu et al. 2010). Furthermore, consequences of these accidents can be classified according to the severity assessment method presented in Rozenfeld et al. (2010). Correspondingly, the accident outcome can be; 'minor injuries' that result in only up to one-day lost-time and cause wounds and scratches, 'medium injuries' that cause bone fractures and burns which result in longer absence of the worker, 'severe injuries' that cause permanent disabilities, and 'deaths'. Applying this scale, occupational fall accidents considered to cause 'severe injuries', and result in permanent disabilities, and deaths. Indeed, Occupational Safety and Health Administration (OSHA, 2017) 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 (2014), 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. The situation is no different in

Turkey. Gürcanli and Müngen (2013) investigated through 1117 expert witness reports submitted to criminal and labor courts in Turkey between 1972 and 2008, and found out that falls account for 54.1% among all fatal occupational accidents within these records, followed by being struck-by objects with a share of 12.9%, and collapses with a share of 9.9%. 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 (Nadhim et al. 2016). 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 (Siddiqui 2014), and the available safety measures and techniques are not sufficient yet to decrease the amount of fatalities resulting from FFH (Chan et al. 2008). Moreover, the success of the conventional methods undertaken against falls in construction sites, such as safety training, is arguable as they are measured by subjective means like surveys through professionals (Jebelli et al. 2016a). 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.

1.1. 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. Unless otherwise is done, inadequacy or inefficacy of prevention strategies against occupational fall accidents will continue to cause to be the main reasons for fatalities, loss of physical integrity with permanent disabilities, and/or long-term costly medical treatments.

In medical emergency domain, time is a critical factor for patients who are exposed to trauma (Lerner and Moscati 2001; Harmsen et al. 2015). 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 (Lerner and Moscati 2001; Rogers et al. 2015; Harmsen et al. 2015). 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 (Locker and Morris 2003). Effective use of this time is expected to reduce the mortality and morbidity rates of trauma patients (Harmsen et al. 2015).

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.

1.2. Research questions

The fatality rates due to occupational falls at construction sites do not show a significant decrease. Until every counter-measure against fall accidents that occur on construction sites have been investigated and corresponding measures have been taken to defeat falls and their serious outcome totally, the reduction of the consequences of these accidents presents a gap in the literature. This gap requires a novel approach to mitigate the overall results of this problem. Considering the criticality of time right after the accident, a wearable device was developed to propose an IoT based system in this study. The developed system is expected to provide a medium for prompt rescue of the victims that are exposed to FFH at construction sites, which then will provide an opportunity for preventing deaths, disabilities and/or serious consequences of the accidents. To achieve this, the accident must be timely detected and reported in no-time to the emergency personnel in order to guide them through the accident scene immediately and provide them with the key attributes of the accident such as the fall height and fall time information. For this reason, below mentioned research questions are defined to be addressed throughout this study.

RQ1: How can FFH accidents be detected timely?

RQ2: How accurately the height of the FFH accidents can be detected?

RQ3: How can FFH accidents and their attributes be communicated to emergency personnel?

1.3. Flow of the document

In the following pages, a background review of this study including occupational falls, relevant technology, and technology based studies in construction, technology based studies in safety domain, and fall related technology based studies, specifically, are presented in Chapter 2. Chapter 3 presents the methodology of this study that explains how FFH accident can be detected at construction sites and what is needed to be done to achieve a better result considering technology selection, system architecture, detection algorithm, and overall system development and implementation. Chapter 4 presents the experiments that have been conducted at a real construction site environment with using dummies and their results and performance for system validation. Chapter 5 finalizes the study by presenting a discussion of the results, including limitations of the study and potential future work.

CHAPTER 2

BACKGROUND REVIEW

2.1. Occupational fall accidents

Construction workers are subject to various accident risks on construction sites due to the hazardous nature of construction industry. Risk-prone working conditions on construction sites may alter due to project-specific factors such as atmospheric condition of the workplace, construction type, area of the site, dimensions of the structure and necessity of the use of heavy equipment and materials during construction. Considering large-scale complex construction projects, working at heights becomes a requirement for many activities in these projects, which then generates the risk of occupational fall accidents on construction sites.

OSHA (2015) mandates to take countermeasures against occupational fall accidents for heights over 1,8 meters (6 ft.) on construction sites. Due to this limit, workplaces that employees are exposed to FFH risks on construction sites can be exemplified as roofs, scaffolds, ladders, openings, fixed and mobile platforms, and vehicles (Huang and Hinze 2003). Falls that occur in these places can have several causes including *individual factors* such as body movement patterns, distraction, inadequate capacities and incorrect use of personal protective equipment (PPE); *work related factors* regarding excessive and atypical efforts, deficient work implementations and removal of protective measures; factors related to *tools and equipment* such as use of unsafe ladders and tools, and failures in the mechanical parts; and *managerial and environmental factors* such as lack of guardrails, poor scaffolding, accessible hazardous areas, exposure to falling objects and products with harmful contents (Chi et al. 2005). Another study, from Hu et al. (2011), has revealed three most mentioned causes of falls as ‘working surfaces and platforms’, ‘workers’ safety behaviors and attitudes' and 'construction structure and facilities' which stands for the stability of the structure's framework and the reliability of the construction equipment. A general list of fall places and causes of falls regarding these places are given in Table 1.

Table 1 Fall places and causes of falls - reproduced from (Chi et al. 2005)

Accident event	Cause of fall
Fall from scaffold, staging	• Lack of complying scaffold • Bodily action
Fall from building girders or other structural steel	• Bodily action • Improper use of PPE
Fall through existing floor opening	• Unguarded opening • Inappropriate protection • Removal of protection measure
Fall through existing roof opening	• Poor work practices
Fall down stairs or steps	• Unguarded opening
Fall from roof edge	• Bodily action • Being pulled down
Fall through roof surface	• Lack of complying scaffold
Fall from ladder	• Overexertion and unusual control • Unsafe ladder and tool
Jump to lower level	• Poor work practices

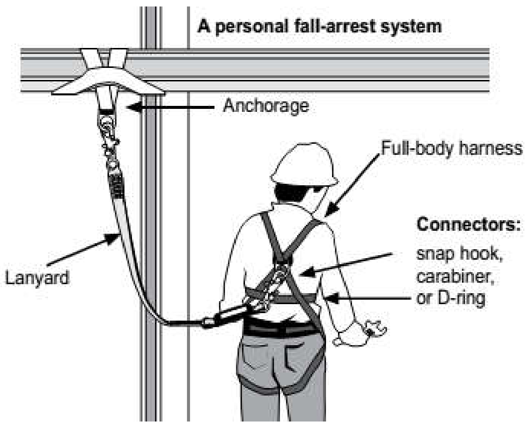
In order to address occupational fall accidents, abovementioned factors are needed to be thoroughly studied in order to eliminate or take under control them using control measures and interventions against accident risks occurring at construction sites. A hierarchical general approach of control measures for occupational falls is applied at construction sites including, starting from the highest effective, elimination of risks by changing the work pattern, substitution of methods used for the corresponding task, use of engineering controls such as guardrails, employing administrative controls regarding safety rules and procedures, and the use of PPE, respectively (Guo and Goh 2017).

Construction workers that are exposed to FFH risks at site (e.g. work at heights above 1,8 meters) are bound with the regulations for fall protection. In the US, provisions for safety issues on construction sites are indicated under '29 Code of Federal Regulations (CFR)' in 'Part 1926 - Safety and Health Regulations for Construction'. Within this standard '1926 Subpart M – Fall protection' covers the regulations and provisions for construction workers that are exposed to FFH risks on construction sites. The subpart is structured as below:

- 1926.500 - Scope, application, and definitions applicable to this subpart.
- 1926.501 - Duty to have fall protection.
- 1926.502 - Fall protection systems criteria and practices.
- 1926.503 - Training requirements.
- 1926 Subpart M App A - Determining Roof Widths - Non-mandatory Guidelines for Complying with 1926.501 (b) (10).
- 1926 Subpart M App B - Guardrail Systems - Non-mandatory Guidelines for Complying with 1926.502 (b).
- 1926 Subpart M App C - Personal Fall Arrest Systems - Non-mandatory Guidelines for Complying with 1926.502 (d).
- 1926 Subpart M App D - Positioning Device Systems - Non-mandatory Guidelines for Complying with 1926.502 (e).
- 1926 Subpart M App E - Sample Fall Protection Plan - Non-mandatory Guidelines for Complying with 1926.502 (k).

Requirements and duties such as providing strong and structurally secure walking/working surfaces and protecting sides and edges above 1.8 meters with using guardrail systems, safety nets or personal fall arrest systems for fall protection that are mandatory for employers running construction projects are presented in 1926.501. Several common fall protection systems are exemplified in Figure 2. Other particular points are also indicated in the same article including leading edges, hoist areas, holes, excavations, etc. In 1926.502, application criteria for the systems required to be installed such as guardrails, safety net systems, positioning device systems and covers to apply protection systems in aforementioned places, are explained. Workers that are exposed to fall risks are trained by the employer according to the criteria indicated in 1926.503. Non-mandatory application guidelines that can be followed by the employers through their prevention practices are present in 1926 Subpart M App A down to E. In addition, it has been noted that, among abovementioned preventive measures, it is claimed by Navon and Kolton (2006, 2007) that only guardrails provide preventive action for FFH accidents and other measures are oriented towards preventing injury by intercepting the fallen worker.

The roles and responsibilities of the contractors and workers during work are subject to the regulations of "Law No. 6331: Occupational Health and Safety Law" in Turkey. The law states legal provisions in health and safety issues for general industry. Occupational health and safety requirements and duties in construction industry are established with an extension to this law as "Occupational Health and Safety Regulations in Construction Works". Rules for work at heights such as preventive and protective measures including the use of guardrails, personal fall arrest systems and safety nets against falls are instructed under "Minimum Health and Safety Requirements for Construction Areas" subsection. Further detailed specifications and requirements for the installation and use of guardrail systems, fall arrest systems and safety nets are stated in the "Attachment – 5" to this regulation. In the regulation, 'work at height' is defined as the work that is conducted at elevations at which it is possible to get injured due to falls. Corresponding safety measures required to be undertaken against falls at these workplaces will be in accordance with the instructions included in these regulations.



a) A personal fall arrest system (Oregon OSHA 2017)

b) A fall restraint system (Oregon OSHA 2017)

c) A guardrail system (OSHA 2015)

d) A safety net system (OSHA 2015)

Figure 2 Protective measures for FFH accidents

Several researchers studied falls and their contributing factors regarding the use of fall protection on construction sites. Using the OSHA IMIS dataset regarding accidents between 1997 and 2012, (Kang et al. 2017) found out that 70.7% of the victims were not using fall protection at the time the fall accident occurred and another 17.9% of them were using it improperly based on 2949 accident investigations that made the fall protection information available to the public. Similarly, Beavers et al. (2009) analyzed 166 fatal case files resulting from OSHA investigations between 2000 and 2005 and denoted that ‘having no fall protection’ and ‘improper use of fall protection’ were found as the leading contributing factors to the falls occurred during the steel erection works. Based on the findings from their analysis of fatalities occurred in steel erection works, Beavers et al. (2009) concludes that OSHA investigation reports are short of comprehensive information and in order to develop more proper intervention strategies they should include more information than only citing the violations.

Occupational fall accidents may produce several consequences ranging from fatalities to severe injuries due to the trauma that victims are exposed to. Other possible resulting impacts of fall accidents may be suffering due to injuries, delays in the construction schedule, loss in productivity, higher insurance premiums, etc. (Hinze and Russell 1995). One of the consequences of the occupational falls that worth to mention is the cost of accidents occur on sites. Due to the fact that victims are exposed to trauma that impairs the integrity of their bodies, most probably they will not be able to work for days and weeks unless it was a fatal accident resulting in death. Several research (Bobick 2004; Bobick et al. 2010; Cressler and Moore 2016) have studied implications regarding the absence of the worker after the accident and calculated the cost effect of fall accidents on construction sites. According to Bobick et al. (2010), severity of the fall accidents can be categorized using the days away from work (DAFW) of the victims and the range can be between 1 DAFW to several weeks or months away from the work correspondingly where they also reported that the median value for all types of falls to a lower elevation concluded 14 DAFW. This reveals an extra burden to the employer/contractor while the cost of these accidents can be much higher in response. Although there are several approaches for calculating the cost of the occupational fall accidents, one simplistic example has been presented by Bobick et al. (2010). According to this study, a direct cost analysis based on missing days was made by using 2006 cost data of fall-to-lower-level accidents and using the numbers of workers who are exposed to falls through roof holes, floor holes, and skylights that missed six or more workdays an estimated value of $71,000 was calculated per each individual case. In addition to direct costs, indirect costs of the accidents such as first-aid expenses, damage or destruction of materials, clean-up and repair costs, construction schedule delays, lowered employee morale, etc. should also be accounted as they might be up to four times the direct costs of the accidents (Schaufelberger and Lin 2014). Birgonul et al. (2016) have also reported that legal sanctions and compensation costs can be significantly high for occupational accidents.

2.2. Relevant technology

With the advent in technology, there is significant progress in adopting technology-based solutions for engineering problems. Lower costs of off-the-shelf available electronic products and extended applications of wireless communication technologies have been increasing this progress for many years. Also, developments in the information technologies (IT) have found increasing application areas in the overall industry and will continue to provide new implementation opportunities by connecting different disciplines with the development of networking capabilities and internet services. In this study, a wearable technology-based solution has been developed which utilizes a microcontroller unit that reads acceleration data from a sensor, processes it and shares information via wireless sensor networking. The developed system is promoting the use of IoT applications in the construction industry while wirelessly connecting workers to a safety monitoring system. In order to have a better understanding, abovementioned technologies as well as their applications regarding construction industry and construction safety field, will be discussed to present a background review in this section.

2.2.1. Internet of Things (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. (2013) 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. Thanks to emerging technologies, derivation of digital data from physical world activities is greatly simplified with highly available sensors and wireless communication capabilities which provide promising opportunities for reliable real-time data processing applications. Such IoT implementations take place at different areas from small to enterprise level applications, allowing users to remotely access and retrieve data over networks and control them over the established connectivity. Simply put, IoT applications ease the abstraction of physical world data and its use in high level applications by end users while connecting anything at anytime and anywhere. An illustration of the application areas and their uses can be found in Figure 3.

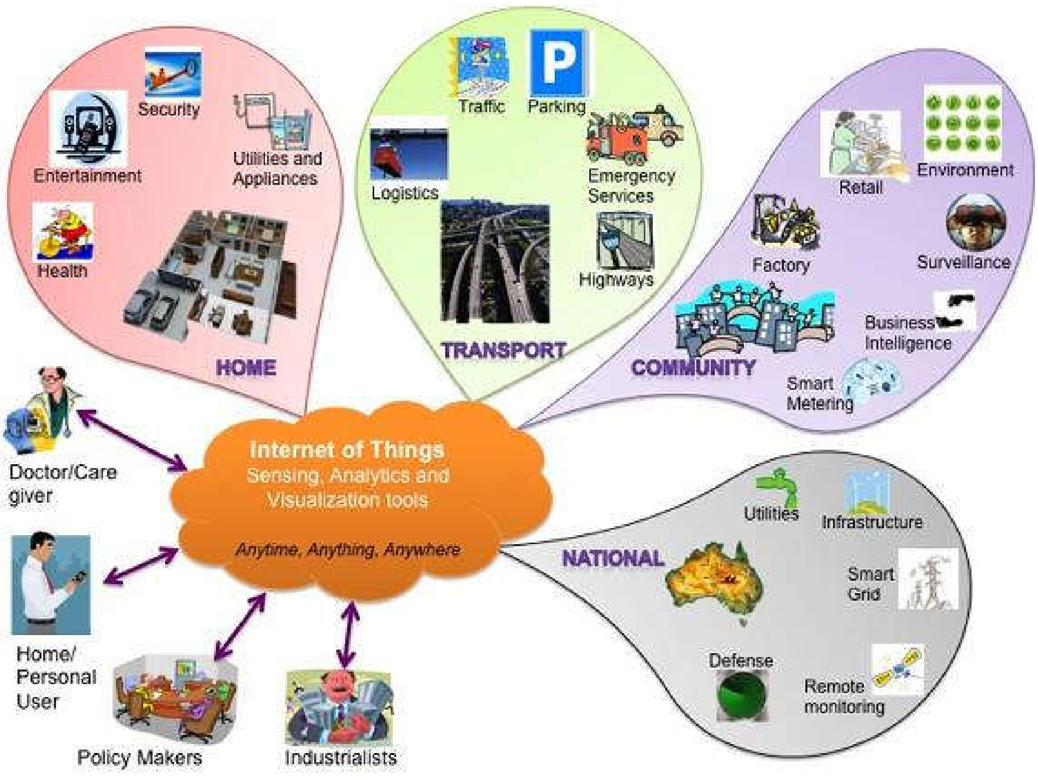


Figure 3 IoT application areas (Gubbi et al. 2013)

As a matter of fact, IoT paradigm has been enabled throughout years by the realization of several technologies and their day by day growing applications which have found discrete implementations to solve problems in different domains. In Gubbi et al. (2013) these technologies are indicated as Radio Frequency Identification (RFID), Wireless Sensor Networks (WSNs) and their relevant hardware including sensors, communication units and processing units, Cloud Computing (CC) infrastructure and services, and visualization tools such as mobile tablets and phones. An illustration of IoT associated technologies is shown in Figure 4.

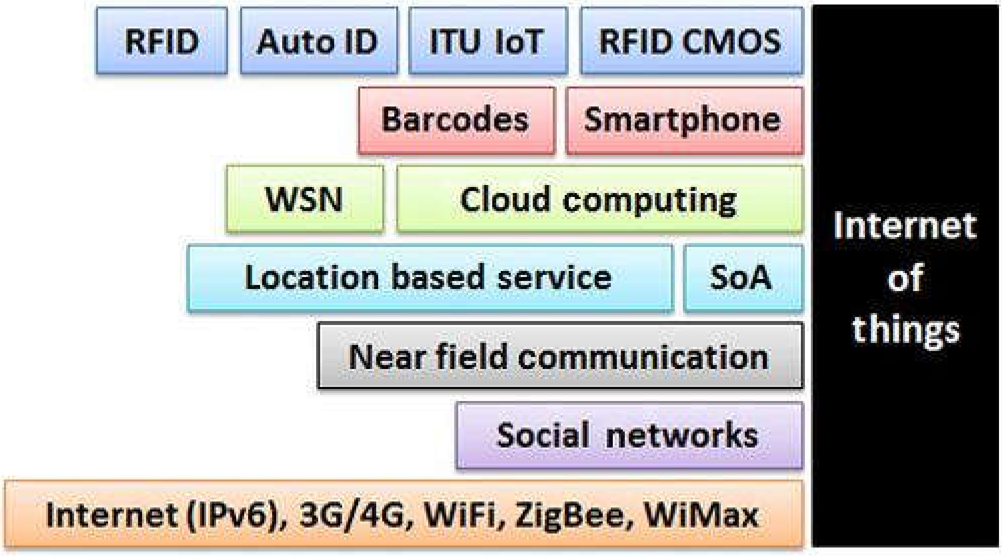


Figure 4 IoT related technologies (Xu et al. 2014)

IoT also has its own characteristics regarding its infrastructure and applications, and some of them are heterogeneity, context-awareness, distributed nature, intelligence, application diversity, and being real-time (Razzaque et al. 2016). 'Heterogeneity' of the devices can be explained as the use of different sensors and embedded devices that can be supplied from different vendors to be used for different purposes and have different cost scales from low cost components to higher order computing devices (Razzaque et al. 2016). 'Context-awareness' is the capability of dynamic modification of the behavior of devices in the network according to the change in the context (Vermesan and Friess 2014). 'Distributed nature' of the IoT refers to the distributed spatial positioning of the networks at varying scales like global and local implementations. 'Intelligence' is another characteristic of IoT that is necessary for acting independently in case of changes in the context and environment. ‘Diversity’ in IoT applications can be explained as the implementation in different domains such as applications from personal domain, industrial applications, smart environment applications, healthcare and smart transportation applications where they might need different deployment architectures and requirements. Finally, ‘real-time characteristic’ of many IoT applications describe the need for on-time delivery of data in mission critical applications such as healthcare and transportation (Razzaque et al. 2016).

A simple three-layer IoT architecture can be illustrated as in . In the first layer, the data is abstracted from the physical world using sensing devices. These can be temperature, humidity, proximity, acceleration, and location sensors depending on the situation. The data abstracted here may or may not be processed and transformed into valuable information at this layer. Either way it is passed to the network layer for secure transmission to the application layer to be used in end user applications. The technology used in the network layer is generally based on wireless communication and examples can be WiFi, Bluetooth, Infrared (IR), Zigbee, and GPRS. It is not rare that the data can be processed in the application layer according to the processing capabilities of the system and then presented to the users through applications. Some of these applications can be exemplified as smart grid and energy metering, smart homes/offices/cities, intelligent transportation, and smart logistics (Gubbi et al. 2013; Vermesan and Friess 2014) or can be monitoring and mitigation of eating disorders, nursing home patient monitoring system, and indoor navigation system for the blind and visually impaired people (Al-Fuqaha et al. 2015), more specifically.

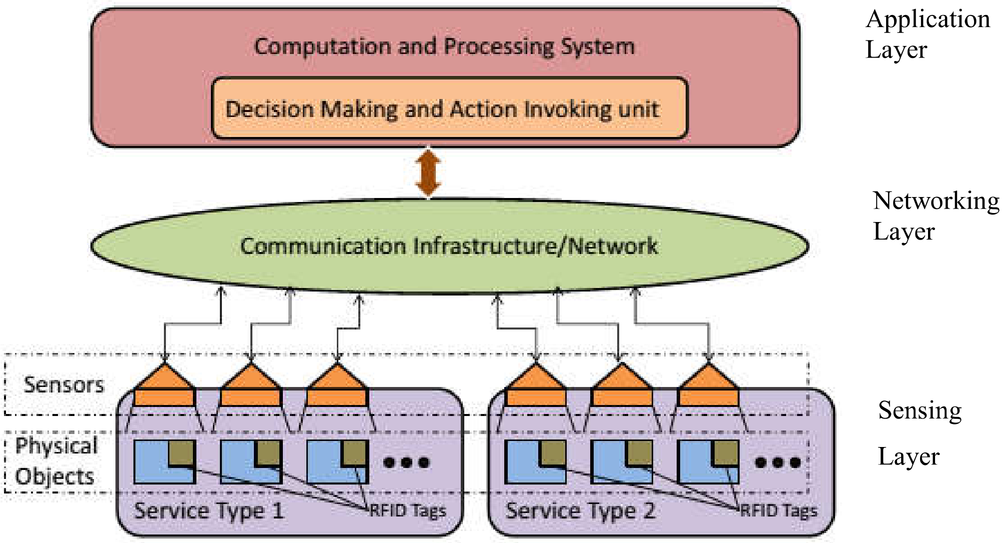


Figure 5 Generic IoT architecture (Khan et al. 2012)

IoT based technological applications might offer a great potential for real-time tracking of progress and construction resources on site (IEEE 2018). Real-time wireless access to remote resources for tracking purposes and obtaining reliable information about their status is getting easier with the decreasing costs of the related technologies over time. This may, in turn, 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 such as tracking activity progress based on man-hour tracking and safety monitoring by surveying the site with eye inspection in order to detect evasive attempts towards unsafe behaviors that are against regulations. 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.

IoT has the potential to transform the way people do things, places people live, vehicles people use, into digitalized and connected intelligent environments. This transformation is expected to bring more efficiency into processes we experience and offer major economic benefits with increasing automation and connectivity as well.

With that said, in order to accomplish successful IoT applications through the realization of IoT vision, several challenges should be considered. As information security and privacy remain as the most prevalent issues among these concerns, interoperability, availability, reliability, scalability, mobility, and performance of the systems are other type of challenges that should be addressed in IoT applications (Al-Fuqaha et al. 2015).

2.2.2. Wireless Sensor Networks (WSNs)

As being one of the most important technology drivers of IoT, WSNs deserve a closer look into this technology. WSNs can be regarded as the backbone of the IoT applications while they provide the physical infrastructure for the realization of the IoT vision. WSNs are composed of nodes that are power sensitive, low-cost, multifunctional, small in size, and able to communicate with other components of the network where sensor nodes are densely deployed into the area of interest near to a phenomenon (Akyildiz et al. 2002). An illustration of a typical wireless sensor network can be seen in Figure 6.

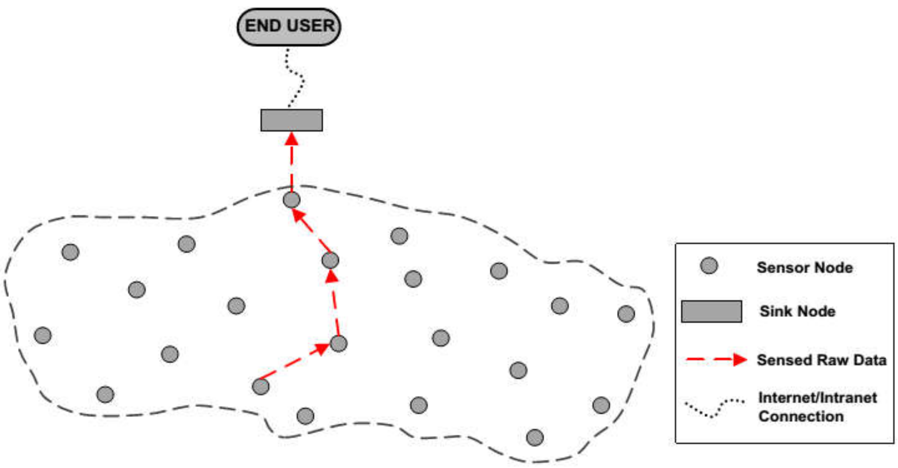


Figure 6 A typical wireless sensor network (Mahmood et al. 2015)

As being able to interact with the environment to sense or control the physical surroundings, nodes in WSNs need to be in collaboration with others utilizing wireless communication through the network in order to accomplish their tasks (Karl and

Willig 2006). These tasks are being handled by the components of the wireless nodes in WSNs. Nodes in a network consist of a sensor unit that transforms physical world phenomenon into electrical signals, a controller unit which has an interface to sensors, a memory and a processor that is used for interpreting the signals that come from the sensor unit, a communication unit that allows to send and receive the information that comes from the controller to the corresponding members of the network, and a power unit which is crucial to perform all processes within a sensor node by providing the energy required for the operations. A simple illustration of hardware components of a wireless sensor node can be seen in Figure 7. These nodes sometimes also include actuators which are electro-mechanical devices that control the ambient parameters by changing the status of other devices (Yick et al. 2008).

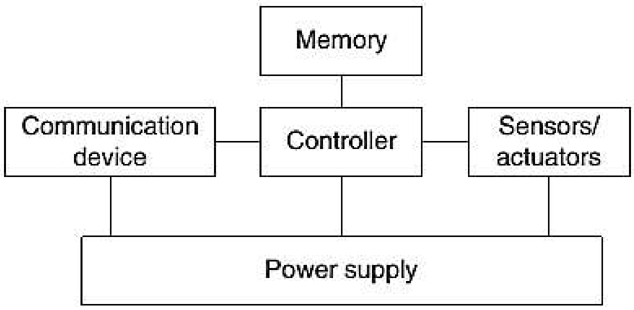


Figure 7 Hardware components of a sensor node (Karl and Willig 2006)

WSNs have a broad range of application areas like healthcare where vital status monitoring or remote surveillance of patients can be made, agriculture and environment where precision farming, cattle tracking and air/water quality monitoring is possible, and public safety where anticipation of natural disasters can be made (Rault et al. 2014). In these applications, networks can have different topologies such as star, tree, and mesh topologies. An illustration of these topologies, taken from Zigbee networks in this case, can be seen in Figure 8. These networks also can have different deployment strategies in a network where sensors can be fixed or mobile based on the network type such as structured type or unstructured mobile ad hoc type networks. While forming WSNs, several factors need to be considered during the design. Some of these factors are '*fault tolerance*' when any node in the network fails to operate due to power loss, environmental interference, and/or physical damage; '*scalability'* where the network should be able to work with different numbers of nodes ranging from a few to maybe several thousand depending on the area of interest as well as required density of the nodes around the actual phenomenon; '*production costs'* of the sensor nodes and the overall wireless network infrastructure in order to make a cost justification over traditional sensor networks; and '*environment'* conditions that sensor nodes have to operate under which can be harsh such as extreme heat/cold, high pressure and extreme noise and interference of signals (Akyildiz et al. 2002).

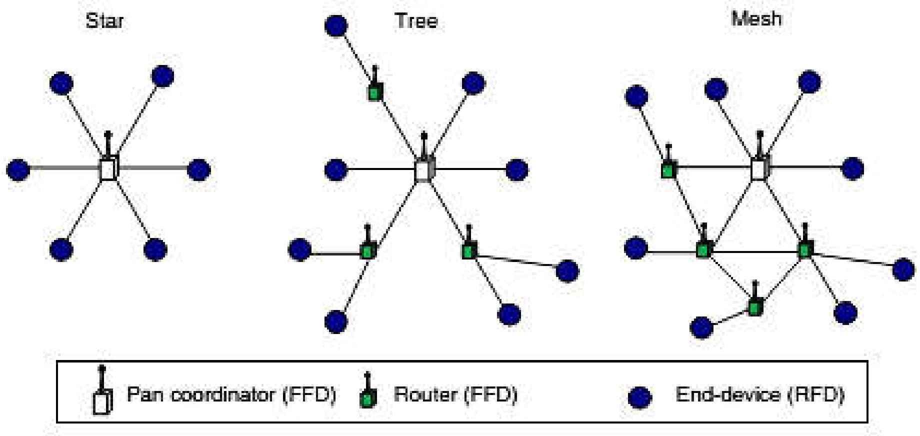


Figure 8 Zigbee network topologies (Baronti et al. 2007)

During the implementation of WSNs, several considerations such as frequency band of the communication standard, provided communication range, data rates, associated power requirements for the network to satisfy lifetime expectancy, and security protocols provided by these standards (Pule et al. 2017) are made while selecting wireless communication standards in order to facilitate the connectivity within the network. Some commonly used wireless standards with their corresponding features have been summarized in Table 2.

Table 2 Wireless standards used in WSNs and some of their features - reproduced from Rault et al. (2014)

Name	Wi-Fi	WiMAX	WiMedia	Bluetooth	ZigBee	Bluetooth low energy
Standard	IEEE 802.11b	IEEE 802.16	IEEE 802.15.3	IEEE 802.15.1	IEEE 802.15.4	
Applications	Internet access web, email, video	Broadband connections	Real-time multimedia streaming	Cable replacement	Low-power devices communication	Bluetooth ↔ low-power device communication
Devices	Laptop, tablet, console	PC peripheral	Wireless speaker, printer television	Mobile phone, mouse, keyboard, console	Embedded systems, sensors	Watch, sport sensor, wireless keyboard
Target lifetime	Hours	-	-	Days - months	6 months - 2 yrs	1 - 2 years
Success metric	Flexibility speed	Long range	High data rates	Cost convenince	Reliability, cost, low-power	Low-power

2.2.3. Wearable technology

With the technological advances in electronics circuitry, Micro Electro-Mechanical Systems (MEMS) and wireless communication, components to any electronic device are getting much smaller in size, low-cost and less power consuming which also enables compact, communication and computation capable sensing nodes (Kahn et al. 1999). 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.

Sensors, also called transducers, are critical parts to wearable devices as they generally bound the type of sensing which may change the requirements for other components in the device. Typically, they are used to infer data for gathering information about the status of the subject of interest that they append to. The abstraction of data is realized by the conversion of the physical phenomena occurring in the targeted area into electrical signals. These can be observation of the light density of a specified area, measuring temperature, measuring distance, detection of presence, measuring ambient humidity, measuring acceleration, etc. All of these phenomena can be digitalized by the use of sensors. Examples of sensors that are used in several conditions can be seen in Figure 9.

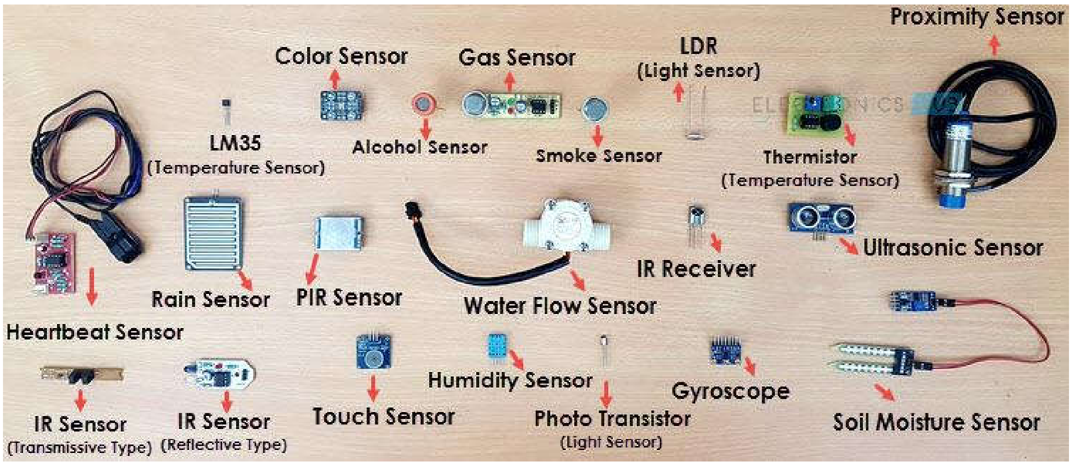


Figure 9 Various examples of sensors

In order to interpret electrical signals that come from sensors/transducers, a processing unit, generally known as CPU, is necessary. Microcontrollers are typical solutions for this kind of operations having a processor with memory capabilities and peripherals including general input/output ports and communication interfaces. These devices can also be regarded as the brain of the wearable technology. They enable operating functions using corresponding sensor data according to a software algorithm that is uploaded for this purpose. A commercial development board can be seen in Figure 10 (a) and an example of different packaging types for ATmega328P microcontroller integrated circuit units can be seen in Figure 10 (b) and (c).

(a)

(c)

(b)

Figure 10 (a) Arduino UNO development board; (b) and (c) ATmega328P microcontroller units in different packaging types

While interfacing sensors to read and manipulate the context data, microcontrollers can also provide the opportunity to communicate with target machines such as personal computers (PCs), workstations, tablets, etc. using wired or wireless means attached to their hardware. The type of communications can use serial ports or TCP / UDP ports depending on the conditions and requirements. When wireless communication is necessary, peripherals of the microcontroller unit need to include wireless hardware units in order to communicate with target machines. These units can use different technologies such as infrared (IR) and radio frequency (RF) and send signals using dedicated devices for these technologies. Transceiver radios, for example, are the components that are deployed to validate the communication between remote nodes. They typically consist of at least two radios for transmitting and receiving information between them and can operate in different frequencies such as 434 MHz, 868 MHz, 915 MHz, 2.4 GHz, etc. based on their RF band features. Depending on the selection of these frequencies, transmitting power of the radio device and the environmental conditions, transmission of RF waves, which carry the corresponding information generated by the microcontroller, to remote addresses is possible. An example of XBee transceiver units can be seen in Figure 11.

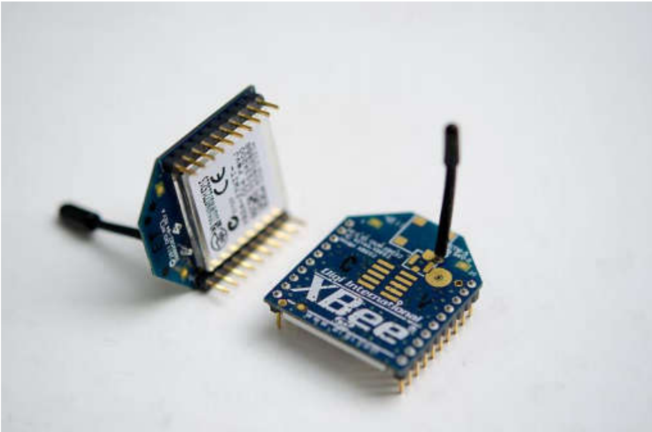


Figure 11 XBee transceiver unit

Other than these, wearable technology naturally imposes the use of battery type power source in order to satisfy mobility. The operating duration on one charge depends upon the power consumption of the components and the capacity of the batteries. Considering also the design of the device, dimensions of these devices are tied to the number of sensors and energy consumption of the components at all. Other components of a wearable device can be exemplified as displays, LED indicators, sound buzzers, vibrating motors, etc.

Several use cases of wearable 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 (Awolusi et al. 2018). 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 (Swan 2012). Several types of wearable devices are shown in Figure 12.

Figure 12 Wearable device examples (Jiang et al. 2015)

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 (Pannurat et al. 2014), whereas, obtrusiveness of the wearable devices is regarded as a drawback compared to aforementioned methods (Lara and Labrador 2013; Pannurat et al. 2014).

2.3. Technology-based studies in construction

Advancements in technology have enabled the use of technology-based applications in the construction domain as well. In this section, several approaches that are leveraging the use of information technologies, sensors, BIM, cloud computing, internet of things, augmented reality, virtual reality and 3D printing technologies are exemplified as general applications particularly in the construction industry.

In their study, Kim et al. (2013) have exploited the use of mobile technology - smartphones in particular - to develop an on-site management system. The system consists of three on-site management functions which are site monitoring, task management and real-time information sharing. In site monitoring, the project information is stored in a database and offered to the site professionals for their use and also site images captured by on-site installed cameras are provided to these professionals that they can use their mobile phones to reach the scenes of construction site in real-time. The task management module is composed of task allocation and task visualization modules. The task allocation module allows managers to assign roles to their site engineers using an application on mobile devices and the task visualization module is used to locate and visualize work tasks using digital maps and tracking engineers that are assigned to a task using Augmented Reality (AR) in terms of overlapping the position information of the site engineer and work tasks on a map and calculating the distance values to check whether the engineer is within the distance threshold limits. Lastly, the real-time information module employs a TCP/IP socket programming protocols to allow users to interactively share and synchronously view the drawings of the project. It is intended to provide the same view of any scene for different users using the same server. The study claims that using this system reduces the travel time of visiting site office for acquiring such project information, lowers the construction cost by eliminating rework through effective information sharing, and improves the quality of the work by reducing the defective processes with sharing accurate work task information.

Chong et al. (2014) reviewed cloud computing applications available in the market which are suitable for the use of built environment. The applications have been categorized and listed due to their intended uses such as general use, cloud BIM applications and project management applications. A suitability analysis has been made for project managers and companies having different scales in order to state potential uses of the applications.

Yuan et al. (2016) proposed a system that monitors the physical integrity of temporary structures on construction sites such as scaffolding. The method uses several sensors including load cells, switch sensors, accelerometer and displacement sensor installed on the scaffolding structure to measure the structural performance of the scaffolding system. A virtual model has been created and connected to a database on cloud instance for representing the physical status of the temporary structure. The system collects data from the physical structure and sends notifications in case of warning situations. The notifications are sent as a picture of the virtual model with the corresponding components highlighted and can be monitored using a mobile app on portable devices. The virtues of the system are expressed as real-time inspection of temporary structures, multi-party remote interaction and early warning and immediate instruction capability for quick identification of hazardous situations.

Zhong et al. (2017) established a study that exploits the use of internet of things applications for enhancing the current situation of prefabrication industry in Hong Kong. By tagging resources with RFID tags, real-time traceability and visibility of these smart construction objects were realized during manufacturing, logistics, and on-site assembly stages of prefabrication. The study claims that real-time capturing of traceability and visualization on a 3D visual BIM platform would enable end users of the system to make advanced decisions while they can have much more control over the project's status, progress and cost fashion.

Ergen and Akinci (2007) have conducted a feasibility study for the use of active UHF RFID systems to track and locate materials in construction industry where harsh and challenging environmental conditions are usually the case. They reported that the range limits of the used tags revealed successful results from the field tests conducted within their study. Accordingly, the use of RFID in construction supply chains is promoted for tracking and locating resources and storing historical data of the regarding materials.

3D printing has many applications in other industries such as aerospace, automotive and healthcare industries (Delgado Camacho et al. 2018), it has recently gained a popularity in the construction industry as well. Also being known as additive manufacturing, 3D printing technology refers to reading a digital model file from computer and using a layer by layer fashion to produce the corresponding model into a real entity. With that approach, custom products with complex geometries are easier to realize and requires less resources comparing to the traditional subtractive manufacturing. Wu et al. (2016) conducted a study reviewing the use of 3D printing technology in construction industry suggesting that it can provide more customization in projects, reduction in construction time, manpower and cost. However, it has been reported that the review of these applications shows that the use of this technology is in its infancy with several fragmented applications and needs to expand its applicability in construction industry. Another review study conducted by Delgado Camacho et al. (2018) is also promoting the use of additive manufacturing in order to exploit the benefits of this technology in construction such as reduction in formwork, decrease in the demand of skilled labor, reduction in waste and decrease in the cost of producing complex parts with custom designs. With that said, it should be noted that the use of 3D printing technology in construction also requires attention due to resultant accuracy of printing works, the cost of 3D printing process, time of printing and the availability of the materials that are used in printing (Wu et al. 2016).

Accelerometer sensors allow measuring acceleration value, which is the rate of change in the velocity, along different axis such as x, y or z-axis in the global coordinate systems. They can sense acceleration in uniaxial, biaxial and tri-axial directions depending on their types. Recent advances in the MEMS technology have led accelerometer sensors to become more affordable, tinier and easier to embed into electronic devices. This development has enabled the use of these systems within a broad scope of applications developed for engineering solutions in industries such as automotive industry, medical industry and others as well. Applications of accelerometers also find place in studies conducted in construction industry to address several requirements and issues encountered on construction sites. One major application area is structural health monitoring (SHM) of structures such as bridges, dams, buildings, etc. to evaluate their behavioral performance under loads. Several examples can be found in Xu et al. (2004), Meng et al. (2007), Chae et al. (2012), and Han et al. (2016).

Other fields of applications can be exemplified as analyzing the acceleration data to derive meaningful information about the physiological status of workers. Such data can be used for the prevention of musculoskeletal disorders (Valero et al. 2016), for the analysis of worker body motions to detect inadequate working postures (Valero et al. 2017), for the detection of on-duty and off-duty activities of workers to track and reduce their on-duty health and safety risks (Lee et al. 2017), for ergonomic analysis of construction worker's body postures (Nath et al. 2017), and activity recognition of workers (Akhavian and Behzadan 2015, 2016; Joshua and Varghese 2011) on construction sites.

2.4. 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. (2013) pointed out that real-time flow of information is a crucial factor to solve safety relevant issues on construction sites and technologies such as 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 (2014) reviewed studies that were published between 2000 and 2014 regarding the deployment of 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.

Yang et al. (2012) developed an identification system using UHF passive RFID sensors and readers for improving the performance of accident prevention on construction sites. Wu et al. (2013) studied real-time tracking of resources on site using active RFID technology in order to develop an information management system revealing preventive information for being struck-by-falling-object accidents on construction sites. In Wu et al. (2010), authors have investigated and identified major near-miss accidents and their autonomous data requirements (i.e., location, identity, environment) on construction sites and proposed an approach using the abovementioned active RFID technology in order to address these requirements for the corresponding near-misses and improve the safety performance.

Another study conducted by Marks and Teizer (2013) investigated the usability, effectiveness, and reliability of RF based proximity and warning technologies in eliminating being struck by objects which is another significant source of fatalities on construction sites. Teizer (2015) presented another study including an implementation named “SmartHat” in which sensors are attached to personal protective equipment (i.e., hardhat) and the system tracks RFID tags on workers using readers for proximity detection that triggers a sound warning system during alert situations. In order to improve blind lifting operations and avoid hazardous safety issues, Li et al. (2013) implemented RFID and GPS solutions to track pre-defined risk zones around the cranes for detecting unauthorized entrance of personnel. Another study that relates to hazardous issues regarding cranes on construction sites was conducted by Zhong et al. (2014) which proposed an IoT based 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.

In their study, Teizer et al. (2013) proposed a new method using remote data sensing and visualization techniques for safety training of construction professionals. In this approach, real time location algorithms are deployed using Ultra Wideband (UWB) radio frequency tags and readers to track the indoor position of the workers or trainees in order to augment the identification of safety issues and raise their awareness regarding these issues. Implementing the technique has shown that hazardous proximity issues on construction sites can be recorded and visualized effectively, which then help to assess the learning process of the corresponding personnel with quantitative results. As a result of this technique, overall safety understanding could be improved among the workers and trainees as they might generate safer work practices.

Guo et al. (2012) used game technologies and created a virtual construction environment in order to assist the safety training of trainees. Using this approach, it is expected to enable trainees to interactively practice related tasks in a visual gaming platform which are normally conducted on construction sites. Trainees would have the opportunity to make incorrect movements and master their skills to exhibit a better safety behavior on real construction platforms. A similar study was conducted by Li et al. (2012), called ‘4D Interactive Safety Assessment’, which proposes a virtual training system for workers with a visual simulation interface using game engines.

Kim et al. (2017) conducted a study that proposes a hazard avoidance system regarding being struck-by safety issues on construction sites. The study uses computer vision techniques to identify the hazardous situations on the site and shows the results on the display of a commercial wearable eyewear product, ‘Google Glass’. Heading direction for hazard orientation, distance, and safety level information are being calculated and assessed through the processing of the images taken by global cameras on construction sites and the hazard information is shown on the worker's wearable screen using AR.

2.5. Fall related technology-based studies in construction

Research studies have also been conducted using technological devices and approaches in the field of fall detection and prevention. Fall related studies that propose technology-based solutions in the construction industry research literature have been reviewed and presented, in this section.

Navon and Kolton (2006) have developed an identification model for hazardous activities in the construction project's schedule in order to automate fall prevention measures. The developed approach identifies the places that require guardrails using a computer program and integrate them into work schedules with corresponding text and graphical reports.

Melzner et al. (2013) have presented an automated rule-based safety checking system for fall protection on construction sites by developing a plug-in to augment the BIM software they used. Deploying predefined rule sets from both German and USA regulations; the rule-based safety checking framework, which was adopted from Zhang et al. (2013), has been applied to a high-rise building project 3D model. As a result of the study, hazardous places requiring fall protection (i.e., slab openings and edges) have been identified for the case project and the necessary quantities of protective equipment (i.e., guardrail system and cover slab openings) and the schedule information for these countermeasures have been generated in order to enable the safety team for further actions against fall hazards.

Another similar study is conducted by Zhang et al. (2015) which proposes an algorithm to check the BIM model and identify the hazardous edges and holes in concrete slabs of a construction project. In the planning phase of the project, corresponding potential fall hazards are identified based on the construction schedule and guardrails are automatically installed to these locations in the visual model to enhance the safety plans.

A prevention through design (PTD) study was conducted by Qi et al. (2014) in order to prevent construction falls. A set of rules have been constructed from safety best practices and employed into the developed software tool for safety compliance checking. It is then used for checking fall hazards automatically in a BIM model in order to provide safety design alternatives to end users.

Lee et al. (2009) proposed a safety monitoring system to reduce dead zones where falls might occur at construction sites. The system includes the development of mobile sensing devices which are mounted on the hazardous spots. Instead of using RF sensors and tagging each individual on construction sites, the study proposed using ultrasound (US) and IR sensors to detect the proximity of workers to the hazardous areas and warn them by raising alarming sounds. The system detects the occurrence of subjects within 2m away from predetermined dangerous zones and warns the subject with sound alarming if the proximity is getting closer. In case of emergency detection, the system also sends wireless notification to the main control unit placed at the site office in order to contact and inform the safety professionals to take further actions to manage dangerous situations.

Goh and Guo (2018) have developed an online knowledge-based decision support system, called FPSWizard, for safety professionals to help and augment them in the design and selection of solutions for working-at-height situations. Using both case-based reasoning and rule-based reasoning in their process, the approach aims to recommend a proper active fall protection system such as fall-arrest systems and travel restraint systems relying on previous design cases.

In order to automate the safety inspection process for fall protection equipment, Fang et al. (2018) developed a computer vision based approach using neural network models to detect the presence of safety harnesses on construction workers working at heights. A database of taken images from different construction sites has been trained and analyzed to validate a two-step algorithm which first detects the presence of the worker and then consequently identifies whether a safety harness does exist on that worker. It has been reported that this method can help with monitoring of the safety behavior of construction workers working at heights and allow safety managers to identify and mitigate the risks.

Some other studies investigated identifying fall risks of construction workers by collecting and analyzing kinematic data of the subjects using inertial measurement unit (IMU) devices attached to their bodies. In Jebelli et al. (2016b), researchers studied walking patterns of ironworkers on a steel I-beam using IMU data in order to investigate the feasibility of using a clinical metric (i.e., maximum Lyapunov exponents) as an indicator for identifying construction fall risk. Authors concluded the study with claiming that the metric they used was adequate to distinguish high-fall-risk walking tasks and low-fall-risk walking tasks. In their another study (Jebelli et al. 2016a), construction workers' fall-risks were analyzed by assessing the postural stability metrics for stationary posture tasks like squatting and standing. Using velocity and acceleration information from IMU kinematic data of subjects and a force plate to validate the results of the IMU sensors, it is reported that the method was useful for measuring fall risks in stationary postures.

Yang et al. (2017) conducted a study that proposes a sensing approach in order to assess the gait abnormalities of workers to identify and locate fall hazards on a surface at construction sites. The study investigates the disruptions in the workers' behavior by collecting the kinematic data of the subject using a wearable IMU device attached to the ankle. The experimental study was conducted in laboratory environment with the subjects that respond to fall hazards such as an obstacle and a slippery surface on a steel I-beam which are set in the laboratory. With the measurement of the magnitude of gait disruption generated due to these fall hazards, quantification of the results has been obtained by comparing them to the reference gait data obtained from non-hazardous locations in the setup. They found a strong correlation between the hazard locations and change in gait patterns due to hazards. As being a feasible solution to identify the existing fall hazards on a surface, it is claimed that it can improve the capabilities of safety managers towards eliminating these hazards on construction sites. However, a considerable issue is pointed out that, significant amount of data needs to be sensed and processed in order to obtain reliable results for hazard locations since bodily responses of workers are not revealing the direct results of worker foot and surface interaction.

Yang et al. (2016) investigated the feasibility of detecting near-miss fall accidents of ironworkers by developing and employing an automated approach using kinematic data captured from a wearable IMU device. They have used a semi-supervised machine learning algorithm to detect near-miss fall accidents automatically, instead of reporting them manually, and predicting hazardous locations by deploying the corresponding algorithm to the data obtained wirelessly from the wearable unit. Using an abnormality detection algorithm (i.e., one-class support machine vector) the researchers attempted to study non-stationary actions of ironworkers in order to infer results from a more realistic scenario on construction sites. However, it is reported that detecting near-misses is a challenging issue due to several considerations including diverse motions on the steel beam such as acceleration and deceleration of the walking pace of the worker, irregular movements of body extensions, diversity of the corresponding construction activities where the levels of loads being carried by the workers differ, the impact of symmetrical or asymmetrical carrying of these loads to the outputs of the signal, and the variability of responses of different workers who are fall-prone. It has been denoted in a further study of Yang et al. (2017) that these considerations make automated detection of near-miss falls very challenging due to the subjective responses of individual workers changing in different circumstances and varying situations. It is also indicated in this study that reliable localization of near-miss falls on construction sites require much more occurrence however fall short due to the trace amount of near-miss falls at construction sites.

Fang and Dzeng (2017) have studied fall-portents in a designated tiling experiment setup with subjects who are worn accelerometers to their bodies. The experiments were conducted to assess the feasibility of a threshold-based algorithm to detect fall-portents on a scaffold where subjects have performed their tasks in controlled physiological conditions such as sleepiness, inebriation, and normal. The system follows an approach that collects data from workers movements using external accelerometers and makes the analysis of the acceleration data with a wearable device (i.e., Android smartphone) based on the algorithm proposed in the study. In case any detection of fall portents occurs, the system raises a warning with sound and vibration from the wearable unit and sends a notification to a remote monitoring unit for further action of the supervisor in charge. Several algorithms have been deployed in trials while investigating imbalanced motions, sudden sways and unsteady footsteps for abovementioned physiological statuses. As a result of these trials, an optimal algorithm (i.e., A19) has been selected as the best alternative among other algorithms deployed to detect fall-portents and it revealed an accuracy rate of 67.31% for normal physiological condition and accuracy rates of 89.17% and 79.31% for inebriation and sleepiness conditions, respectively.

Identification of fall risks with the detection of fall-portents requires overcoming several challenges and barriers in order to obtain realistic results. That is, a strong correlation between falls and portents still needs to be studied and since detection of portents may be subject to vagueness due to individuals' perception, sometimes it may be impossible to distinguish, for instance, a sudden sway that stem from a work related motion or loss of balance of the worker (Fang and Dzeng 2017). That being said, it may also require analyzing every work and non-work related behavioral patterns of any trade from the construction sites that relate to fall risks for identification of fall risks using fall-portents. Even demographic characteristics of workers such as their gender, age, race and culture, their physiological conditions while performing tasks and their level of perception regarding the risks that they are exposed to may require further investigation. Also, complex and dynamic nature of construction tasks may diminish the reliability of fall-portent detection approach. For instance, while one of the algorithms Dzeng et al. (2014) used (i.e. A1), demonstrated a fairly higher accuracy of 88.5% in their previous study, the very same algorithm showed an unsatisfactory result with an accuracy of 5.43% in Fang and Dzeng (2017) study. The reason of this phenomenon is explained in the latter study as the change in the experiment design regarding the motions of the workers on the scaffold. As compared to the previous one, workers followed more complex motion patterns such as stooping or squatting during picking up the tiles which are not investigated in the former study while performing the same tiling construction task and this caused more noise during the fall-portent detection. Thus, for the tasks being conducted in their natural course at construction sites, using a threshold-based approach will require more diligent calculations to determine a more realistic threshold value while addressing the detection of fall-portents.

Above mentioned research studies have been implemented towards addressing falls at construction sites. Various methods and technologies, including applications such as identification of risky places in combination with visual models of the projects, use of ambient sensors to detect and notify the proximity of workers to hazardous places, and detecting the presence of personal protective equipment on workers using vision based systems for safety inspection, have been proposed. The kinematic data of the workers, which help to assess the postural stability and abnormalities, have also been used to investigate identifying the fall risks and locate them in different situations by utilizing wearable devices. Using acceleration data, several research have also studied fall-portents by deploying detection algorithms; however, it is found to be more challenging while identifying fall risks with the detection of fall-portents since it is mainly based on the perception of the individuals, and the nature of the work would eliminate to distinguish fall-portents from usual work. Near-miss falls have also been investigated by utilizing acceleration output. Nevertheless, the trace amount of near-miss falls at construction sites still requires much more occurrence to localize near-misses reliably. Subjectivity of the responses of workers while reporting near-miss falls makes it challenging to automatically detect, as well. It is obvious that a lot more research regarding FFH accidents at construction sites is needed to address this issue. Surveying the literature, it is found that there is a need for the mitigation of overall consequences of FFH accidents, which presents a gap in the literature, and deserves to be studied.

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 order to address the gap stated above, an IoT based approach has been implemented by deploying an approach using a wearable device. The study aims to contribute to the literature by automatically detecting occupational falls at construction sites with its key attributes such as fall height and fall time and providing EMT with corresponding information to provide an immediate response to the victim at accident scene in order to reduce the consequences of the FFH accidents.

CHAPTER 3

DETECTION OF OCCUPATIONAL FALLS

As discussed earlier, falls are the most frequently encountered fatal accidents at construction sites. Similarly, it is a major concern in elderly care domain as well. Introducing what has been done and how the detection of falls has been handled in this field, technologies that are used for the detection of falls and the methodology used in this study will be discussed and explained in this chapter.

Falls are one of the major sources of deaths and injuries among elderly people (Aziz et al. 2014; Bagalà et al. 2012; Mubashir et al. 2013; Pannurat et al. 2014). Correspondingly, fall detection is one of the topics widely discussed in elderly care domain. Researches in this field studied activities of daily living (ADL) for elderly people in order to improve the quality of their life and provide assistance through caregiving services. The main focus is to help reducing fatalities or disabilities resulting from the falls of elderly people that might occur during their daily activities. In order to do this, many researchers deployed technological solutions in their studies for detecting falls of the elderly. Most of the studies have exploited the use of wearable sensors in order to investigate the fall mechanism in elderly people. Bourke et al. (2007) used tri-axial accelerometers to investigate the feasibility of automatically distinguishing between the ADL and falls of elderly people; Ojetola et al. (2015) conducted experiments using inertial sensors to create a data set for further use in identifying fall mechanisms for the elderly; Wu et al. (2015) developed a wearable device in order to detect falls among elderly activities and send a request to caregivers; and Aziz et al. (2014) and Kangas et al. (2008) evaluated the effectiveness of wearable sensors attached (i.e. accelerometers) to different body locations such as waist, wrists, sternum, ankles and head for fall detection in elderly. In addition to wearable units used for elderly falls, Paoli et al. (2012) used a combination with ambient assisted living (AAL) infrastructure deploying ambient sensors to the living area; and Kwolek and Kepski (2014) added vision based approach using a Kinect sensor in their study to detect falls in elderly.

3.1. Fall detection methods and technologies

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 (Mubashir et al. 2013). 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 IR sensors to detect presence, etc. Paoli et al. (2012) used IR sensors to detect motion in several locations of the house, pressure sensors on the bed and sofa to detect presence of the subject, and magnetic sensor (i.e., reed switch) to recognize if the door is opened in combination with the wearable type of sensing used in their fall monitoring system implemented for the elderly. The schematic placement of these sensors can be found in Figure 13. Cheng et al. (2016) deployed a system that include 6 light dependent resistors (LDRs) at the bottom of a small bathroom with a class 2M laser line beam attached to an actuating module which scans predetermined grids and triggers corresponding LDRs along with the algorithm implemented in the system to detect falls and send alert messages to caregivers for intervention.

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. The increasing number of sensing mechanism with its complementary peripheral setup will inflate the cost of installation as well as computational costs regarding a consistent fall detection system resulting in greater overall complexity and cost.

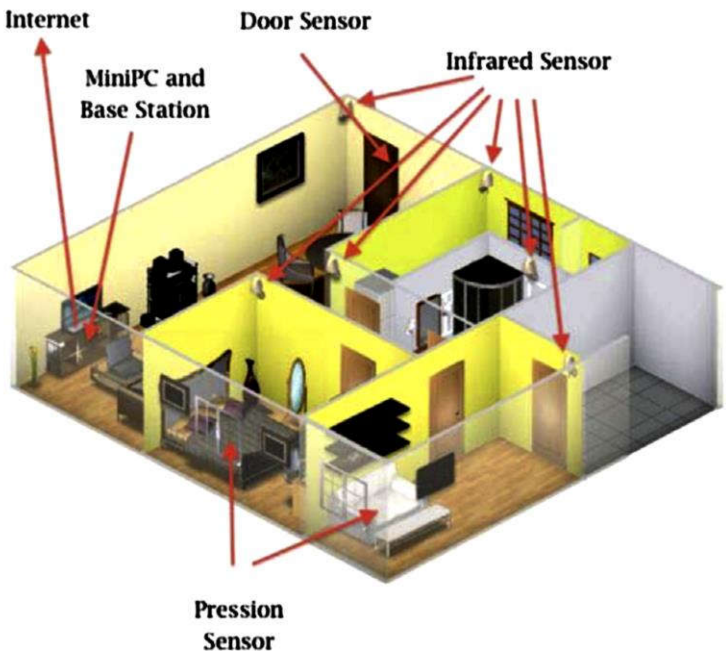


Figure 13 Schematic view of ambient sensors used in Paoli et al. (2012)

Another approach used in fall detection studies is computer-vision-based sensing. Computer-vision type of sensing uses camera-based solutions (see Figure 14) 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 (Seo et al. 2015).

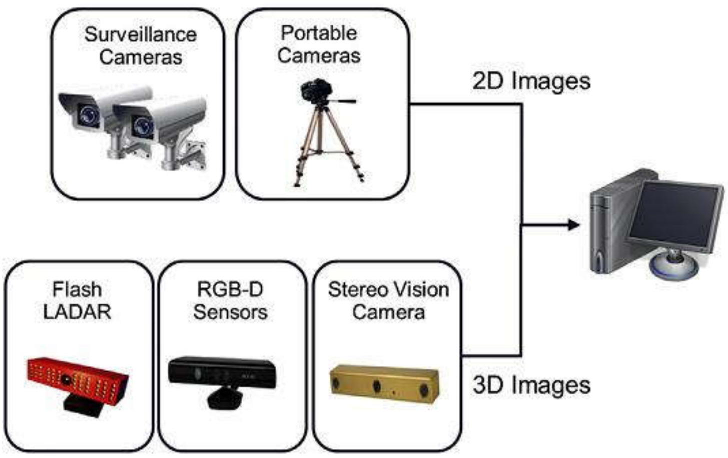


Figure 14 Computer vision based sensing solutions for capturing data (Seo et al. 2015)

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 could not be performed (Delahoz and Labrador 2014). 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. Additionally, selection of camera positions is another considerable issue, especially on construction sites, due to dynamic changes in the task scenes, limited accessibility to that scenes and occlusions in the view while multiple activities are being performed (Seo et al. 2015). As comparing to other approaches, computer-vision based sensing will require much more computation resources to deploy sensing algorithms on regarding images. The increasing number of cameras installed in order to overcome aforementioned issues on construction sites will also increase the requirement for computation. Accordingly, computational costs and installation costs of these vision-based systems might be additional sources of concerns regarding the selection of a proper fall detection approach. Furthermore, Seo et al. (2015) discuss that workers being continuously monitored by cameras may change their attitude and this surveillance can downshift their performance and motivation due to privacy concerns.

Considering the dynamic nature of construction sites, progressive work environment limits the use of ambient-sensing and vision-based approaches and makes them unattractive. Construction of walls of the project, for instance, will block the line-of-sight and require additional installation of new cameras in order to provide a coherent view of the scene and to meet the accuracy objectives in fall detection. Also, ever-changing form of corresponding scenes such as project related changes in building elements like covering walls, plastering and painting will require the ambient sensors to be de-installed and installed again for providing a real-time and continuous monitoring of activities and workers on construction sites. As being open to the environmental and atmospheric conditions and harsh environment of the construction sites, it would require special attention in the deployment and maintenance of the external sensors used in ambient type of sensing.

Establishing a trade-off between ambient sensing, computer vision based sensing, and wearable device use, to select the best option among these alternatives, a wearable device based approach is adopted in this study to detect occupational fall accidents on construction sites. Several studies such as Dzeng et al. (2014) and Fang and Dzeng (2017) have also used wearable devices in their fall related studies. By 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 (Abbate et al. 2012; Akhavian and Behzadan 2016; Dzeng et al. 2014; Fang and Dzeng 2017) 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. (2014) 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 (Habib et al. 2014). It is also reported in Casilari et al. (2015) that as being able to multitask, smartphones are more prone to failure while featuring coexisting functionalities such as phone calls, instant messaging, web browsers and multimedia features, and need special attention while using fall detection systems with other ongoing applications.

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 system.

3.2. Proposed system

3.2.1. 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. (1996), 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. Another definition has been made for falls as 'an unexpected event in which the participant comes to rest on the ground, floor, or lower level' (Hauer et al. 2006). With this definition, it is understood that the fall event ends up in a steady state of the subject after colliding with the ground. In order to describe the physical behavioral segments of a fall event, Paoli et al. (2012) suggested a fragmented successive staging for fall characteristics including (1) initial free fall where the subject accelerates towards zero g, (2) impact in which the subject exposed to higher acceleration values, (3) motionless phenomenon which corresponds to a period of inactivity of the subject after the accident, and (4) position change that refers to the change in the posture of the subject from verticality to a laid down position. Kangas et al. (2008) developed their fall detection algorithms accounting the phases of a fall event, i.e. beginning of the fall, falling velocity, fall impact and posture after the fall. In these studies, staging of the fall events were discussed to distinguish falls in the elderly population from the normal ADL. Correspondingly, since it is a fall-to-a-lower-level behavior in their cases, the overall time occurred during a fall event is relatively short. Figure 15 shows an example acceleration output of these types of falls where the acceleration tends towards zero-g but spikes with an impact without having enough time to oscillate around zero-g plateau. In these types of falls, even though it is possible to recognize the first phase by detecting the declination towards free fall, the short duration of time that passed along the detection of the first phase limits distinguishing the behavior whether it is a free-fall or a normal acceleration output that stems from ADL. This might increase the rate of false positives during the detection of elderly falls unless a combinatory approach is used. Thus, in order to eliminate false results and strengthen the method, the findings from posture recognition are usually being used as complementary to the algorithms used to detect falls in elderly cases.

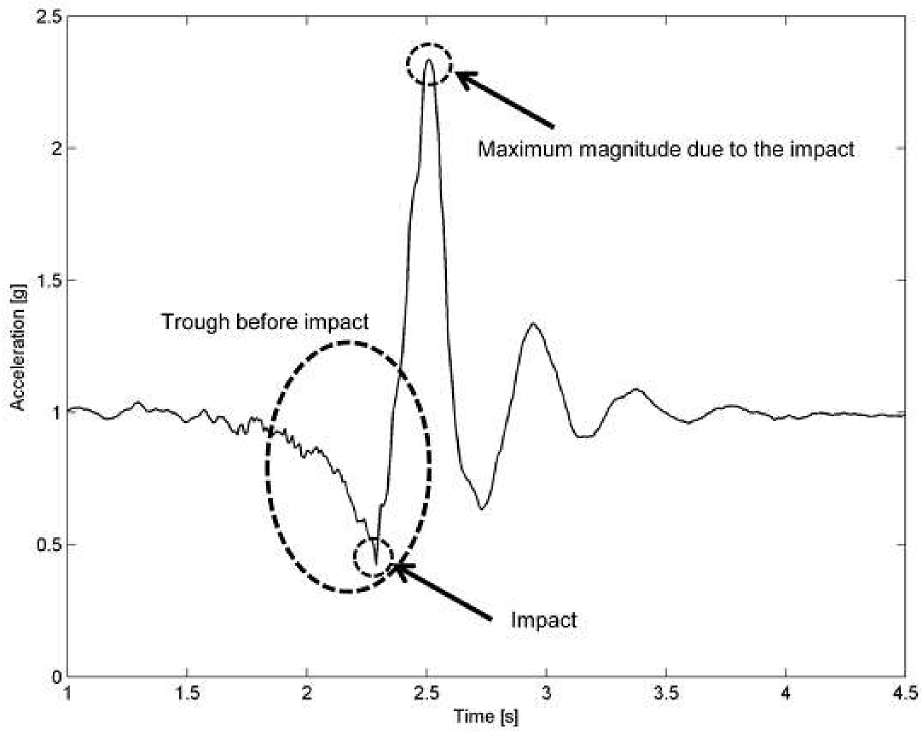


Figure 15 A generic real world example of common elderly falls (Bagalà et al. 2012)

In addressing FFH accidents at construction sites, a three-phase fall model (see Figure 16) has been used in this study as a method for the detection algorithm containing free-fall phase, collision phase, and steadiness phase, respectively. In order to have an understanding about the resulting behavior for FFH events, an acceleration graph obtained from a fall event during our preliminary FFH tests that contains both three different axis accelerations and their sum vector magnitude (SVM) is illustrated in Figure 17. Moreover, a detailed graphical illustration of accelerations regarding a fall event with corresponding phases can be seen in Figure 18.

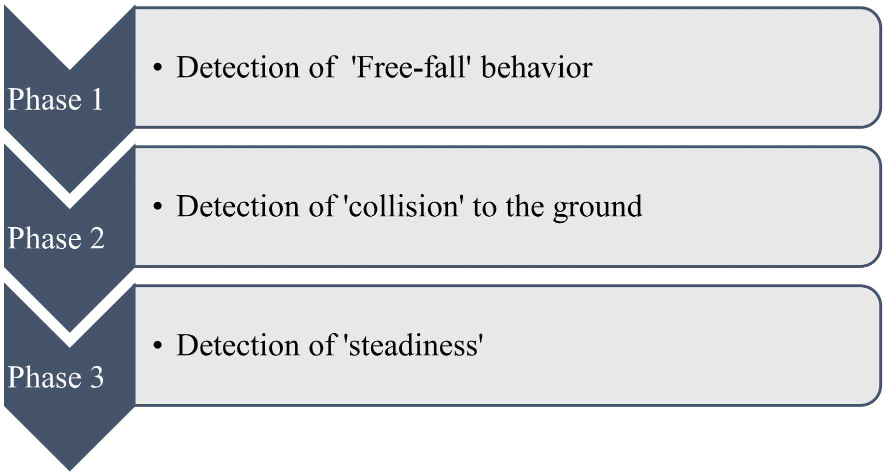


Figure 16 Phases of the fall detection method

Based on these graphs, it can be easily acknowledged that the free-fall behavior can be observed from the plateau laying slightly over the zero-g value. At the end of this plateau, collision to the ground causes an impact of striking a higher acceleration value. After this peak point, a fluctuation of acceleration values prior to steadiness around 1-g can be observed which corresponds to the crashing behavior between the subject and the ground. After all, the subject reaches to a steady state that corresponds to a motionless phenomenon.

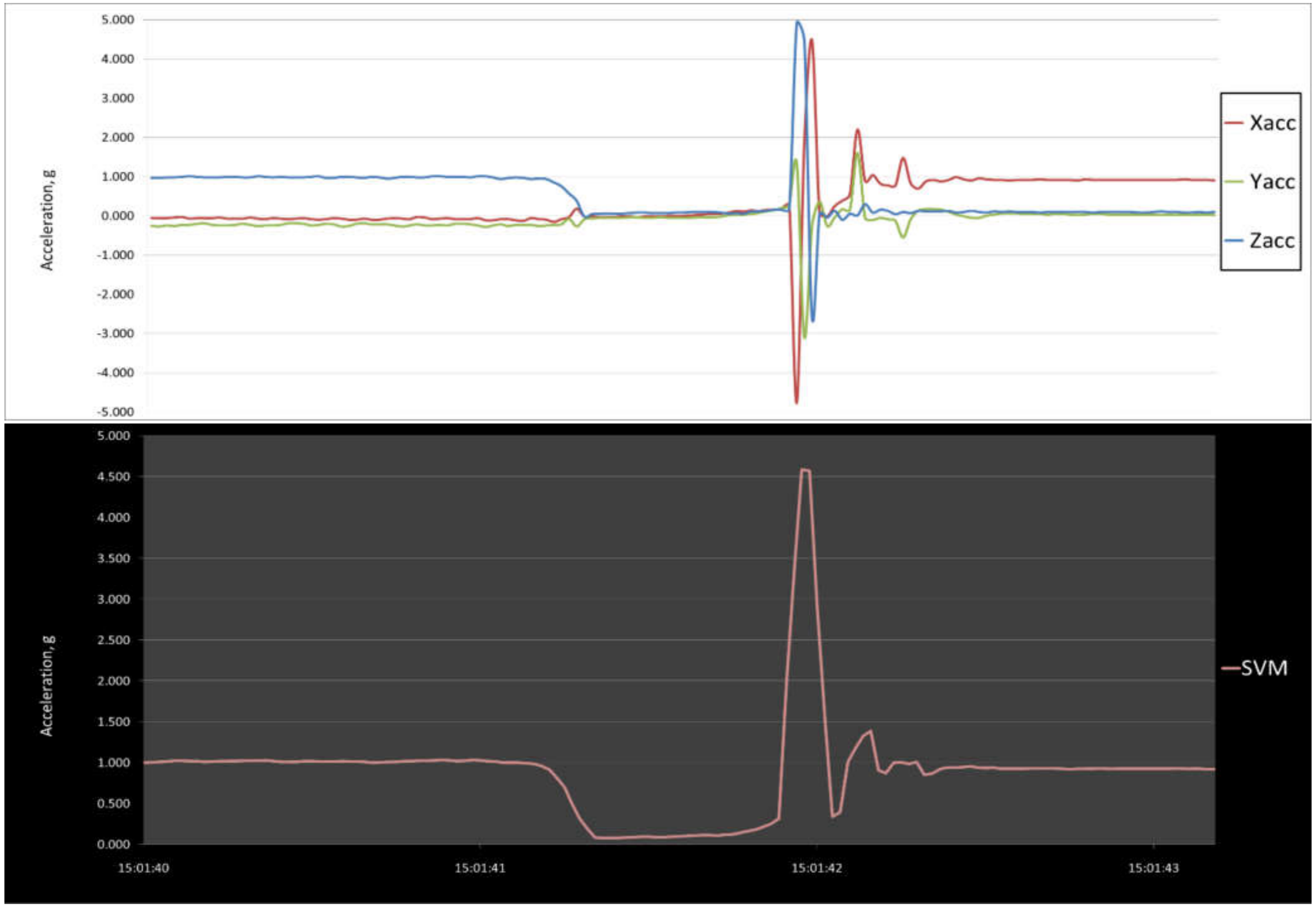


Figure 17 Axial accelerations and SVM output

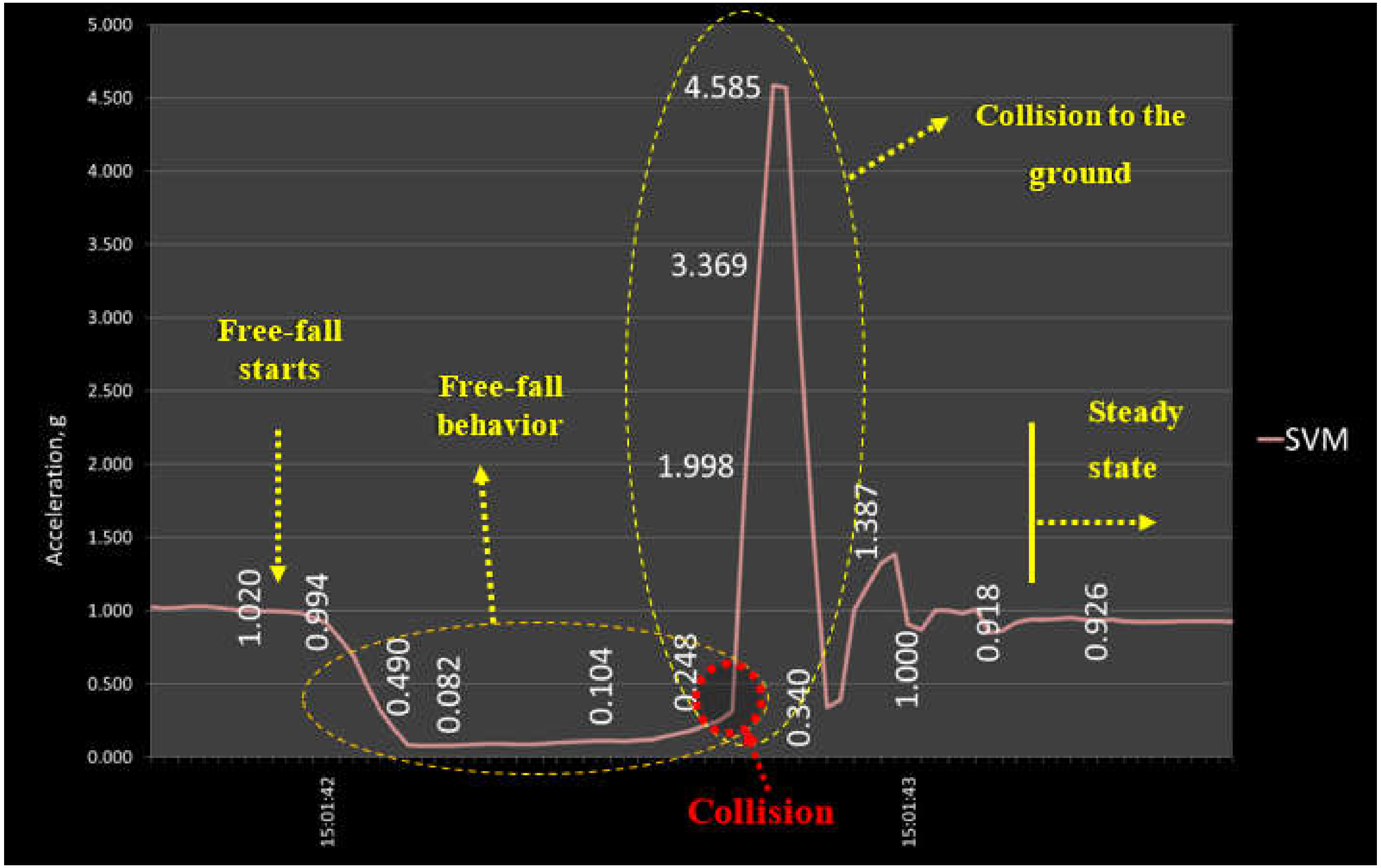


Figure 18 Acceleration values during a fall behavior

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. It is a well-known fact that an object that is exposed to free-fall, is always subject to the gravity acceleration towards earth's center of gravity. As can be seen from Eq-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.

$$a = \partial v \,/\, \partial t \tag{1}$$

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. The collision surface, orientation of the human body while interacting with the ground and the height of the fall which is stated in Eq-2 as a function of gravitational acceleration and time spent during fall, are other main concerns of the occupational fall related injuries. While the height of fall (see Eq-2) increases, the time spent during the fall increases which then will increase the instant velocity of the body right before the collision.

$$h = {}^{1}/_{2} * g * t^{2} \tag{2}$$

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. The wearable device is designed for not to disturb the user during the regular work-related activities being handled on construction sites. Also, the outputs of the system should not be biased or misinterpreted due to the positioning of the device on worker body. Hence, it is placed along the body axis and to the nearest point of the body center on the waist. The device is decided to be positioned near to the core of the body and no other body extremities are considered as alternative places to position the device in order to prevent false positives of the system outputs due to job activities performed using these extremities.

In this study, the detection algorithm of the occupational fall accidents is using a multi-phase rule-based approach that works on thresholds. The steps of the algorithm are designated to provide a solution aiming zero false positives while workers perform their normal duties at construction sites.

3.2.2. System architecture

According to the system architecture, as can be seen in Figure 19, 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 then 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.

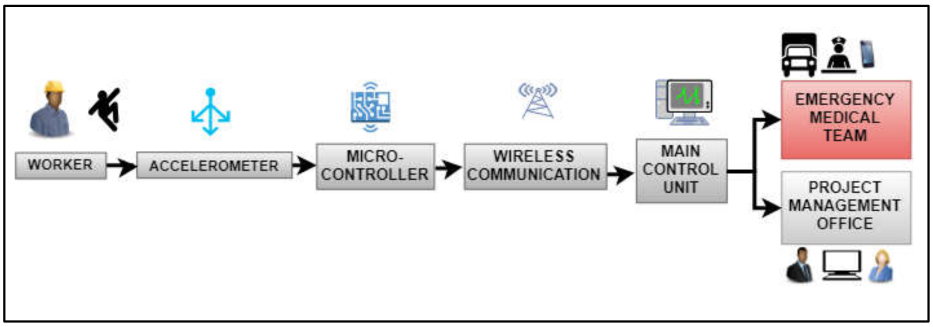


Figure 19 System architecture

After the detection of the accident, usable location information should be provided to expedite the emergency response process for the patient. Generally, this is achieved by using GPS that can provide reasonable positioning information for outdoor environment. However, considering additional costs on the implementation of the system and the poor positioning results that stem from the deficient signal quality indoors, a simple but elegant approach is proposed in this study for providing prescribed location information regarding the corresponding zone of the construction site which is the zone the worker is connected to the wireless network.

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.

3.2.3. Fall detection algorithm

As it has been stated, wearable units containing accelerometers are commonly used in the fall detection domain. Studies usually exploit the use of acceleration values by running threshold based algorithms on the output data in order to detect fall mechanisms. Pannurat et al. (2014) reviewed systems that detect falls among elderly and apparently, the number of studies conducted using wearable devices in order to extract information about fall monitoring outweighs the use cases of ambient type sensing. Particularly, accelerometers are considered to be the most effective and the most commonly used type of sensing. Among these, most of the studies used 'sum vector magnitude (SVM)' in their approaches in order to deploy their threshold-based and rule-based algorithms in their experiments. Studies used solely simple threshold-based algorithms to detect falls are found ineffective since they might generate the same signal value with ADL that can be misinterpreted and mistaken. That is, single threshold value for the detection of falls is more prone to producing false positives due to other activities carried out by subject during normal activities. Due to this fact, investigating the physics of the fall behavior and cutting it into phases having threshold values per each phase, together with construction of a rule-based approach becomes a necessity to distinguish fall behavior and obtain better results. To do this, the algorithm implemented in this study was structured based on the phases determined based on the fall characteristics explained in the previous sections.

This study refers to a multi-phase rule-based fall detection algorithm that trains the real-time streaming acceleration data generated due to the movements of the workers on construction sites and applies threshold values for the extraction of events. 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. The flow of the algorithm can be seen in Figure 20.

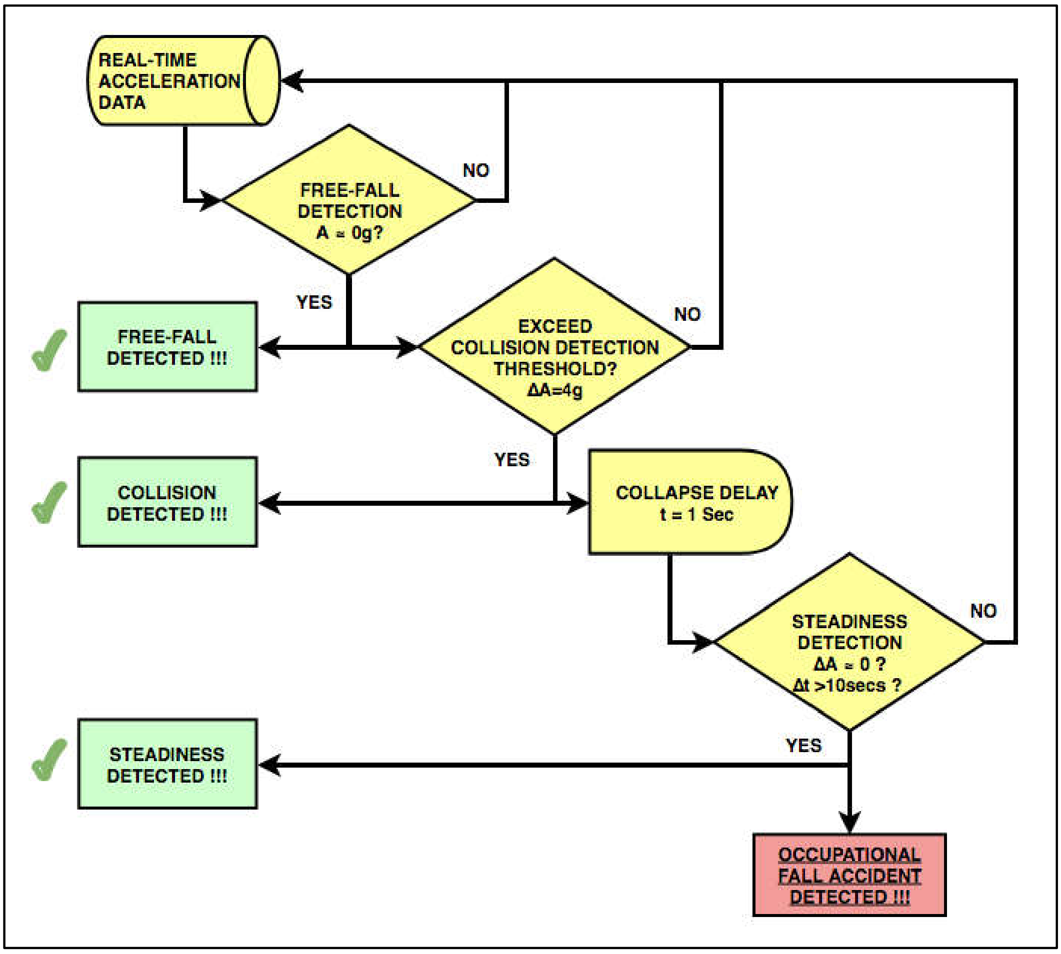


Figure 20 Fall detection algorithm

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 calculated using the root-sum-of-squares of each axis – SVM (see Eq. 3) to detect and verify 'free-fall' behavior which is the acceleration towards earth's gravity center with gravitational force – zero g.

$$SVM = \sqrt{Ax^2 + Ay^2 + Az^2} \tag{3}$$

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., 4g) 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 being exposed to major trauma. Between the second and third steps, delay timing (i.e., 1 sec) 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.

3.3. Implementation of the system

3.3.1. Wearable device

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 (Awolusi et al. 2018).

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 in order to address unobtrusiveness. Having out-to-out dimensions of 11,4cm by 8,2cm by 3,2cm (see Figure 21), the wearable device developed for this study consists of a tri-axial accelerometer sensor (i.e., ADXL345 ±16g), 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 2600mAh 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. A schematic illustration of the above explained hardware structure is shown in Figure 22. The hardware components and composition of the developed wearable device is shown in Figure 23 as well.

(b)

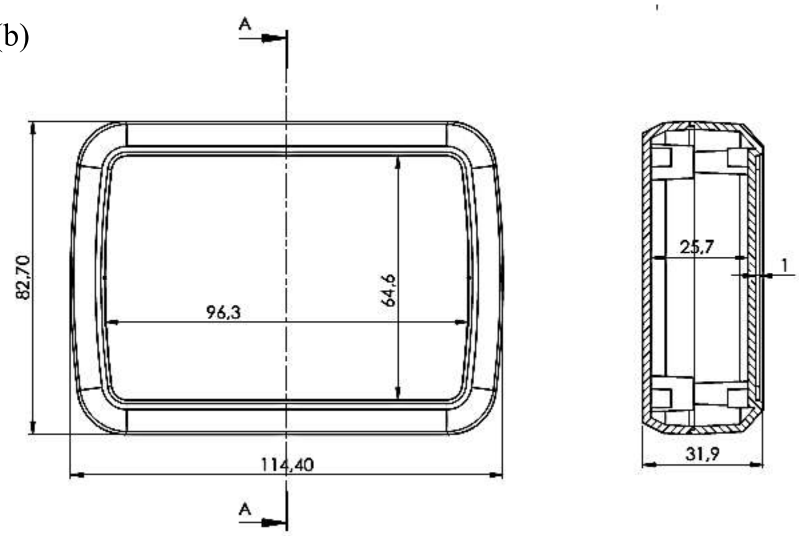


Figure 21 (a) enclosed view and (b) dimensions of the wearable device

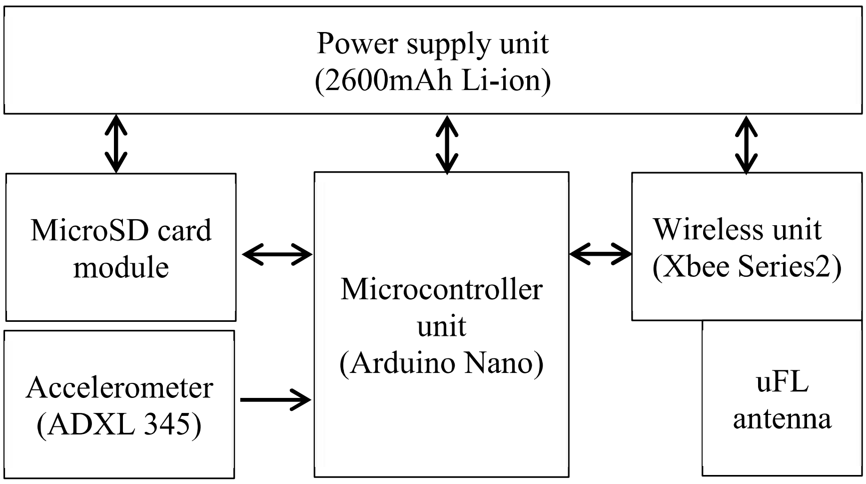


Figure 22 A schematic illustration of hardware structure

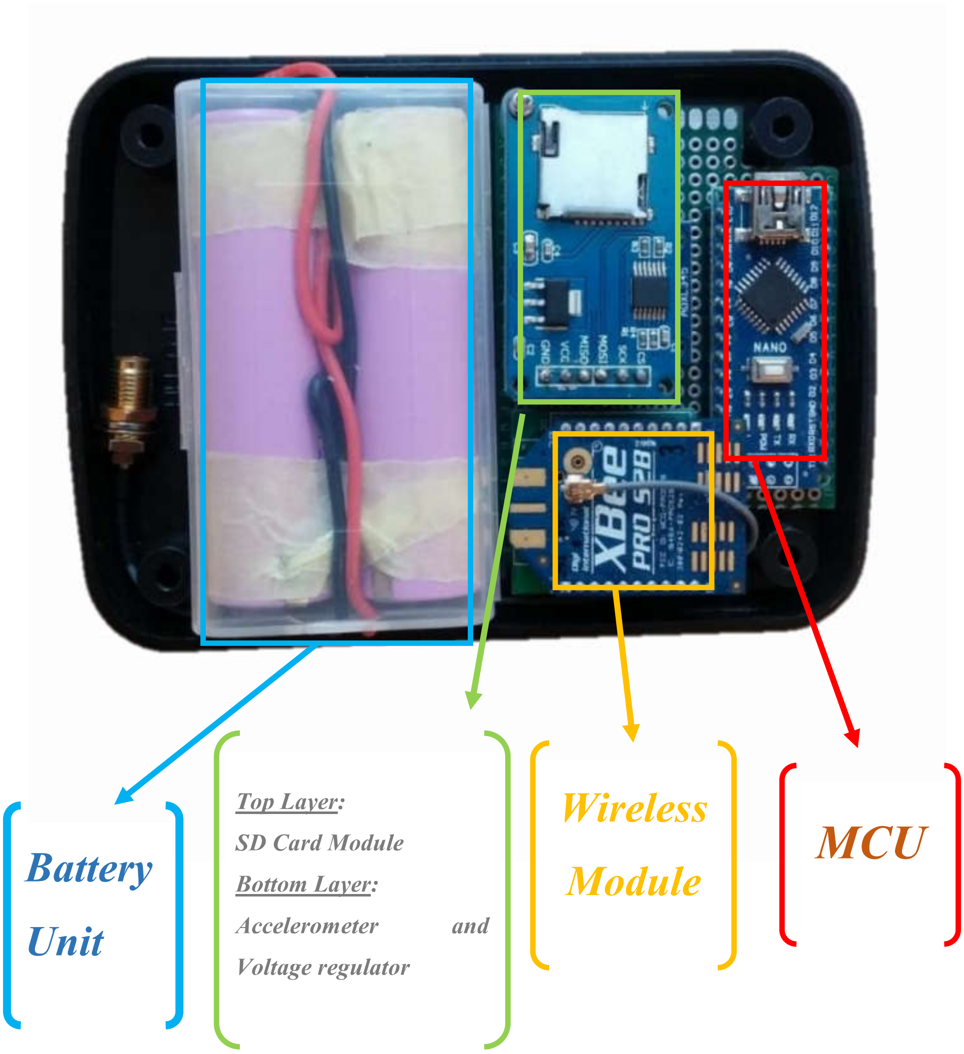


Figure 23 Hardware components and composition of the wearable device

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 (Pannurat et al. 2014). The main reason for this is collecting the overall acceleration from the near body center of the worker as much as possible instead of being deceived by the free motion of body extremities during activities and to prevent false positives of the system outputs due to job activities performed using these extremities.

The system was kept as lean as possible to remediate several concerns about the use of the wearable devices in construction areas. There are several practical issues that limit the use of these sensors in construction sites. These issues can be sources of diminishing factors of proper operation of the device. The wearable device used in this study simply consists of only an accelerometer sensor unlike the other approaches which may fuse different data output using several complementary sensors such as magnetometers and barometric pressure sensors. For instance, using a magnetometer in addition to an accelerometer may seem an attractive solution for detecting falls using orientation feature of the sensor in other applications. However, since construction sites are full of metal materials that may possibly deviate the output of a magnetometer sensor. The use of barometric pressure sensors also have been discussed in several studies regarding the detection of elderly falls (Bianchi et al. 2010; Lu et al. 2016; Wang et al. 2014). However, as can be seen in Figure 24, the barometric pressure sensor would need to have access to the open air through the tiny ventilation hole on its shield to function properly. Thus, possible sources at construction sites would eliminate the sensor from revealing accurate results due to the existence of dust and/or involuntary blockage of the ventilation hole with other materials such as equipment of the worker. As a result, these prevent us using this sensor in areas like construction sites.

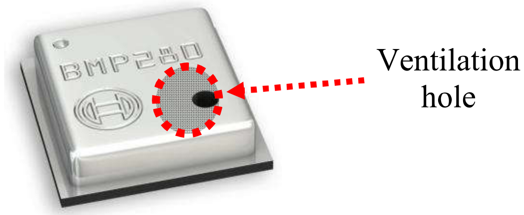


Figure 24 Bosch BMP280 digital pressure sensor

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.

3.3.2. Main control unit and wireless networking

The other tier of the developed system is the main control unit which manages the incoming events from the wearable units properly. At this side of the system, a terminal software had been developed particularly for the system as a middleware to mediate the events of alert situations to its correspondents. In case of fall detection, the wearable units send the alert message to this tier and main control unit handles the situation and routes the alert message directly to the addresses provided in the mail configuration tab of the user interface (see Figure 25).

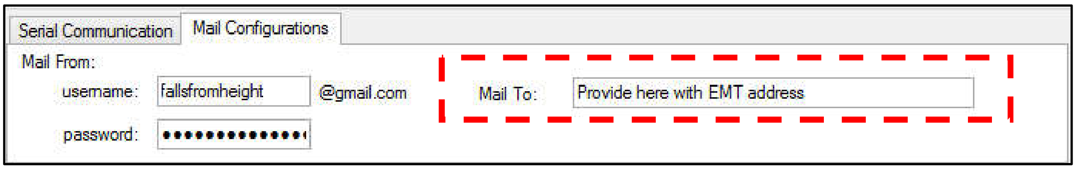


Figure 25 Mail configuration tab

After this configuration, the serial communication tab (see Figure 26) is used to configure the connected coordinator device information which consists of a radio transceiver that is deployed to run as coordinator in the network. The device runs as a sink node in the network to collect the incoming messages from the wearable units which are configured as router devices within the same network. The allocated XBee firmware installed at these radios allows communication and a routing mechanism among the nodes in order to deploy a mesh network (please refer to Figure 8 for an illustration of mesh network topology).

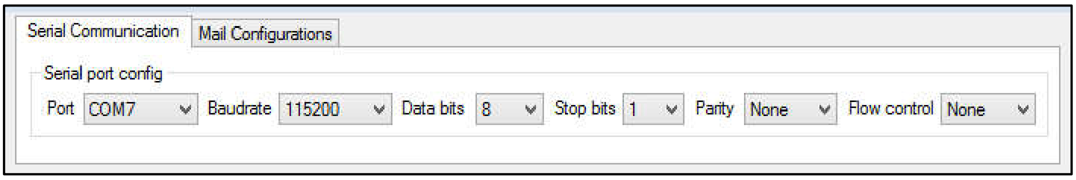


Figure 26 Serial communication tab

In case that FFH accident occurs at construction site, the victim node starts a simple handshaking protocol and broadcasts an alert message through neighbor nodes until the coordinator node receives the message. When the coordinator device (i.e. main control unit) notifies an alert message from the victim node, it responds to the victim node that the message has been reached to the coordinator to stop broadcasting from the victim node. As soon as the alert message is received by the main control unit, it raises alert notification to the corresponding addresses provided in the terminal software. An example content of the alert message is seen in Figure 27.

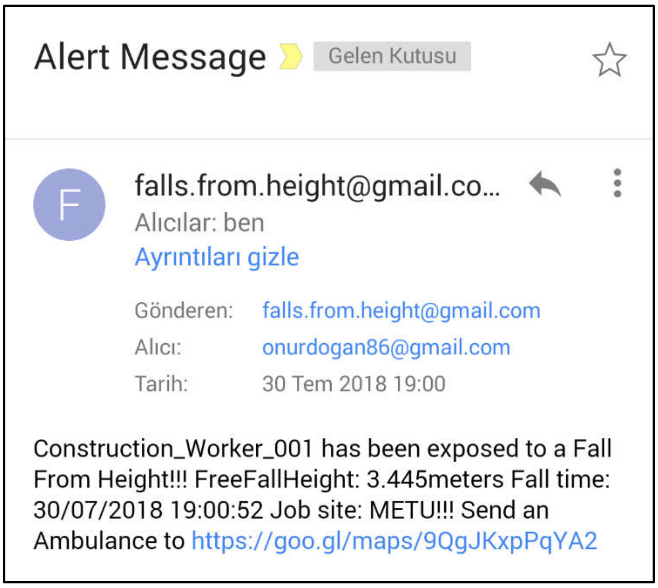


Figure 27 Alert message

As can be seen in the figure, the content of the message includes the fall height that the victim node was exposed to and the time that the message has been sent from the main control unit in order to provide EMT with supporting information about the accident. Also, a URL link of the map for the prescribed address of the site location is embedded into the message to guide the EMT to the corresponding location of the accident.

Although all these processes handled automatically in the background, the user interface of the main control unit also enables to interact with the remote wearable units to send and receive commands via terminal software for configuring the monitoring options for regarding nodes. By default, the software runs with a blank screen and only shows incoming notifications in case fall detection occurs. However, it can be enabled to show the real-time acceleration information of any worker node if it is necessary to track the data at that particular time. shows the user interface with streaming acceleration information of a wearable device on the worker side.

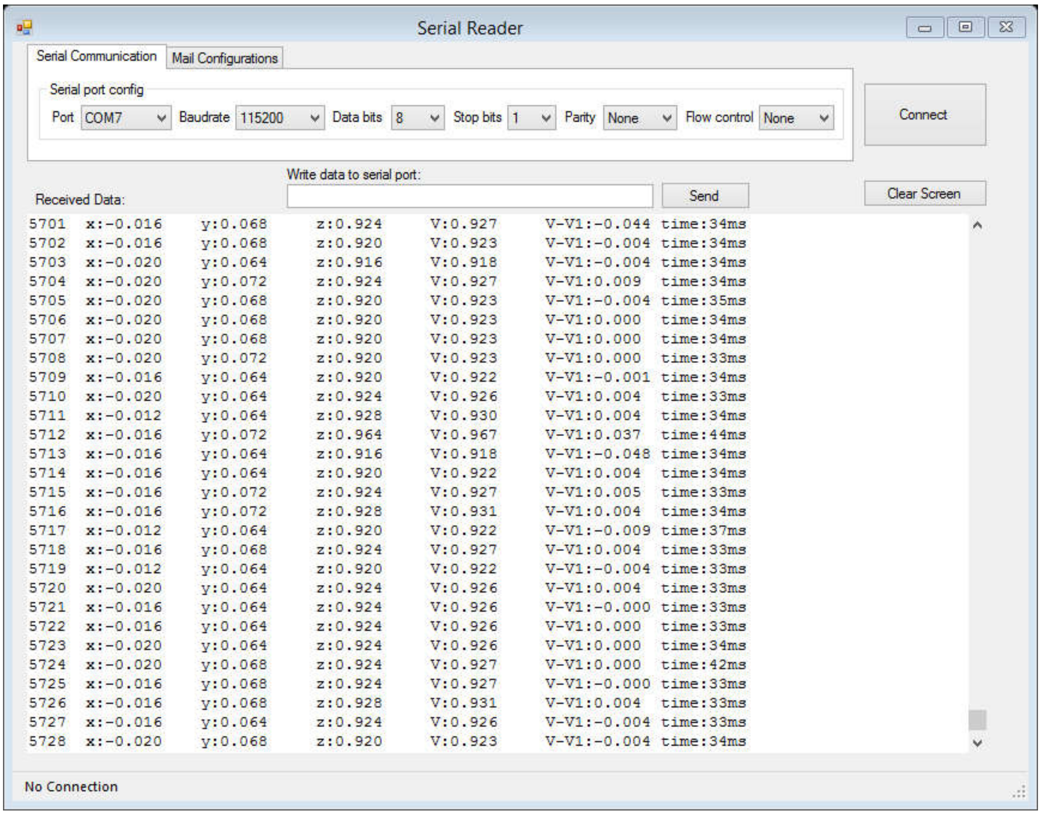


Figure 28 User interface with streaming data

Moreover, after the detection of the fall, the system keeps the duration of disconnected time at the wearable node and reports it in the alert message to provide the EMT with the happening time of the accident, in case any interruptions in the network occur between coordinator and victim node. The solution is simply based on accumulation of the time until the wearable node provides a connection with the main control unit which is verified using the abovementioned handshaking protocol and transmission of the message with the latest disconnection time in the buffer.

In accordance with the studied physics of fall, a multi-phase rule-based algorithm was proposed with the developed wearable device to detect FFH occupational accidents at construction sites. The system surveys the acceleration values of the worker based on the rules included in the algorithm and raises alert notification to the main control unit in case any detection occurs at the worker side. It is then sent with the key attributes and map location of the accident, such as fall height and fall time, to the correspondent EMT personnel to provide an opportunity for a prompt rescue to the victim within the possible shortest amount of time in order to recover unwanted consequences of the accident. The developed system was tested during jobsite experiments, and the results are shared in the content of the next chapter.

CHAPTER 4

EXPERIMENTAL RESULTS AND VALIDATION OF THE SYSTEM

The developed system has been tested primarily in an indoor office environment for the verification of the outputs of the device. In this chapter, preliminary tests have been conducted following the instructions indicated in the regarding section below and the results are shared in the corresponding tables.

Installation of the network into a real construction project that is executed by Yüksel Proje at METU campus and execution of the site tests have been realized to see if the device and the system will work properly on the construction site. The developed wearable device which runs a tri-axial accelerometer and executes the proposed algorithm in this study have been used to emulate FFH accidents. The device is attached to the dummy's waist in order to provide a noise-free behavior while detecting FFH accidents. The data is then collected from the waist-mounted device during designated experiments and the validation of the proposed system is realized for reliable detection of FFH with true fall height and fall time attributes, and against false positives which might occur due to common motions that are performed during construction activities.

The experiments will include falls from elevations of the structure that is mentioned above. The project was ongoing at the moment the experiments were being conducted and the concrete framework of the structure was already finished at the project site. The site experiments have been conducted in order to model the fall behavior and the results obtained from the cases have been collected to derive useful information about the FFH accidents at the construction sites. The height of fall shows variation for the observation of extra data from different cases. The detailed information about the experiments are introduced in the corresponding cases of emulated falls.

4.1. Preliminary test results

The system has been tested in a controlled office environment in terms of fall detection sensitivity and fall height accuracy. Corresponding results are shown in Table 3. 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%.

Table 3 Preliminary 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				

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 4, 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 4 Delay results

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

4.2. Installation and validation of the wireless network

The sensor network has been implemented at the jobsite to observe the performance of the developed system in a real construction environment. Thus, in order to validate if it is functioning well in a real case network scenario, wireless radios have been placed at ground floor level and into the locations indicated in the layout below (see Figure 29). The structure where the experiments have been conducted was a 3-story reinforced concrete classroom hall building structure facilitated at METU Campus. Having different sizes of classrooms on one side and 4 auditoriums on the other side, the building is 53.0 mt in one direction and 52.4 mt in another. At the time the experiment was held, the reinforced concrete framework structure of this three-story building was completed. Also, 25 cm. partition walls that are made from autoclaved aerated concrete blocks were installed except the one where the end device is positioned and, therefore, there was no line-of-sight in between the radios. While the test was being conducted, all the radios were above the floor about one meter. The distances between routers and end device can be seen in Figure 29. The closest router was about 22.50 meters far from the coordinator. Under these circumstances, the implemented setup had been tested to see the performance of the network and a successful communication had been achieved within these ranges between each device.

After the validation of the network communication at ground level, the end device has been attached to a dummy and elevated to 4.30 and 8.60 meters which are 1st and 2nd floors of the building that can be seen in the section cut drawing of the structure (Figure 30). Using only two radios, one was coordinator and the other one was the end device attached to the dummy in this case, communication performance between these nodes was still at its best for functioning and capturing data. The approximate distances between the radios are shown in Figure 30. There was no line-of-sight between the radios during the tests.

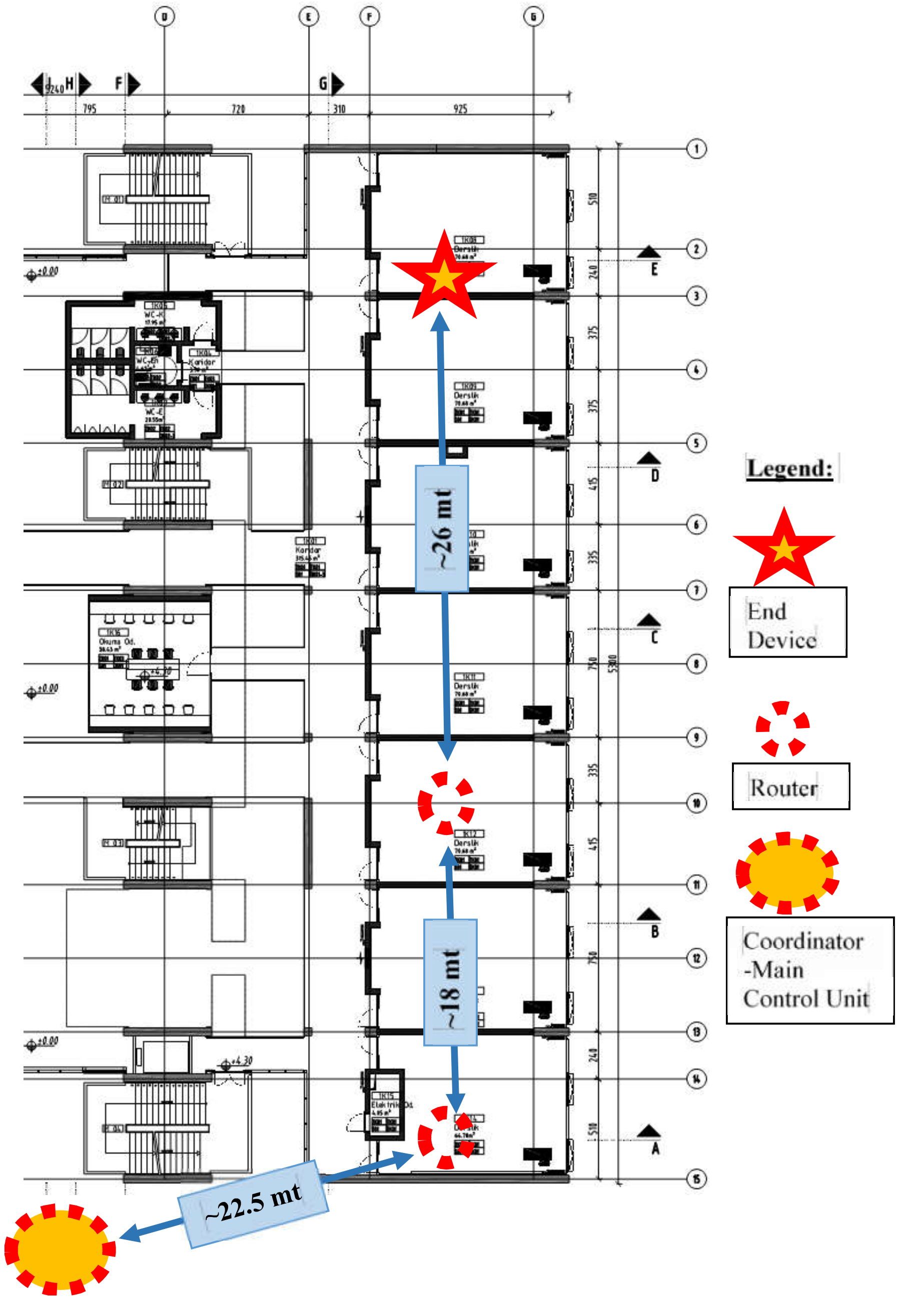


Figure 29 Placement of the radios (ground floor)

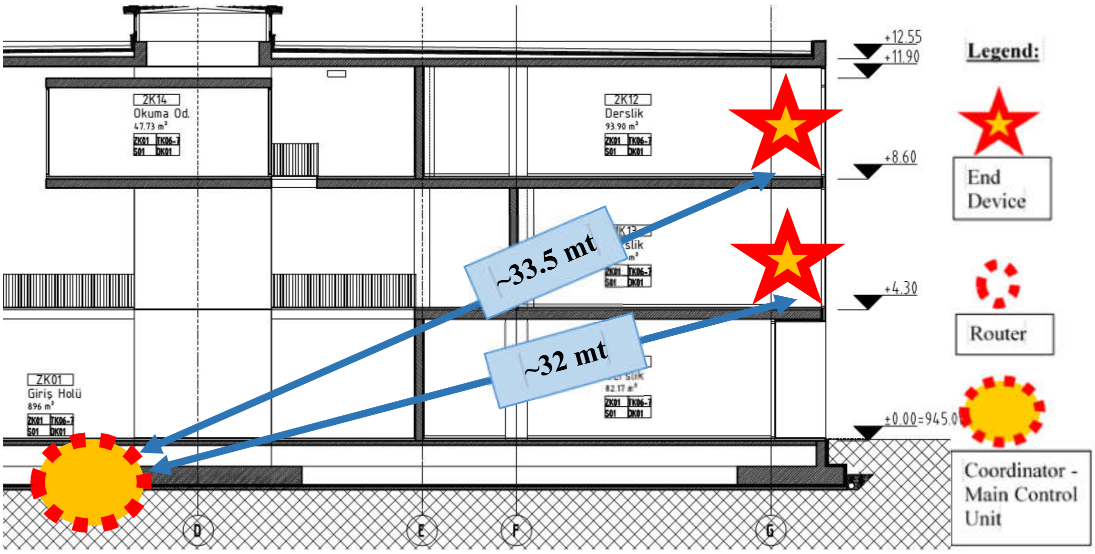


Figure 30 Test elevations (section cut)

4.3. Jobsite experiments

Right after obtaining satisfactory network results, the system has been tested against justification of the system features prior to starting fall experiments on construction site. The only issue encountered during the trials was threshold related. While the subject was falling, it exited the algorithm flow due to the fluctuations in acceleration values that occurred during projectile motion of the dummy. This created a requirement for the revision of the threshold (i.e., 0.25 g) that is formerly used for the free-fall phase of the algorithm. After interrogating the acceleration values produced from these trial tests, a new threshold value (i.e., 0.47 g) was allocated. The execution of the experiments and the validation of the system for its robustness on construction sites have been completed after making this necessary revision for the system.

4.3.1. Data collection

The wearable device was attached to a dummy that weighs as 8 kg. The tests have been conducted at the first and second floors of the building (see Figure 31) to validate the performance of the system. Tests that have been conducted during this work are summarized and can be seen in Table 5. Accordingly, two different test elevations have been used for each floor. During first two experiment sets, a sudden release of the dummy from the edge of the floors (see Figure 32 and Figure) has been done which showed projectile motion during the fall of the subject and a direct release of the dummy from a height of 0.7~0.9 meter above the floor levels (see Figure 33 and Figure 35) has been tested that showed only linear motion without overturning of the dummy subject during falls.

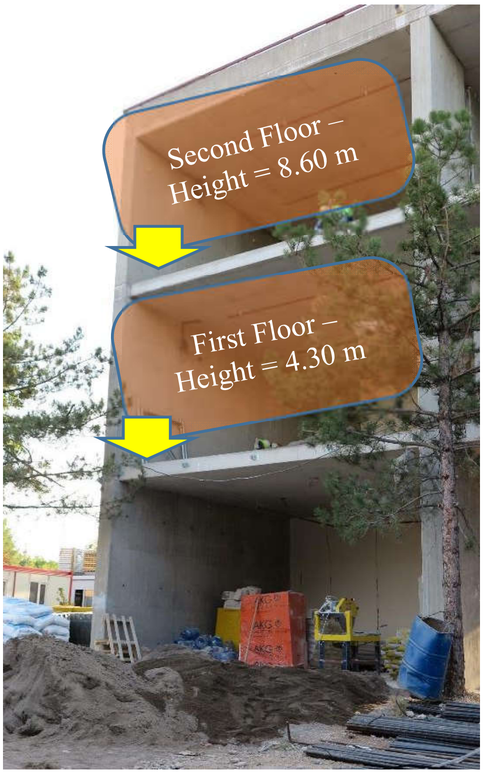


Figure 31 Building floors – FFH test elevations

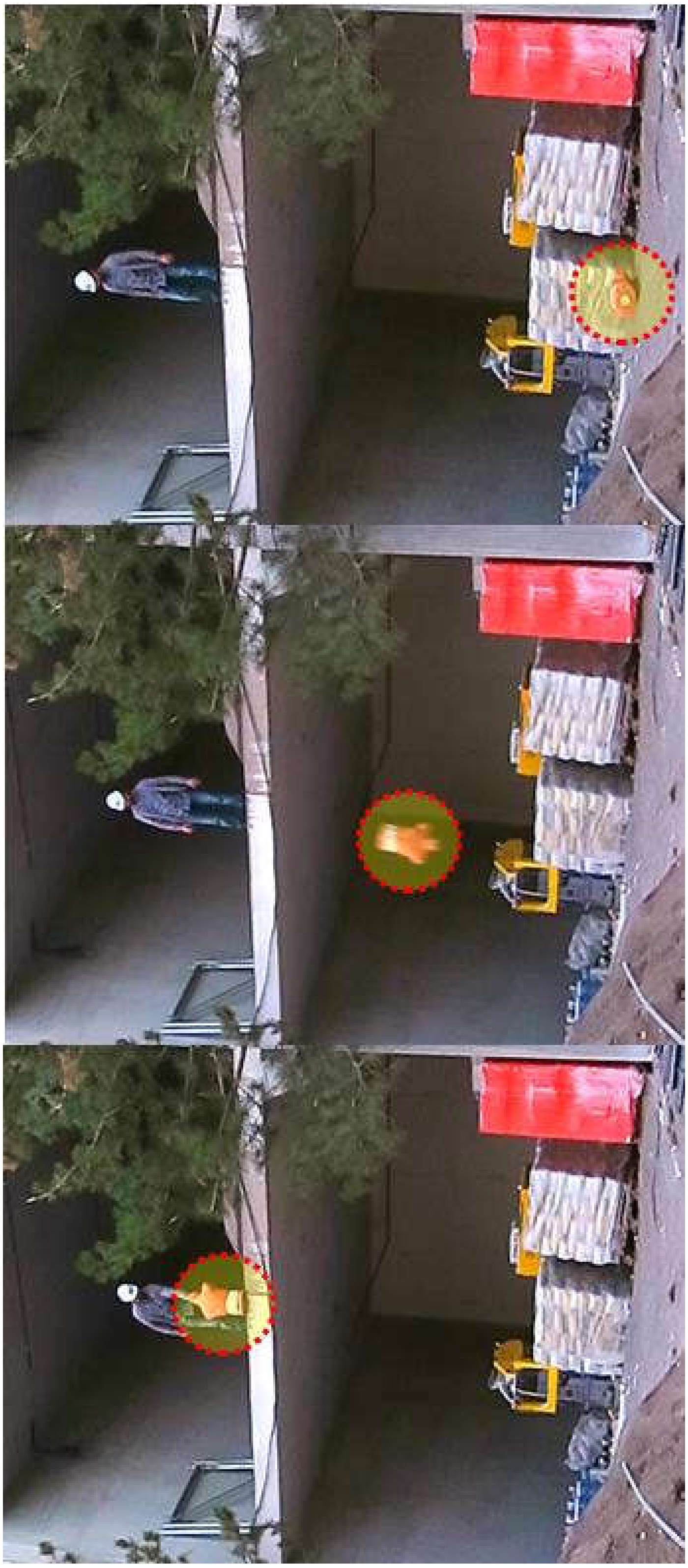


Figure 32 Floor 1 projectile motion FFH test

Figure 33 Floor 1 linear motion FFH test

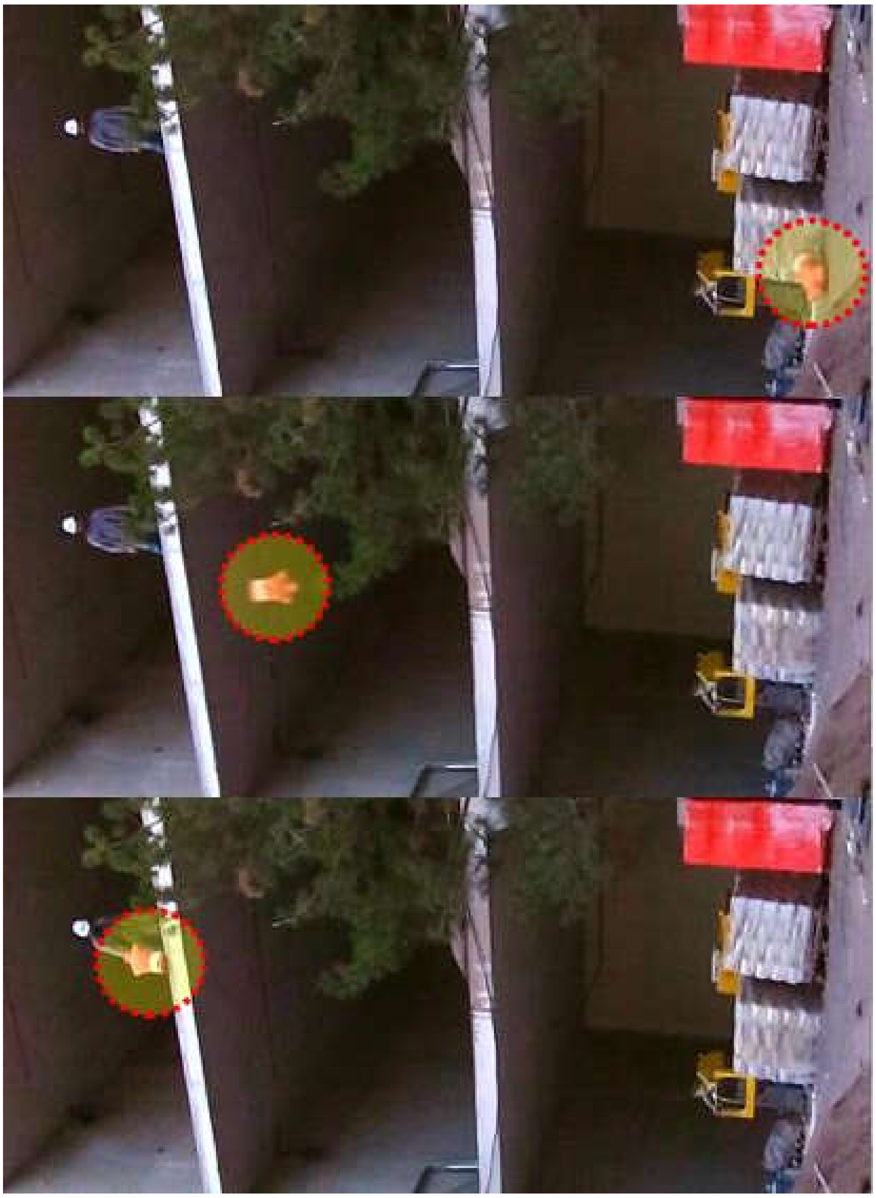


Figure 34 Floor 2 projectile motion FFH test

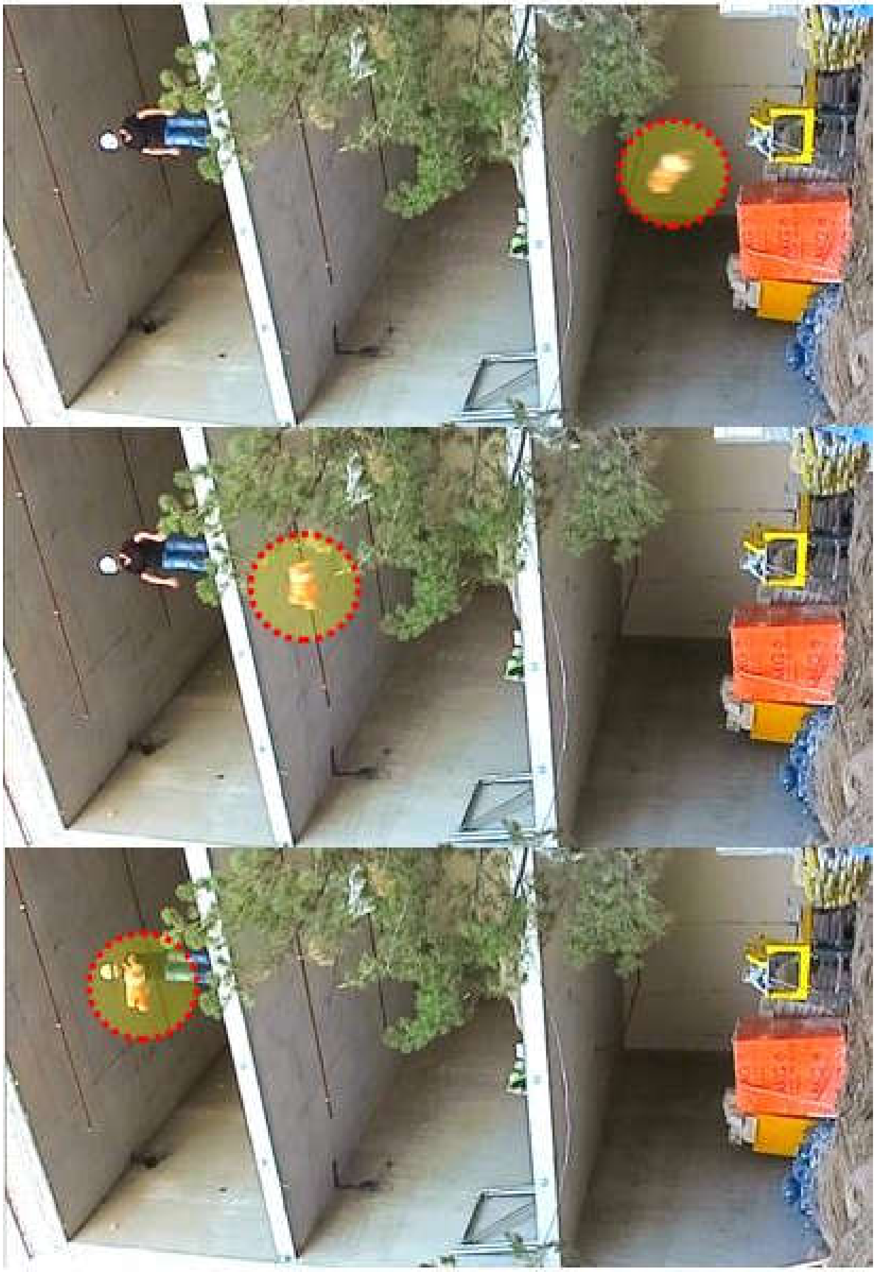


Figure 35 Floor 2 linear motion FFH test

Another test set has been conducted to see if there could be false positives while wearing the device (Figure 36) during daily work activities. In order to do this, the system has been tested for validation against the conditions that may result in false alarms. In this set (Table 6), walking upstairs and downstairs, running upstairs and downstairs, jumping from a trestle and squat have been performed for the tests.

Table 5 Test sets

Experiment	Fall Height (m)	Description
EX1	4.30 / 5.20	FFH
EX2	8.60 / 9.30	FFH
EX3	-	Refer to Table 6

Figure 36 Positioning of the wearable device

Table 6 Experiment 3 validation tests

Experiment	Samples
EX3	Walking upstairs and downstairs
	Running upstairs and downstairs
	Jumping from a trestle
	Squat

4.3.2. Results and performance of the system

As it has been stated in the previous section, jobsite experiments have been conducted for 2 different fall types, 4 different elevations and 4 different movement patterns on the construction site in order to evaluate the performance of the developed system and validate the outputs against false alarms during jobsite activities. To accomplish this, 12 FFH tests from the specified elevations that are indicated in Table 7 have been executed as 6 linear motion (LM) tests and 6 projectile motion (PM) tests. Test drop heights for the dummy and the reported heights in the alert messages of each case have been denoted in this below table. The amount of deviation from the original heights has been calculated as percentage error values for every individual test. The maximum deviation occurred among the tests is 12.7% and the closest one was 0.5%. The overall error rate of the calculated fall heights for these 12 experiments was 5.8% which shows a good overall accuracy of the results reported by the system. Examples of acceleration values for each type of falls from different elevations are given in Figure 37, Figure 38, Figure 39 and Figure 40. As can be seen from these figures, the fall behavior in each test showed similar results with the behavior and phases explained in the method of study section. During free-fall of the subject, the acceleration values reached to zero-g plateau and at the time the dummy collides with the ground, values showed a peak acceleration. Also, there has been variations in the acceleration values due to the type of motion. When released from a height directly, in linear motion, acceleration at free-fall showed much more close values to zero-g. In projectile motion instead, the dummy created accelerations above zero-g due to the overturning of the dummy. These data have been investigated and taken into account for the revision of the algorithm threshold values as well.

Another set of experiments were conducted on the site for validation of the system. In these tests, several motions that may be performed during any kind of construction activity were examined in order to test the potential false positives of the system. Walking/running upstairs and downstairs, jumping from a trestle and/or squat while performing regular tasks on the construction sites were tested with 10 different cases for each type of experiment. No false alarms have been generated during these tests. The results are summarized in Table 8.

Table 7 FFH tests results on site

Experiment	Test case	Drop height (m)	Reported height (m)	Error %	Overall error %
1st floor PM	1	4.30	3.816	11.3	5.80
1st floor PM	2	4.30	4.026	6.4	
1st floor PM	3	4.30	4.279	0.5	
1st floor LM	4	5.20	5.542	6.6	
1st floor LM	5	5.20	5.265	1.2	
1st floor LM	6	5.20	5.053	2.8	
2nd floor PM	7	8.60	8.074	6.1	
2nd floor PM	8	8.60	8.251	4.1	
2nd floor LM	9	8.60	7.505	12.7	
2nd floor PM	10	9.30	10.270	10.4	
2nd floor LM	11	9.30	9.355	0.6	
2nd floor LM	12	9.30	9.946	6.9	

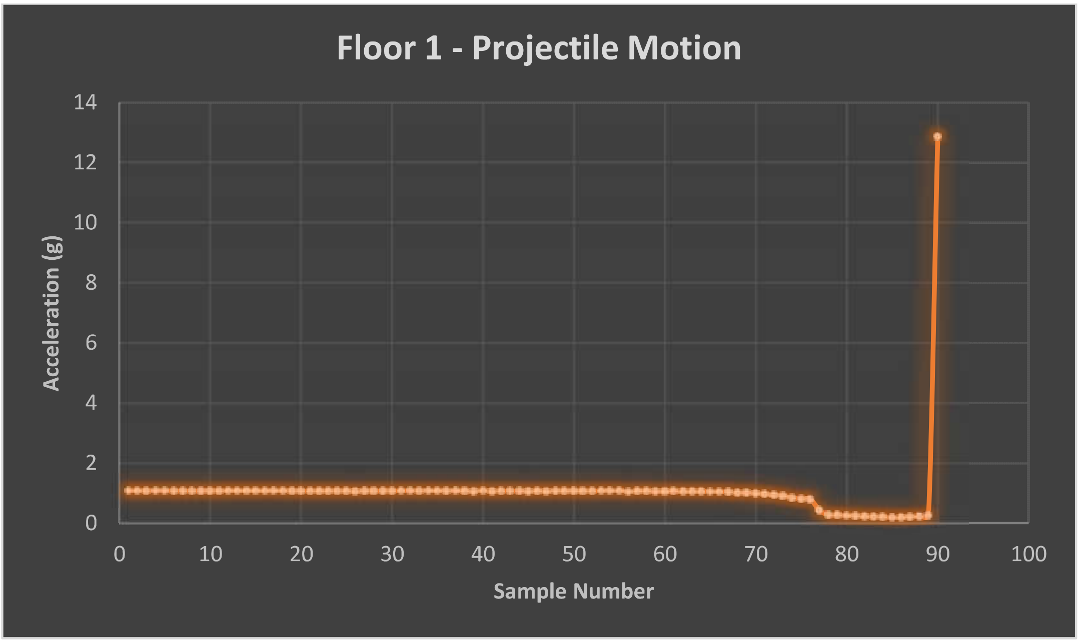


Figure 37 Floor 1 projectile motion FFH test sample acceleration values

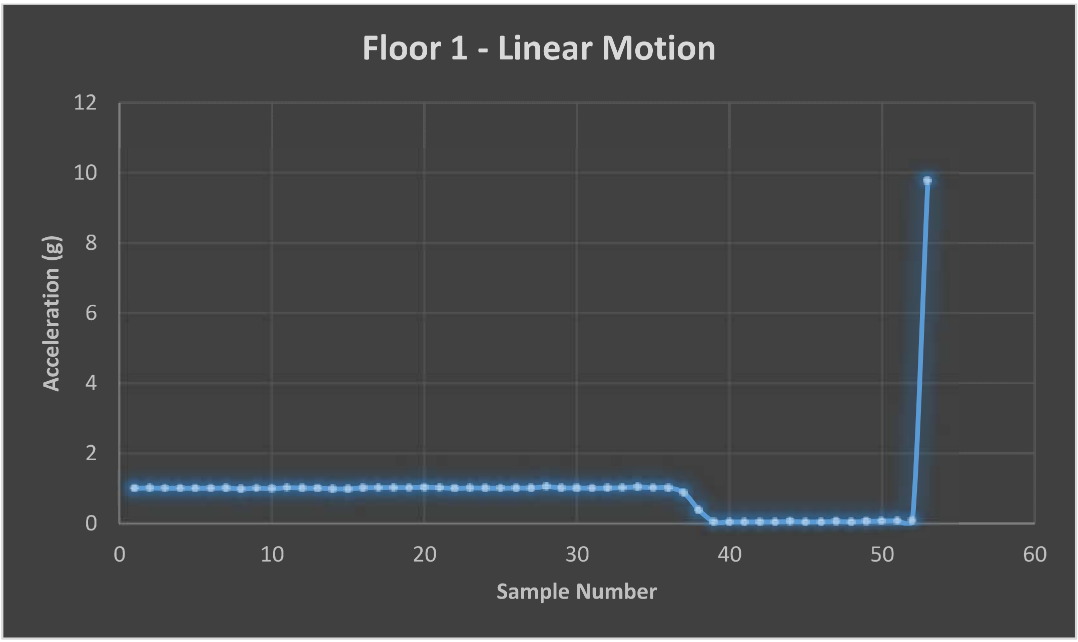


Figure 38 Floor 1 linear motion FFH test sample acceleration values

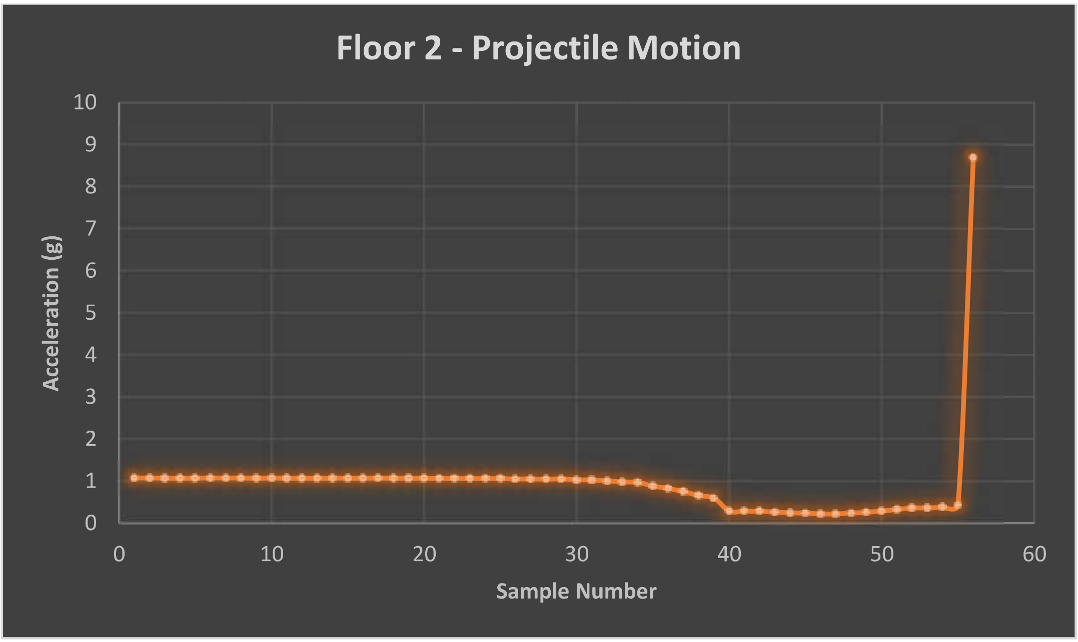


Figure 39 Floor 2 projectile motion FFH test sample acceleration values

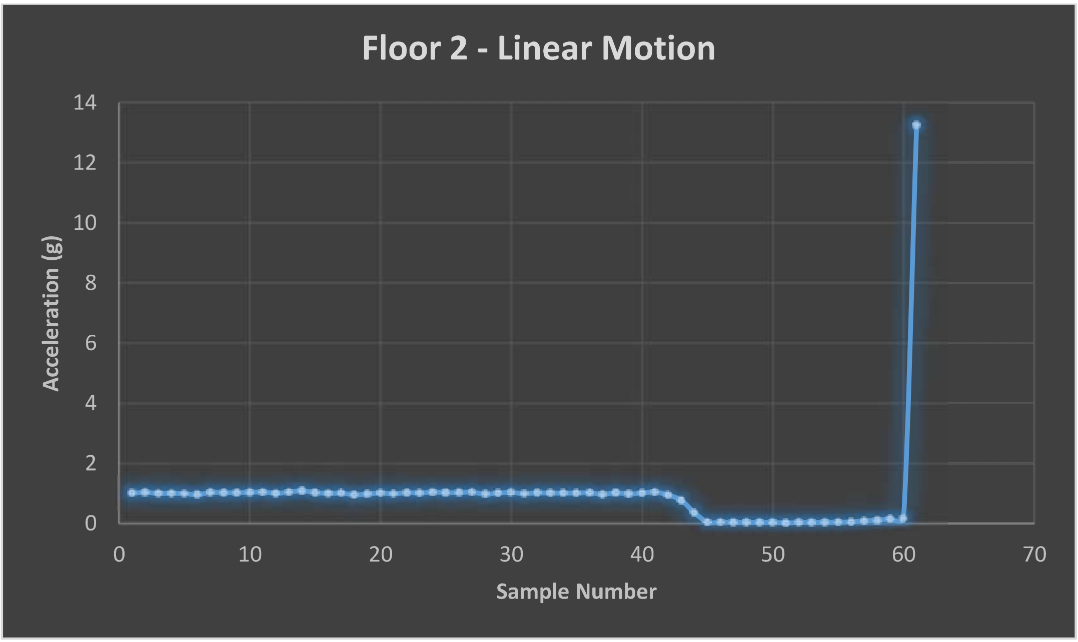


Figure 40 Floor 2 linear motion FFH test sample acceleration values

Table 8 Validation tests results of the system

Experiment	No. of tests	No. of false alarms
Walking upstairs / downstairs	10	None
Running upstairs / downstairs	10	None
Jumping from a trestle	10	None
Squat	10	None

Examples of acceleration values captured during the tests of 3rd experiment set, which have been conducted to verify the system robustness against false alarms, are illustrated in the below graphs separately for each type of motion (please refer to Figure 41, Figure 42, Figure 43 and Figure 44).

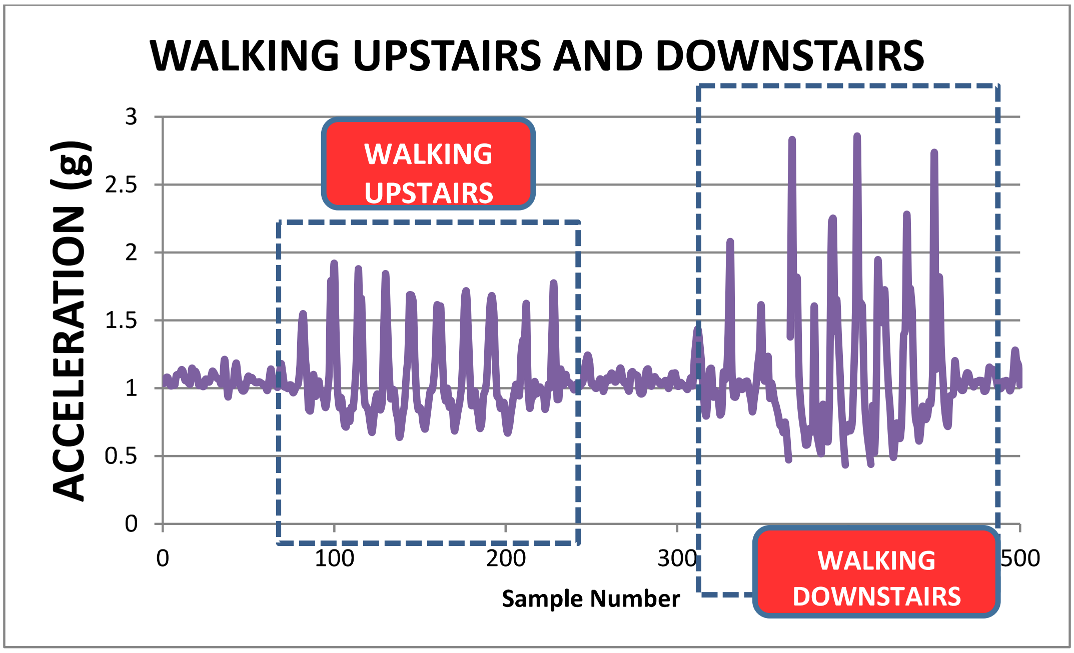


Figure 41 Acceleration values for "walking upstairs / downstairs"

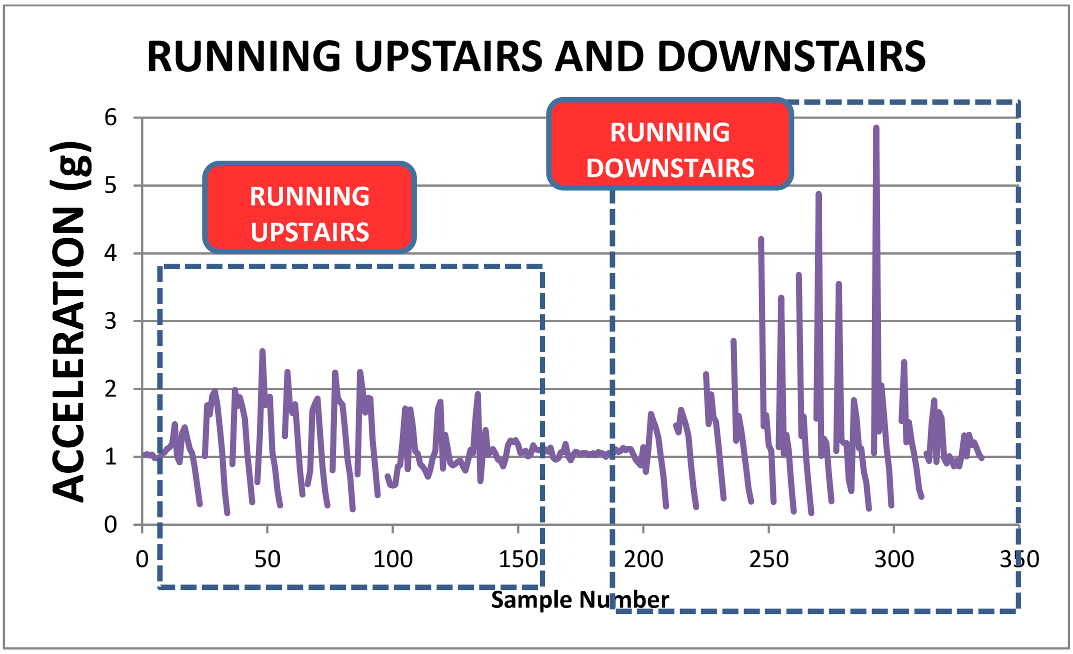


Figure 42 Acceleration values for "running upstairs / downstairs"

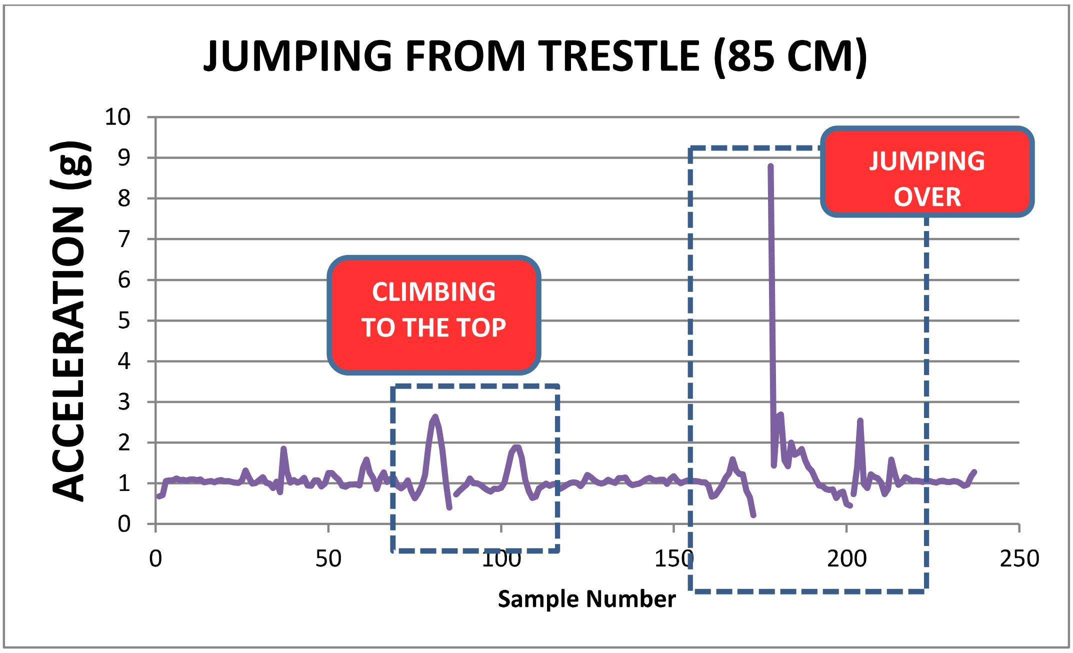


Figure 43 Acceleration values for "jumping from trestle"

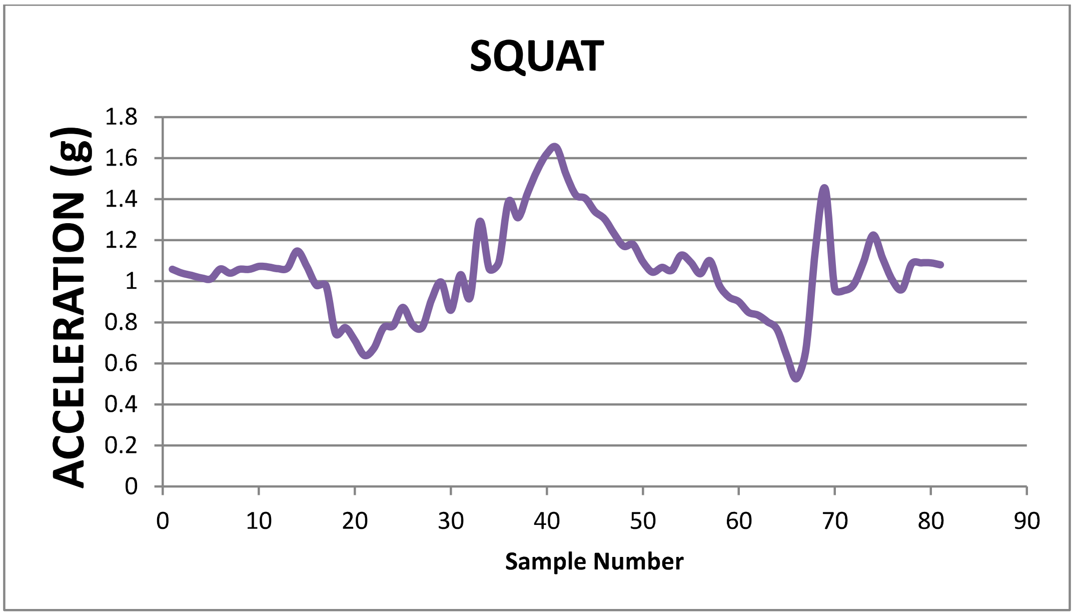


Figure 44 Acceleration values for "squat" motion

During the tests for validation of the system against false positives at construction activities, none of the tests produced false alarms. In walking upstairs and downstairs tests, fluctuations in the accelerations have shown deviations of 1.5-g around 1-g plateau while walking upstairs, and 2-g around 1-g plateau while walking downstairs. The deviation values were about 2-g and 5-g for running upstairs and downstairs, correspondingly. Even though intermittent free-fall values have been produced during running up- and downstairs tests, none of the falls conform to the behavior that is explained in the fall detection mechanism. The steps can be counted easily from the figure and the durations between two consecutive steps are very short due to the low height of these steps which has never yielded a false alarm as a result. Jumping from trestle could have yielded false positives due to the similarity of the behavior with falls if the algorithm was not robust enough to distinguish these patterns. It can be seen from Figure 43 that while jumping over a height of 85 cm the results have shown an intermittence in the graph, that corresponds to free-fall phase, and a peak acceleration above 8-g with a steadiness phase after the collision to the ground on foot. However, free-fall phase was not long enough to conform to the algorithm's first rule. Lastly, the acceleration values of the squat motion showed no similarity with the fall mechanism.

In this chapter, the experiments that have been conducted to verify and validate the system's robustness were introduced with their results. These results will be discussed with concluding remarks in the following chapter.

CHAPTER 5

DISCUSSION OF RESULTS AND 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. Until all the root causes of fall accidents that occur on construction sites have been investigated and required corresponding actions have been taken against these factors to eliminate falls and their serious results totally, the approaches for reduction of the consequences of these accidents still presents a gap in the literature. This gap necessitates a novel approach towards minimizing the overall results of the current problem. For this reason, possible root causes of deaths and disabilities after accidents have been investigated. Incorporating the knowledge of the medical literature, time passed after the accident is found as the most critical factor to a trauma patient that is exposed to FFH accident. If the victim can be provided immediately with an appropriate definitive care by using the time efficiently right after the accident occurs, it may reduce the consequences of FFH accidents by saving lives and/or helping to avoid disabilities.

To achieve this, an IoT-based system has been proposed by developing a wearable device that enables the true and immediate detection of FFH accidents while attached to the waist of the subject of interest and communicates with EMT immediately after the accident occurs. The device hosts a tri-axial accelerometer sensor to abstract acceleration data of worker, a microcontroller unit for processing the algorithm, a wireless communication module to provide remote communication of nodes, a storage module to store the collected acceleration data, and a power supply module containing rechargeable batteries inside.

With the wearable system developed in this study, physiological status of workers is monitored using a tri-axial accelerometer that is facilitated to capture the changes in the acceleration values of the subject of interest to detect occupational fall accidents 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. The major benefit of the system can be achieved when FFH accidents occur at locations away from sight (such as elevator openings, staircases, or not visible locations at night work), since the detection of the fall by site employees might be delayed in such cases. Another main contribution proposed by this system 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 (2003) suggest that the height of fall can give information about the injury mechanism and trauma situation.

In order to detect FFH, the algorithm that runs on the device has been generated by investigating the physics of fall behavior during a fall accident. Accordingly, the acceleration values are put to training for seeking three consecutive phases of the fall mechanism which are '*free-fall*', '*collision to the ground*', and '*steadiness*' correspondingly. To verify phases of the fall, acceleration threshold limits are defined and assigned to each one of them. Using these thresholds, a multi-phase rule-based approach is used in the flow of the algorithm. Based on this algorithm, successive verification of the threshold values during the flow yields an alarm of FFH detection on construction sites.

The produced alarm is then processed through the main control unit to be sent to the prescribed EMT address in no-time with accident attributes such as fall height, fall time, and prescribed location map link of the accident area. In case of Internet and/or network disconnection, the system calculates the disconnection time and embeds this information into the alert message to advise the EMT properly regarding the accident once the connection establishes again.

The system has been tested to emulate FFH accidents 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%.

Additional tests have been conducted at construction site using dummies in order to validate the performance of the system. Several trials have been conducted beforehand to justify the algorithm and its threshold values. Accordingly, the setup has shown that free-fall threshold value of the algorithm needed to be revised due to the projectile motion of the fallen object. The flow of the algorithm stopped many times due to the increase in the acceleration values while the dummy was subject to overturning during free-fall. Particularly, the free-fall threshold value required a change due to the acceleration values obtained at free-fall phase of the fall trials. The acceleration output of the trials has been investigated and this threshold was increased to a value of 0.47g from 0.25g. This made the algorithm more robust during the falls and the system performed as expected without exiting the flow due to the acceleration effects that stem from the projectile motion of the dummy subject.

Consequently, the experiments have been conducted with the revised threshold value at the construction site. Only showing an overall 5.80% deviation from the specified height values, the system performed as expected. From two different floors with two different fall types per each floor, maximum error rate for calculation of the height value was 12.7% (109.5 cm) and the minimum error rate was 0.5% (2.1 cm).

Using the new threshold value, the system had been put to a performance test in order to validate the results against false alarms that may occur on construction sites. To do this, an interrogation for the activities of construction sites that may reveal false alarms has been done. As a result, several motions that are commonly performed during construction tasks have been chosen. While attached to the waist of a human body (see Figure 36), the wearable device had been tested against the motions such as walking upstairs/downstairs, running upstairs/downstairs, jumping from a trestle, and doing squat. For each type of motion, the system has been tested with 10 trials per motion. Results have shown that none of the experiments produced any false alarm during the validation of the system.

The system has been developed to exhibit a different approach from a novel perspective with the priority of addressing the detection of FFH accidents on construction sites. In addition to this, 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. Moreover, it can also be beneficial to use this system integrated with different functions and services that could be used on construction sites such as part of an automated safety management system. With that kind of system, it can also be enhanced to track the unauthorized personnel in restricted or prohibited areas.

5.1. Limitations of the study

The developed system proposed in this study has been tested using a dummy that consists of the upper body part and weighs around 8 kg. The output of the system yielded acceleration data that are only relevant to this dummy. These efforts have been undertaken to emulate FFH accidents at construction sites. Even though it is expected that the system should work properly in real human falls, since the use of real humans were not possible at these fall experiments the acceleration outputs may differ in case of human falls. Free-fall phase acceleration threshold value has been revised due to the production of additional acceleration values during the overturning behavior of the dummy in projectile motion. The threshold values also might require revision for using the wearable device on a human subject.

As mentioned in the methodology, the system uses an algorithm that requires a collision to the ground impact while the subject is falling to a lower level from higher elevations. Falls to safety nets are not tested and the used algorithm might reveal false negatives since the deceleration period will be much longer and the impact will not exist due to the bouncing of the subject on the net when compared to the crash behavior to the ground.

5.2. Future work

As future work, the number of tests is planned to be increased to obtain more results on different movement patterns that may relate to construction job activities. It is also thought that it would be useful to make an extension study that broadens the analysis of outputs of the system based on different trades of construction work on jobsites. Accordingly, trade-based data collection would help to recognize the movement patterns of each trade in a classified manner. Experimenting for customization of potential false positives of the system output for corresponding trades would also be helpful to improve the robustness of the system on construction sites.

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