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Improving the prevention of fall from height on construction sites through the combination of technologies

María del Carmen Rey-Merchán [a], Jesús M. Gómez-de-Gabriel [b], Juan-Antonio Fernández-Madrigal [b] and Antonio López-Arquillos [c*]

[a] *Consejería de Educación y Deporte, Junta de Andalucía, Spain;* [b] *System Engineering and Automation Department, University of Málaga, Spain;* [c] *Economics and Business Management Department, University of Málaga, Spain;*

Fall from height is a cause of concern in the construction sector. Appropriate use of a harness can be the difference between an incident or a critical accident. Monitoring the proper use of a harness in the workplace using Bluetooth Low Energy (BLE) devices is a recent and effective approach. The aim of this article is to identify typical limitations in a BLE monitoring system in order to propose solutions according to the existing literature. Alternative solutions found in the literature showed that the integration of BLE with other technologies such as building information modeling, radio-frequency identification or the global positioning system can improve the effectiveness of current monitoring approaches based only on BLE and reduce rates of fall from height accidents. For correct integration, both technological factors (cost, compatibility, data transmission) and cultural factors (social acceptance, procedures, etc.) must be taken into account.

Keywords: construction safety; fall from height; harness; beacon; safety at work

1. Introduction

The construction sector is considered one of the most dangerous industries in many countries [1,2]. It is particularly hazardous because construction projects are dynamic and complex, and sites and workforces are changing in their interactions continuously and unpredictably. Different occupational risks have been identified and addressed in these environments, such as slipping, trapping, overexertion or electrical contact, but fall from height (FFH) is considered the most dangerous due to its frequently fatal consequences [3–5].

There are a number of safety strategies and measures focused on preventing FFH accidents, such as prevention through design (PtD), collective protection – guardrails or safety nets – and personal protection equipment (PPE), e.g., safety harnesses, which are considered the last defense to avoid injuries due to FFH. The misuse and non-use of PPE many times turns an incident into a critical accident or a disease [6]. The use of fall protection equipment is regulated in general by national rules, and particularly by safety plans in each construction project. Broadly, it is considered that employees who work at a height over 2 m are exposed to FFH accidents and, thus, at least the use of a harness should be considered.

In the USA, employers are allowed to use any or all of the three fall protection systems (safety nets, guardrails or personal arrest system) according to Occupational Safety and Health Administration (OSHA) rules. In other countries, this is more strictly regulated. In China, e.g., it is stipulated that employees working at a height of 2 m or higher must use fall arrest equipment in every case. Unfortunately, in spite of these legal requirements, workers often do not use a harness properly because of discomfort, restriction of movements or low risk perception.

Education and training are therefore very important to change worker behavior and, in general, safety culture at the worksite [7], but, also, safety managers need practical tools to control the adequate use of safety measures in dangerous areas [4].

In the construction sector, technology adoption is lower than in other industries, but pressure to improve productivity, improve safety and reduce costs has developed a positive environment [8]. Cited authors pointed out that the key to technology adoption is integration into the organization's process, systems and cultures rather than technology itself. In addition, it is important to consider that the cost-saving potential has been identified in the literature as a primary factor for adopting technology by construction firms [9].

In order to address these issues, different technologies have been proposed; particularly, using electronic devices in construction has definitely contributed to manage safety conditions. For example, radio-frequency identification (RFID) can be applied to detect the use of PPE or access to

*Corresponding author. Email: investigacioncatedra@gmail.com

a dangerous zone [10], ultra-wide band (UWB) can serve to identify and locate materials [11] and the global navigation satellite system (GNSS) can detect a risk area and worker location [12]. More recently, in order to monitor the proper use of harnesses, a sensor system based on bluetooth low energy (BLE) beacons has been proposed [13].

Although the cited technologies certainly contribute to improve safety conditions, all of them present some technical limitations when they are applied separately. Due to the fast development of electronics, many previous reviews only focus on providing a comprehensive collection of existing solutions [14–16], while research aimed at integrating them in order to address their individual limitations is scarce. One example of the latter is the work by Valero and Adán [17], where the integration of RFID and other technologies in the construction sector is tackled, although from a generic perspective not based on practical cases.

To the knowledge of the authors, no previous studies exist concerning the integration of beacons with other technologies for improving safety in construction; having these devices with a wider range of possibilities while keeping the cost low, it is very interesting to analyze their possibilities in the context of their integration with other devices that can overcome their intrinsic limitations.

The objective of this article, therefore, is to set the basis for addressing the limitations and weaknesses of harness beacon monitoring systems through adequate integration of these beacons with other technologies. The structure of the article is as follows. In Section 2, a description of an existing beacon-based BLE system and its limitations are presented. Section 3 describes the technological solutions proposed to cover those limitations, and discusses them. Finally, a conclusions section reviews our work and proposes future steps.

2. Methodology

Our current research is the second phase of a research project focused on the application to construction sites of harness monitoring systems based on BLE beacons. The project phases are presented in Table 1.

Table 1. Main phases followed in this project.

Phase	Step	Description
1	1 – Problem detection 2 – Practical solution based on beacons	Monitoring proper use of a harness in the workplace • Design of a novel harness monitoring system based on Bluetooth Low Energy • Prototype of the proposed system • Test of the system in real scenarios
2	3 – Limitations of the approach	Identification of limitations according to the results in the real implementation of the prototype
	4 – Search for improvements	General literature review about available technologies applied in construction safety
	5 – Proposal of technological solutions	Analysis of the possibilities of each technology and proper combination of diverse ones

Phase 1 was completed as reported by Gómez-de-Gabriel et al. [13], while Phase 2 is discussed in this article. We include in the following a brief description of the previously developed harness monitoring system to put the study into context.

2.1. Description of a harness monitoring system based on BLE

The system is composed of a harness, as shown in Figure 1, that has been instrumented with a BLE receiver. A first beacon has been installed at the lifeline carabiner hook, and a set of additional active BLE beacons placed along the risky entry paths of the workplace. BLE devices transmit a signal that can be used to estimate the distance between the transmitter and the receiver based on the received signal strength indicator (RSSI) technique. In a RSSI model, if the distance increases then the signal strength fades, and RSSI values decrease. However, RSSI values are noisy and they can suffer effects such as reflection or diffraction due to environmental objects. Then, in order to obtain consistent RSSI values and to detect the worker status, a hybrid statistical filtering/finite state machine method deduces in real time both the area in which the worker is located and whether the lifeline has been attached before entering a risk zone, using only the RSSI measurements of just three beacons with a minor configuration and therefore low cost (Table 2).

A brief description of the previous monitoring systems based only in beacons is shown in Figure 2. A beacon receiver (R) with a programmable microcontroller is included in the safety harness. Two beacons (A and B) are placed in the access way to the risk area, where FFH risks are important. The last beacon (C) is integrated near the lifeline hook.

2.2. Limitations of the BLE monitoring system and possible solutions

In our previous work [13] we assessed the many advantages the BLE system has, such as robustness in the detection of risk, easy relocation of the beacons as the construction zone evolves and no need for calibration, communication infrastructure, external processing support or configuration/map updates. However, after implementation at a real construction site, some limitations have also

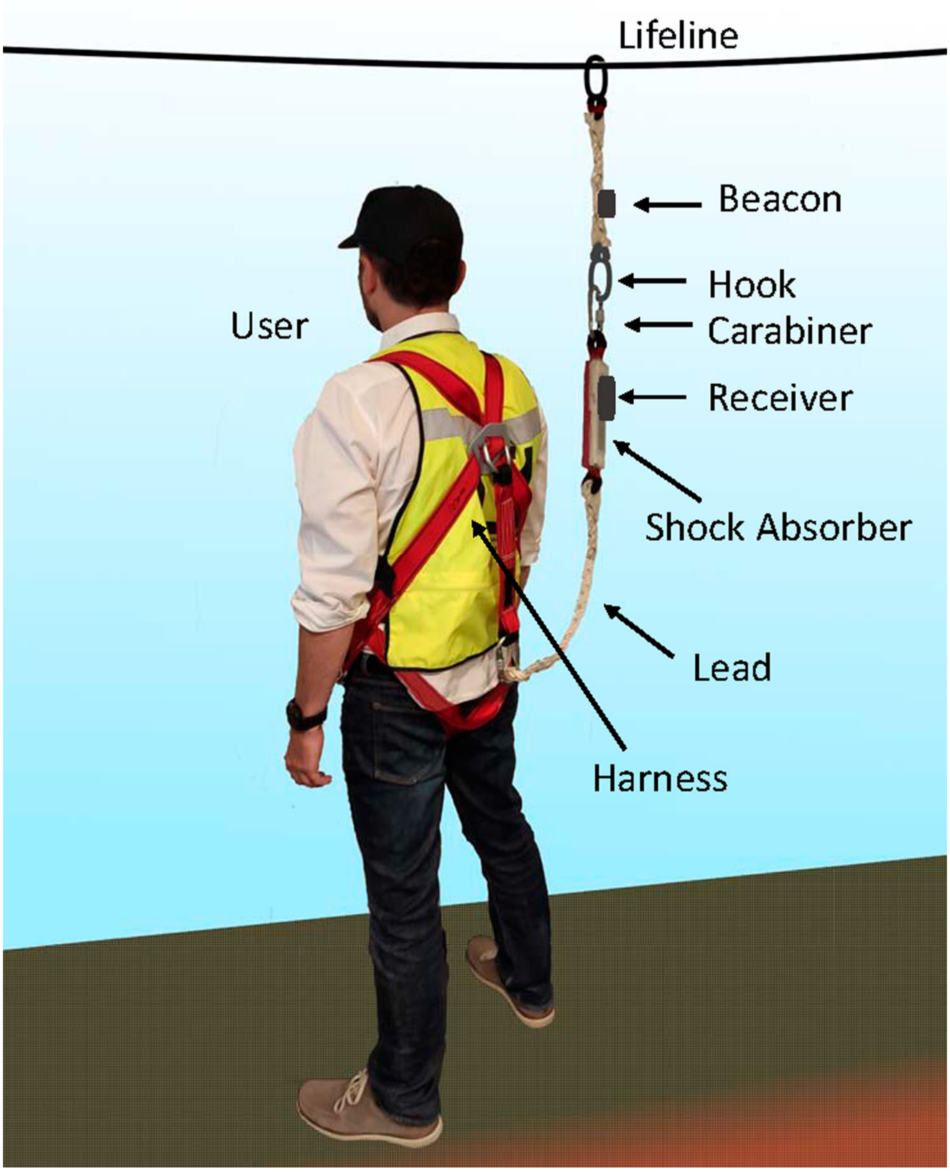

Figure 1. Harness with a Bluetooth Low Energy receiver and lifeline beacon system.
Note: The harness attaches to a lifeline by connecting the carabiner to the lifeline rope. A shock absorber is also included between the carabiner and the harness. A radio-frequency beacon and a receiver are used to detect the proper engagement of the harness.

been detected by workers and safety managers (Table 3). The most important limitations are as follows:

- dangerous zones must be identified before the worker enters;
- the worker is able to cheat the system if he undresses the harness while letting it connect to the lifeline;
- monitoring is carried out in a remote station, thus the system currently does not provide real-time feedback to the worker;
- in isolated zones, WiFi is not always available;
- the software is currently designed for embedded platforms with limited computing resources, which forces some simplifications in the probabilistic estimation of the location of the worker with respect to the beacons.

After these limitations had been detected, a literature review was carried out with the aim of identifying and analyzing available solutions in the current technological scenario. This review has been conducted using the following databases, identified as relevant: ISI Web of Science [18], Scopus and Science Direct. We did the search by title, abstract and keywords fields. Duplicate documents from different databases were removed, and findings were classified according to the technology applied. Finally,

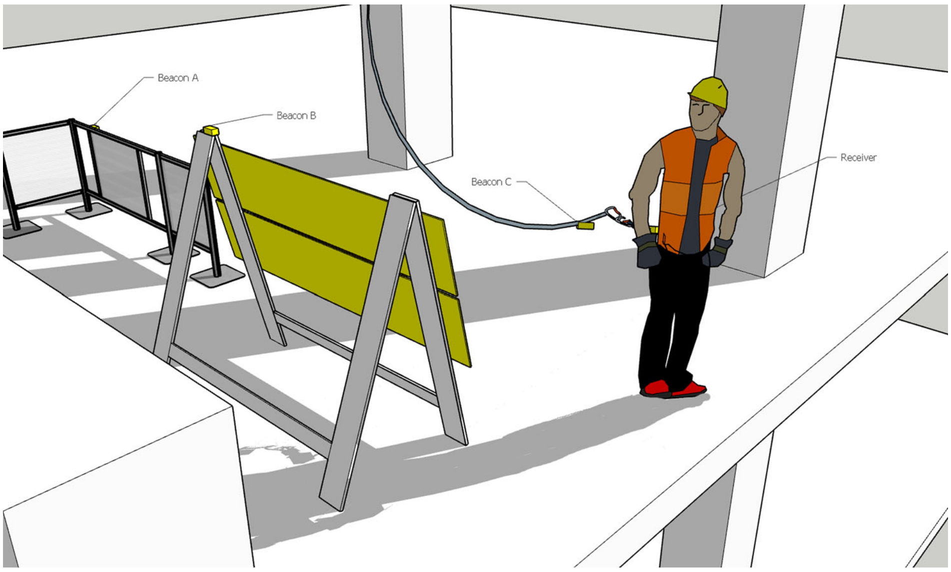

Figure 2. Detection of the use of safety measures can be done with just three beacons.
Note: Beacons A and B are placed in the transition between a safe place and a risk area. Beacon C is located at the lifeline carabiner.

Table 2. System components.

Component	Name	Description
Device	Beacons A and B	Beaconing devices from Bytereal Telecommunications International on the Texas Instruments cc2541, Texas
Device	Beacon receiver C	ESP32 chip from Espressif, systems, Shangai, with WiFi and Bluetooth communications, powered with an 18650 lithium-ion battery
Software	Proximity detection filter	Extended Kalman filter
Software	Finite state machine	MATLAB

we selected specific solutions according to the existing literature that are amenable to being combined with BLE.

3. Technological solutions

In this section we describe and analyze the solutions that can exist for the main limitations of a beacon-only approach, based on our findings in the literature and in our practical implementation, and classify them according to the applied technologies.

3.1. Building information modeling + BLE beacons

The first limitation of a harness beacon system is that, previously to its use, identification of the risk is always necessary to delimit it (by placing beacons). The risk of fall can be identified manually, but this procedure has some problems as the determination of the safety equipment is based on the safety manager's experience, and many issues are not included on building plans; it is also difficult to identify the risks at different construction stages based solely on 2D drawings. In order to address this, we propose adoption of building information modeling (BIM) to improve the efficiency of defining zones to be delimited by beacons.

BIM is defined by the National BIM Standard (United States) as 'a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onward'. The application of BIM-based methods is increasing in construction design and planning due to their benefits from 4D (3D + schedule) methods when they are compared to traditional projects using paper-based 2D methods [19]. Several research studies show BIM as a tool that contributes to construction progress tracking, scheduling, implementation of lean construction, data integration and cost reduction [16,20]. It has also been revealed as very useful in site safety management [21] because it can solve some of the problems linked to traditional methods, such as manual fall hazard identification and planning, e.g., Zhang et al. [19] developed an automatic BIM-based fall hazard identification and planning tool. This would identify potential fall hazards dynamically based on the construction schedule that assists the beacon harness system to delimit the risk areas. Aligned with the integration of BIM and alternative technologies, Dong et al. [6] have designed a real-time location system (RTLS) with pressure sensors to detect the proper use of PPE.

Table 3. Limitations of the beacon harness system.

Description	Limitation	Possible solution
Identification of risk zones is not carried out by Bluetooth Low Energy. Previous analysis of hazards is needed	Risk zone identification	Building information modeling
Undressing the harness and the beacon detector together is possible. If they remain close, the system does not detect that the worker is cheating	Cheating detection	Movement detection
Monitoring is done in a remote station, thus the worker has no real-time feedback of risk exposure	Worker warning system	Alarm device
In isolated zones, WiFi is not always available	WiFi absence	Global positioning system or Universal Serial Bus (USB) flash-drive storage records
Interference with metals and other materials can disturb the signal	Interference	Duplicate detection system with radio-frequency identification
The estimation of worker placement with respect to beacons has to be simplified	Limited computation	Remote or cloud computing

3.2. *Movement detection + BLE beacons*

The second limitation found in the use of the beacon-only system is worker cheating. A person can connect adequately all beacons and lifelines, but, once everything is detected, undress the harness and leave it connected to the lifeline. In that situation, the system will not detect the cheating because both remain connected inside a risk zone.

A feasible option to detect the proper use of a harness is computer vision. There are many examples in the literature of studies for computer vision-based safety and worker monitoring. They can be classified depending on whether they incorporate object detection, object tracking or both, or even action recognition. An example of object detection can be found in the study by Du et al. [22], where the use of a hard hat is detected in 2D video sequences by reviewing face features, motion and color information. Another example, but this time using 3D images and detecting objects and tracking them using image-matching techniques, can be found in the study by Chi et al. [23]. Action recognition based on 3D images and motion data has been previously used to detect unsafe actions during ladder climbing on construction sites [24].

Related to movement detection, the convolutional neural network (CNN) has been demonstrated as effective technology to recognize and classify images based on machine learning. More specifically related to our goals, there is previous research on using computer-vision-based approaches for safety harness detection [25]. In the cited study, two algorithms for the analysis of visual imagery were developed using CNN: one to detect the presence of workers (Faster-R-CNN) and another to identify whether the harness is attached (CNN models). Their results demonstrate that by combining these CNNs, a high degree of accuracy could be achieved in detecting workers who were not wearing their harness.

This is a promising line of development, but we have to note some issues that must be carefully considered. Some limitations are problems in recognizing both the worker and the harness, cluttered construction sites that occlude the line of sight and, in some cases, models that are not able to detect workers. Notice that any solution based on CNNs only provides up to a certain degree of confidence, assessed statistically, and thus a non-zero probability of (unpredictable) failure is always present.

An additional disadvantage with modern computer vision systems is the need for configuration and installation of the imaging sensing devices. Many factors should be considered, such as the type of data (2D or 3D), the environment (indoor or outdoor), the sensing range or the portability. All of these requirements are continuously changing in a construction project, thus the complexity and the investment necessary to implement computer vision are expected to be high.

3.3. *Wearable devices + BLE beacons*

An alternative to control the proper attachment of the harness with a lifeline can be the addition of a wearable device. Although the term wearable can be applied to many gadgets, here we use it only for systems focused on the monitoring of workers' physiological parameters.

The application of wearable devices in construction has been previously studied by several authors [15]. The variety of sensors and studies on monitoring human body activity is wide. For instance, electrocardiogram sensors are a useful tool for monitoring heart rate activity [26]; in a similar way, accelerometers and gyroscopes are very effective to analyze human body movements, and they can be applied to improve balance control and, thus, to reduce falls [27].

Both solutions look interesting to avoid some limitations of our beacon-only proposal. With an electrocardiogram sensor, the worker cannot undress the harness while leaving it connected to the lifeline because the sensor will detect there is no body under the harness. The integration of inertial sensors in the harness can be detected by the absence of movement due to the worker not wearing the harness any longer. The cost of these solutions is not very high, although the former is more difficult to add to the workers' garments.

3.4. Warning alarm + BLE beacons

In order to address the worker real-time feedback limitation, the use of a warning alarm should be assessed. Warning alarms can be classified into three groups: acoustic, visual and vibration-based. In construction environments it is not easy to choose the most appropriate category, e.g., acoustic alarms are not always effective because the noise level in the environment is quite high – different sounds such as tonal, multi-tonal or broadband alarms can be used; visual alarms may be occluded; vibrations can be ignored by the worker if his work already involves harsh movements. Depending on the strategy used, the sound detection thresholds, equal loudness, perceived urgency and sound localization will be different [28].

Due to the fact that the worksite is dynamic, it is not easy to place a visual alarm in the eye field of the worker either, although they can be useful when mounted on heavy machinery in movement in order to warn about dangerous operations of the machinery [29], and they can also use flashing or static lights depending on the hazard detected.

Concerning vibration alarms, some authors suggest that the choice of the type of warning should be considered depending on the type of task being carried out on the construction site [15]. In an attempt to obtain as effective a warning system as possible, a gadget with audible, visual and vibratory warnings should therefore be desirable. Some commercial smart-watch or similar could be developed with this function if they are specifically adapted for the construction site.

3.5. Global positioning system + BLE beacons

Another limitation detected in the harness system proposed by the authors is that the WiFi infrastructure is not always available, especially in isolated workplaces. A solution for this issue could be the addition of a global positioning system (GPS) or GNSS technology (as long as the working environment is open). A GNSS can be defined as a constellation of satellites providing signals from space that transmit positioning and timing data to GNSS receivers. The receivers then use these data to determine the location [30].

Some examples of a GPS or GNSS applied for safety in construction can be found in the literature. One of these is the system for worker localization and proximity to risk areas in railway construction proposed by D'Arco et al. [12]. Similarly, Park et al. [31] propose to calculate the risk level of the worker according to the proximity and movement of heavy equipment, measured with these devices. Another remarkable study, based on a GPS, proposed a system to analyze equipment on construction sites [32].

3.6. RFID + BLE beacons

In some environments with metals and other similar materials, the BLE signal can be disturbed. One possible solution for this matter could be the use of a second RFID signal to verify the correct use of a harness in danger zones. RFID is a commonly used system for proximity detection. Kelm et al. [10] have developed a RFID system to control the use of PPE and the access to risk areas, although the system is not yet prepared for continuous monitoring.

3.7. More computation + BLE beacons

The last limitation observed in our original BLE solution, and the one that requires the most technical analysis, was that the available computational power for performing estimation in the wearable device is not too high. The solution proposed by Gómez-de-Gabriel et al. [13] was designed specifically for the execution of the estimation algorithms in embedded platforms (the receiver that the worker carries is an ESP32, Espressif systems, Shangai, with 520 kB of RAM and a central processing unit [CPU] clock of up to 160 MHz), which leads to several important simplifications in the estimation processes related to locating the worker with respect to the beacons.

If we relax this computational power limitation, e.g., through remote computation (at the expense of a shorter battery life due to the communications), we could afford improvements in the estimation of the closeness of the receiver and the beacons. In particular, we could then implement a range-only simultaneous location and mapping (SLAM) algorithm. SLAM is defined as the process by which a mobile robot can build a map of the environment and, at the same time, use this map to compute its location [33]. Such a solution would allow one to adapt automatically – after a suitable period of walking through the environment – to multiple beacons placed in diverse, unknown locations. Since each beacon can carry its own identifier, which is transmitted to the receiver, a complete map of the environment, i.e., the set of beacons and their locations, plus a full path of the worker would be provided, unlike in our previous solution, where we only estimate his/her instantaneous distance to the beacons. The map and the full path are very interesting to trace worker behavior in the case of an accident, and also to have a more robust deduction of the entry to risky zones.

A suitable method to solve the range-only SLAM problem that uses particle filters and sums of Gaussians to represent the map (the set of beacon locations) and that can naturally cope with 3D environments can be found in the study by Blanco et al. [34]. There, it is used for estimating the map and path of a mobile robot in a real environment populated with UWB beacons. The UWB uses short

Table 4. Cost and feature comparison of the combination of other technologies with BLE beacons.

	Technology						
Cost	BIM	Movement detection	Wearables	Warning alarm	GPS	RFID	Location methods with external computing
Infrastructure (comon)	Medium (computing and BIM system)	High (cameras, image processing, storage, neural nets, network infrastructure)	Low (no networking needed)	Low (visual warnings)	None	Medium (RFID readers)	High (computing infrastructure, wireless network)
Cost of devices (for each worker)	Low (BLE receiver + beacons)	Low (BLE receiver/beacon)	Medium (biomedical and inertial sensors)	Medium (vibration and acoustic devices)	Medium (GPS receiver	Medium (RFID tags in equipment)	Medium (wireless network)
Reconfiguration costs	Low (beacon relocation driven by the BIM dynamic planning)	Medium (changing scenes and light conditions)	Low (local detection methods)	Medium	Low (GPS is a global method)	None	Low (map change)
Expected impact on safety	Integration and planning capabilities	Unobtrusive risk assessment	Human presence and activity detection	Proper worker supervisor awareness	Outdoor only	Presence protection equipment	High-quality indoor localization

Notes: BIM = building information modeling; BLE = Bluetooth Low Energy; GPS = general positioning system; RFID = radio-frequency identification.

Table 5. Solutions for the limitations of the beacon harness system.

Limitation	Possible solution	Advantages	Disadvantages
Risk zone identification	BIM	Accuracy	Cost and update
Cheating detection	Movement detection by computer vision	Accuracy	Configuration and installation complexity
Cheating detection	Wearables	Low cost	Reliability
Real-time feedback of risk exposure	Alarm device	Easy and cheap to integrate	Low effectiveness in busy environments
WiFi absence	GPS	Low cost	Low accuracy, not possible in some environments
Interference	Duplicate detection system with RFID	Easy and cheap to integrate	–
Limited computation	Remote or cloud computing	Low cost	Configuration

Notes: BIM = building information modeling; GPS = general positioning system; RFID = radio-frequency identification.

(nanosecond) bursts of electromagnetic energy in the form of short-pulse RF waveforms over a large bandwidth (bigger than 500 MHz) [35], but its adaptation to BLE does not present special difficulties; moreover, on a construction site we do not have 3D exactly, but a number of 2D floors, which could be exploited to reduce the cost of estimation.

As for the finite state machine in charge of detecting sequences of states that are of interest for assessing the risk assumed by the worker, the structure (graph) depends on the relative location of beacons. In our first solution, the graph was defined manually for a given placement of beacons. If we implement range-only SLAM, we will eventually get a map of the beacons, with those that indicate risky places correctly identified along with the connectivity among them – through the estimated path. This information could be exploited to automatically construct the finite state machine, although that would require an initial stage where the worker passes through all possible (or at least critical) paths.

Another interesting alternative to improve estimation in the proposed device is the addition of a smart ID card to the system [36]. A smart ID card can include sensors such as an accelerometer, magnetometer, moisture sensor, pressure sensor, ambient light sensor or temperature sensor. Systems based on a smart ID card were probed as highly effective in the detection of PPE in the workplace [36].

Similarly, previous research about RTLSs for monitoring safety of the machine operators [37] identified an UWB technology-based system very useful for reducing the risks of accidents in the operation of machinery.

4. Cost and maintenance of the integration of technologies with BLE beacons

The use of additional technologies to improve the BLE beacon harness system will involve extra costs linked to the acquisition of additional devices and their integration and maintenance. Some of them, like those related to the choice and configuration of computer vision devices, have been already commented on in the previous section.

The economic cost of additional devices is influenced by many factors, such as sensor accuracy, power source, etc. The ranges of cost based on commercially available data are presented in Table 4.

However the economic cost is not the only kind of cost. Some integration costs should also be considered: configuration, data processing, software development, data store, data transmission, information technology (IT) infrastructure, etc. In order to obtain a first, qualitative approach to this, the costs presented in Table 4 have been estimated and classified as low, medium or high (Table 5).

5. Conclusions

This work has identified some lines of future improvements to address the limitations detected in a monitoring harness system based solely on BLE beacons. Our approach has consisted of identifying those limitations, carrying out a literature review on the possible solutions and proposing an integration of diverse technologies with our original framework.

During the literature review we found a wide variety of technologies that are currently being applied for construction safety, but their use is not as extended as in other sectors of industry and their potential applications in order to prevent FFH are not totally explored. Furthermore, there are very few studies on the integration of these technologies, especially using as a starting point a practical solution that is already working.

In this work we do not provide a universal solution for all the limitations, but a number of improvements that can lead, after further research, to a suitable approach.

5.1. *Future research*

A possible future research approach could be to integrate the solutions identified and proposed in this work into the existing monitoring harness system, in order to prove their effectiveness for a real construction site. However, real tests with experimental safety devices are not always possible due to safety conditions and ethical issues.

Another interesting topic of research identified during the current study is the existing barriers to adopt and integrate technologies into the construction sector. In the majority of cases, social and cultural barriers are more important than technology itself. Then, it is important to consider industry factors, as existing procedures, and traditional practice for a successful integration of technologies.

5.2. *Impact on construction*

The integration of other technologies such as BIM, GPS or RFID with BLE is low in a majority of scenarios, especially when they are compared with the total budget of many construction projects.

Although the construction sector is very traditional about their procedures, and it is difficult to introduce technological advances, if the solutions proposed were integrated properly, then workers' safety levels would be improved. In consequence, FFH rates would be reduced.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

María del Carmen Rey-Merchán http://orcid.org/0000-0001-9236-5792
Jesús M. Gómez-de-Gabriel http://orcid.org/0000-0001-5960-3453
Juan-Antonio Fernández-Madrigal http://orcid.org/0000-0003-1376-7967
Antonio López-Arquillos http://orcid.org/0000-0002-2477-1227

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