The Optimized Process for Effective Decision Makings to Minimize Fall From Height (FFH) Accidents on Construction Site

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Abstract –

As one of the most hazardous industries, the construction sector is specifically dangerous due to its dynamic and unexpected working conditions. Among all the occupational risks, Fall From Height (FFH) accidents remain the riskiest ones for a long time, resulting in a huge loss for projects. Although numerous technologies have been adopted to reduce the occurring rates of FFH accidents, the results are not as satisfying as expected. This research aims to figure out both the casual factors or indicators of the FFH accidents and the limitations of the current sensing system for preventing FFH accidents by conducting a systematic literature review. Based on the findings, this study provides potential solutions to each limitation. In addition, this study proposes the optimized process of FFH accident prevention that enables the relevant stakeholders to make effective decisions on the safety issues associated with FFH accidents. This proposed process will set the foundation for system development to minimize FFH accidents, serving as a contribution to the body of knowledge.

Keywords –

Fall from height; Construction safety issues; Technological solutions; Improved system process flow

1 Introduction

Considered as one of the most dangerous and risky industries, construction sector is extremely hazardous due to its dynamic and complex inherence [1] caused by poor working conditions, direct exposure to outdoor environments, and unpredictable change orders [2]. Interactions between workplaces and workforces are complicated but unorganized under some circumstances. As a result, various occupational injuries are identified and addressed [3], causing by trapping, slipping, overexertion, electrical struck, and especially falling from height (FFH) of both objects and human. Based on the reflections from the NIOSH FACE reports [4], FFH is considered as the most significant occupational risk due to its frequently fatal consequences. Additionally, according to the statistics from Occupational Safety and Health Act (OSHA) 2021, the number of violation cases of fall protection is 5295, much more than the number of respiratory protection violations which is 2527. Consequently, there is an urgent requirement to mitigate the problem and decrease the fatality of FFH.

After introducing the significance of FFH to the safety management of construction site, the general types and leading causes for FFH accident will be discussed. As summarized by Liy, Ibrahim [5], six major types of FFH are presented as: falling from roof, falling from scaffolding, falling through holes, falling from ladder, falling from aerial lift platforms, and falling from building girders or other structures. Among all the types, "falling from roof " is considered as the most hazardous type on the basis of a questionnaire for construction professionals and several secondary data such as literature review and case studies. Moreover, four main kinds of causes for FFH are concluded, including "dangerous actions", "dangerous working conditions", "communication barriers", and "failed management commitment". Among all the causes, the highest contributors are "failed to wear Personal Protection Equipment (PPE)" for dangerous actions, "poor site housekeeping" for dangerous working conditions, "information unclearness" for communication barriers. Therefore, these are the key topics under discussion about solving problems on construction sites using technologies currently.

Based both on experiences and regulations, traditionally, three key approaches for FFH protection are setting safety nets, installing guardrails, and wearing personal protection equipment according to OSHA rules. However, these measures are not accurate which including locally specific and worker specific, leading to low efficiency and effectiveness of worker protection. Nowadays, numerous technologies such as radio-frequency identification (RFID) [6], ultra-wide band (UWB) [7], global navigation satellite system (GNSS) [8], and Bluetooth low energy (BLE) beacons are applied to increase the accuracy and effectiveness for solving safety issues [9]. Here are some current functions and purposes of those technologies concluded from previous research (see Table 1).

Table 1 Purposes of some technological implementations on site for falling prevention

Technology	Purpose	Source
RFID	Detect and control PPE on site.	[6]
UWB	Identify, track and locate equipment and materials.	[7]
GNSS	Detect, categorize and organize risk area for workplace.	[8]
BLE	Monitor and harness on site.	[9]

However, although numerous technologies are presented to construction site managers, due to the uncertainty of device effectiveness as well as the limitation and prerequisites for some solutions, many site managers remain suspicious and conservative. In order to explore more, a systematic literature review is conducted for understanding the specific reasons. After figuring out why most site managers refused to adopt technologies for mitigating negative impacts of FFH accidents, an improved process flow aiming at assisting stakeholders with decision making for safety issues on construction site will be proposed, based on the benefits of high-tech devices, prerequisites and capital costs, as well as the conditional effectiveness. Additionally, this proposed process flow will set the foundation for system development of minimization of construction risks, serving as the contribution to the body of knowledge.

2 Research Methodology

The research methodology selected for this research is a systematic literature review, including necessary procedures that defines the key words for searching as well as selection and exclusion strategy for extracting valuable literature information are required. Therefore, this research follows the guidelines created by Thomé, Scavarda [10] which contains four steps as: determine the purpose, select the database, select the keywords, review the relevant articles.

2.1 Determine the Purpose

In order to explore the reasons why site managers are reluctant to implement technological devices in a large scale, the process and mechanism of FFH accident prevention must be understood in advance. Also, the limitation, advantages, and shortcomings of current solutions are under investigation. Based on the results from literature review, elements and indicators that influence the decision-making process of site managers would be acknowledged, served as the foundation for framework establishment.

2.2 Select the Database

Based on the analysis of journal coverage, topic relevance and academic influence from the research done by Mongeon and Paul-Hus [11], Web of Science is chosen due to its significant influences on natural science and engineering.

2.3 Select the Key Words

Since the purpose of literature review is investigating the process and mechanism of FFH accident prevention as well as finding out the pros and cons of current solutions, the topic key words for searching are selected as “fall from height”, “technology”, and “accident”. After first round selection, 81 articles from all time are shown (see Figure 1).

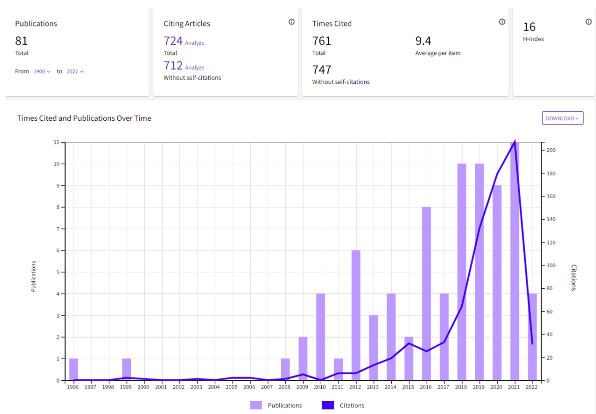

Figure 1 Results from first round selection of literatures for reviewing

2.4 Review the Relevant Articles

Based on the purpose, number of citations and topic relevance, numerous articles are selected for reviewing. Among them six publications are considered as the main materials for literature review due to their relevance and contribution (see Table 2). Three categories are set for the articles as: (a) FFH casual factors, (b) FFH prevention process, and (c) introduction of technical solutions about FFH. The categories are listed along with the titles of literatures.

Table 2 Final literature selection for reviewing

Title	Reason of Selection
(a) Falls from Height in the Construction Industry: A Critical Review of the Scientific Literature [12]	A total of 297 articles concerning fall incidents were reviewed, which are enough to support a critical review.
(a) Analysis of the Contributing Factors for Fatal Accidents due to Falls from Heights in Malaysia and the USA [13]	Official data from the department of Occupational Safety and Health (DOSH) in Malaysia and Occupational Safety and Health and Administration (OSHA) in the USA are the research objects.
(c) Improving the prevention of fall from height on construction sites through the combination of technologies [14]	This research provide several alternative solutions found in the literature about the integrations between different technologies for FFH prevention.
(b) Intelligent Platform Based on Smart PPE for Safety in Workplaces [15]	This research proposes a comprehensive architecture about data transmission process with PPE.
(b) Leading Indicators-A Conceptual IoT-Based Framework to Produce Active Leading Indicators for Construction Safety [16]	This research presents a methodology about utilizing IoT system to collect quantifiable data for actionable response in real time, serving as another approach for optimizing FFH prevention process.
(b) (c) A Fall from Height prevention proposal for construction sites based on Fuzzy Markup Language, JFML and IoT solutions [17]	This research illustrates the benefits that IoT and Fuzzy Logic Systems (FLS) could provide to support decision-making process for FFH prevention.

Three main purposes are set for the systematic literature review: determining casual factors and indicators of FFH, understanding current cyber infrastructure and system architecture, and discovering the limitations and prerequisites of current system and technologies for falling protection. The next step would be the utilization of these information. As the research goal is to assist stakeholders with decision making for safety issues on construction site, the methodology for this research is designing a system architecture for them, helping them reduce the loss caused by FFH accidents while controlling the budget required for technological implementations (see Figure 2).

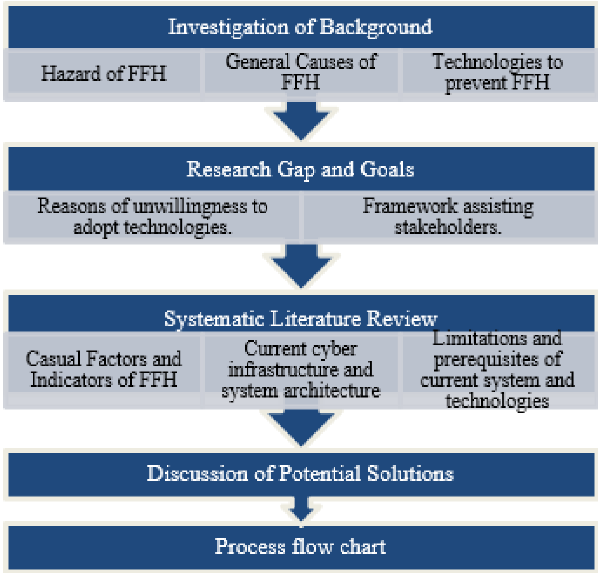

Figure 2 Research Methodology and Process

3 Literature Review Findings

3.1 Casual Factors and Indicators of FFH Accidents

In order to provide the research background about causal factors and indicators leading to FFH accidents, a proven classification obtained from Nadhim, Hon [12] has been applied for this part, explained as below (see Table 3).

Table 3 Classification of risk factors and indicators for FFH accidents from the work of Nadhim, Hon [12]

Risk factors	Indicators	Quantitative variables (unit)
Risk Activities	Working at height	Workplace level or height (ft)
	Complex, difficult, and prolonged tasks	Estimation of working time (hr/person)

Individual Characteristics	Demographic information	Age, gender, weight, ethnicity
	Knowledge level	Education level, working and training time (hr)
	Human behaviours	Times of misjudgement and unsafe behaviours
	Worker's well-being	Absence time due to fatigue, illness, average sleeping time (hr)
Site Conditions	Insufficient illumination	Number of lights, illumination level (lux or lumen/sqft)
	Unprotected platform and surface	Coverage area under protection (sqft)
Organization, Management	Lack training programs	Compulsory training time (hr/person)
	Improper self-protection	PPE availability (counts) and ratio of wearing
	Improper shifting	Shifting times and break periods (min)
	Pressure from schedule	Time until the end date (day)
Weather, Environmental conditions	Bad weather	Temperature (F), humidity (%), noise (dB)
	Untidy workplace	Empty place in a certain area (sqft)

Indicators from Table 2 demonstrate the possible reasons which are responsible for the increasing number of FFH accidents based on the descriptions mainly from OSHA. Also, it would be considered as the criteria for evaluating FFH risk level, a significant part for the establishment of the conceptual framework.

3.2 Cyber Infrastructure and System Architecture for Preventing "Fall from Height" Accidents

By investigating the prototype system from [16], [17], and [15], a normal FFH accidents sensing system contains three major layers as: perception and physical detection layer, transmission and computing layer, and service and cyber-secure applications layer (see Figure 3). This whole system is relying on the Bluetooth Low Energy (BLE) beacon monitoring system.

- Perception and physical detection layer: As the lowest level of the whole architecture, all the physical devices such as sensors, actuators on the helmet, belt, and even bracelet are covered in this layer. Not only aiming at collecting data and gathering status information of both workers and workplace conditions, but also this elementary layer is also responsible for sending the data to the upper layers.
- Transmission and computing layer: The purpose of this layer is to transfer and process the primitive data coming from the first layer and send the transformed data which is considered as the input data to the application layer. This layer contains three key components as local aggregator, service gateway and transmission protocol. The local aggregator is responsible for initially organizing and filtering raw data from sensors, making it transmittable. Service gateway is considered as the "gate" for service and application layer due to its function of receiving and securing data transmission. Normally, there's a modification and repetition loop between the local aggregator and the service gateway, managing to adapt and optimize the system based on user preferences and environmental conditions. As for the last component, one of the widely adopted protocol is the Message Queue Telemetry Transport (MQTT), which is established on the basis of TCP/IP [18].
- Service and cyber-secure applications layer: Considered as the upper part of the structure, this layer is importing information and store them in the cloud environment for both visualization and data analysis such as deep learning models and machine learning algorithms.

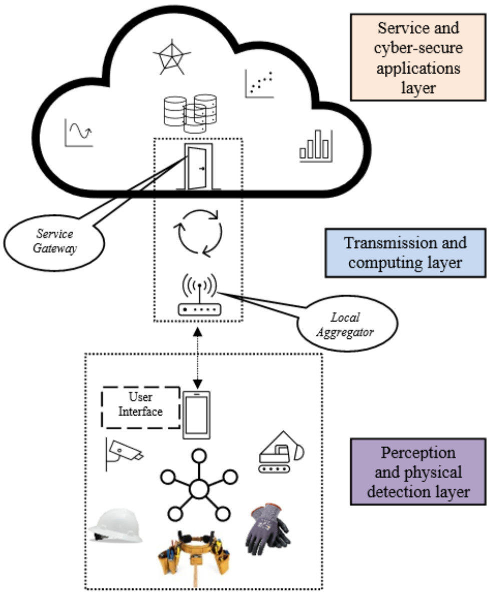

Figure 3 Cyber infrastructure for FFH accidents sensing system

The procedures of FFH accident prevention of this sensing system could be summarized as the following steps: equip workers with self-protection BLE lifeline system, detect and categorize safety area in workplace, send warnings to both workers and management system, and record the parameters from the hazardous situation and save them at the database (see Figure 4).

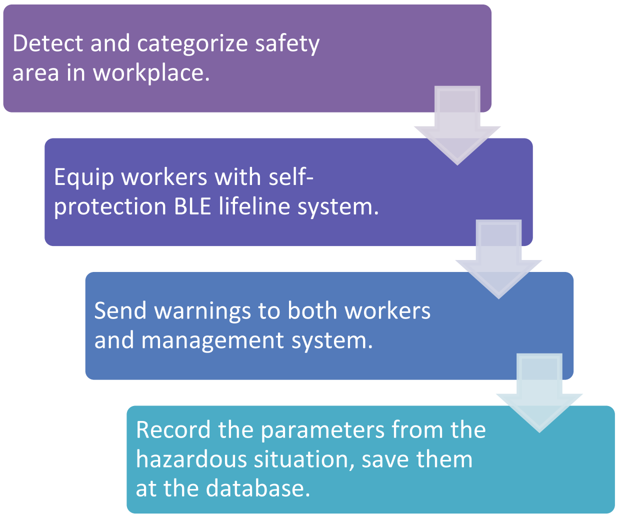

Figure 4 Procedures of FFH accidents prevention

3.3 Limitations and Prerequisites of Current System and Technologies for Falling Protection

Although BLE monitoring system demonstrated strengths in the robustness in risk detection, convenience in installment, calibration and relocation, as well as availability of external support of map updates [9], several important limitations which can't be ignored are presented to construction site managers, too (see Table 4).

Table 4 Limitations and prerequisites of BLE monitoring system

Items	Prerequisites	Limitations	Ref
Risk zone identification, categorization	Analysis of certain areas, locational information	Inaccuracy of area identification due to insufficient number of BLE beacons and opaque or dim conditions.	[9]
Wearable BLE devices	Preinstalled devices and routinely maintenance	Cheating detection required, lag of warning due to poor interference of signal, lack of real-time feedback of risk exposure due to remote monitoring	[19]
Data transfer through Wi-Fi system	Reinstalled Wi-Fi routers	Unavailable in isolated zones, interfered by metal materials	[20]
Computational analysis of worker and workplace data	Sufficient locational and worker data, cloud-based database for storing	Estimation of worker placement with respect to beacons has to be simplified, low accuracy for insufficient data.	[14]

4 Discussion of Potential Solutions

After figuring out the limitations and prerequisites of current sensing system, potential solutions should be identified and analyzed to mitigate the negative impacts caused by limitations. Based on the previous Table 4, keys to solving the limitations are proposed (see Table 5).

Table 5 Potential Solutions for limitations/problems of current sensing system

Items	Problems	Solutions
Risk zone identification, categorization (1)	- Inaccurate area detection & categorization. (1.1)	- GPS system + BIM model + K-means clustering [21]
	- Determination of required beacon number. (1.2)	- Simulation on BIM model
	- Potential FFH risks are not on building plans. (1.3)	- Automatic-BIM based FFH identification and planning tool [22]
Wearable BLE devices (2)	- Cheating detection. (2.1)	- Computer vision-based movement detection
	- Warning lag, lack of real-time feedback (2.2)	- Real-time location system to detect the proper use of PPE [23]
Data transfer through Wi-Fi system (3)	- Unavailable in isolated zones. (3.1)	- Global Navigation Satellite System (GNSS)
	- Metal material interference. (3.2)	- Second RFID signals
Computational analysis of worker and workplace data (4)	- Localization of workers in the certain workplace. (4.1)	- BIM model + Simultaneous location and mapping (SLAM) algorithm [24]

Explanations of the solutions:

- (1.1): In order to categorize the area and set the boundaries accurately, Global Positioning System (GPS) is applied for locating the coordinates of essential points on site. By combining the data with 3D BIM model rather than traditional 2D building drawings, a more accurate risk distribution map could be made for construction managers, while the K-means algorithm could categorize the whole project area into different clusters based on their historical data about FFH accidents, risk factors, demographical information of workers, etc. Results from the analysis will be directly shown to site managers for further operations.
- (1.2): One of the applications of BIM modeling is the 4D simulation for clash detection and making scheduling alternations. Hence, if 4D BIM is used for determining the exact location and number of sensors that are required on site, the cost for real-time experiment could be diminished since the managers could experience the real-time situation simply during the simulation.
- (1.3): According to the paper by Zhang, Teizer [25], they created an automatic BIM-based FFH identification and planning tool, which could help with the beacon harness system to confine the inspection areas for risk detection, better than general inspections that are time and money costing.
- (2.1): In some cases, all the BLE devices are connected properly, but some workers undress the harness and leave them to the lifeline since it's not comfortable to wear them all the time, cheating the system eventually. With the help of computer-vision-based movement detection, even if the devices are connected, warnings will be sent if cameras detect suspicious cheating movements.
- (2.2): In order to have real-time feedbacks between workers and the system, Dong, Li [23] designed a real-time location system for detecting proper use of PPE and giving feedbacks to workers under urgent circumstances.
- (3.1): For some specific projects, including

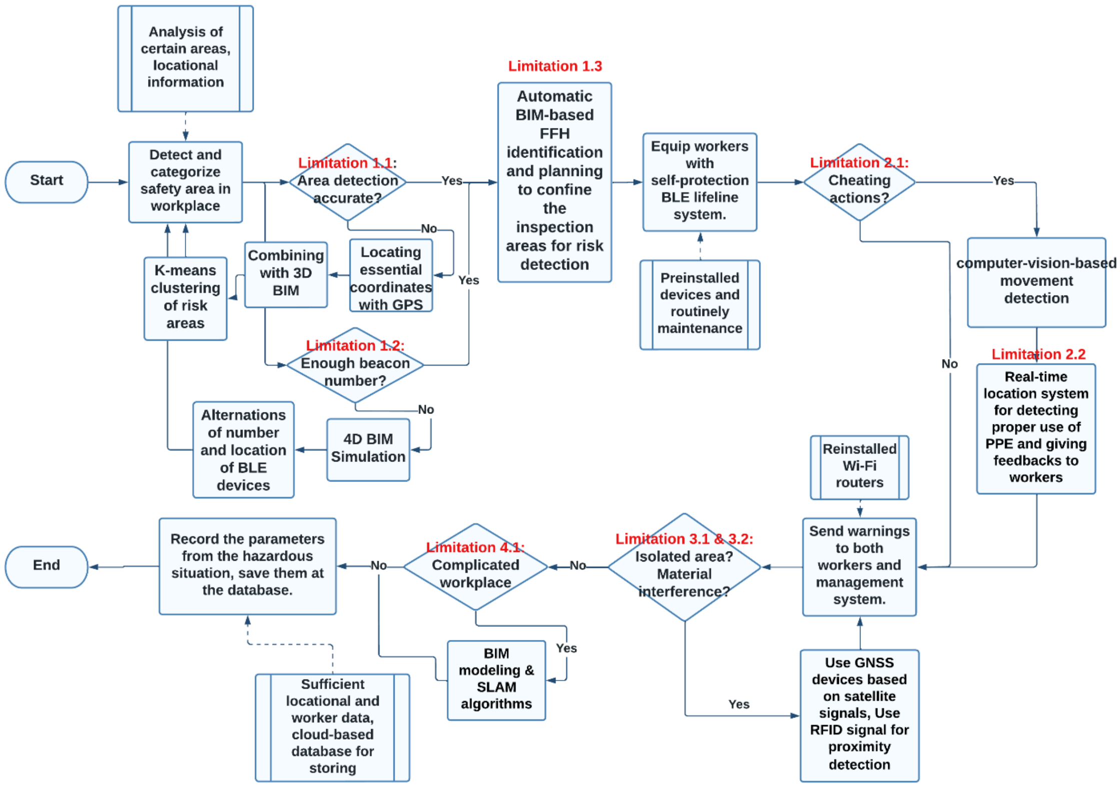

Figure 5 Optimized procedures of FFH accidents prevention

highways, railways, and tunnels, Wi-Fi signals are not always consistent, resulting in lag of communications or ineffectiveness of Wi-Fi relied on devices. Thus, GNSS devices based on satellite signals are especially useful under this circumstance.

- (3.2): If the BLE or Wi-Fi signals are blocked by metal materials such as steel beams and steel nets, the second RFID signal is needed for proximity detection, controlling the use of PPE in some hazardous areas.
- (4.1): If the working environment is complicated, by using BIM modeling and SLAM algorithms, the map and environment could be worker-based, meaning the localization is based on worker's position. The locational relationship between workers and workplace is adapting automatically.

After applying those potential solutions to the current system processing procedure, several alternations could be made (see Figure 5).

5 Conclusion and Future Research

This study identified and analyzed the casual factors and indicators of FFH accidents as well as the limitations of the current sensing system for preventing FFH accidents by conducting a systematic literature review. Based on the analysis, this study also proposed a novel process flow that can support site managers' decision making for minimizing FFH accidents. The proposed process flow will serve as the foundation for future system development of FFH accident minimization software and cloud-based management platform. The findings will contribute to the body of knowledge by 1) enabling the construction industry to deeply understand FFH accident and how to prevent it and 2) providing a practical framework for optimized procedures of FFH accidents prevention.

Future studies will focus on the justification of the effectiveness for each solution, validating that the improved system can actually reduce the FFH accident rates on site. What's more, the realizability of different integration and implementation of technologies should be under further investigation, along with the guarantee of cyber security during the data transmission process. Last but not least, comparison studies for the cost of the system implementation between previous versions and the improved versions will be made to demonstrate that the proposed improved process flow not only satisfies the goal of accident rates reduction but also controls the total budget of the project.

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