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Research Article

Monitoring Worker Exposure to COVID-19 and Other Occupational Risks Using BLE Beacons

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The COVID-19 pandemic has become a public health priority during 2020. Social safety distance is one of the most effective strategies to stop the spreading of the virus, as it reduces the dose of infectious particles that a person can receive. Real-time location systems (RTLS) based on ultrawideband (UWB), radio frequency identification (RFID), Global Position System (GPS), or Bluetooth Low Energy (BLE) can help keep workers safe at the workplace. The aim of the current paper is to develop a dosimeter proposal to monitor and control the distance and exposure time between workers based on BLE beacon technology considering viral load. Our proposal is based on a set of BLE beacons and safety distance estimation by filtering RSSI measurements with a Gaussian extended Kalman filter. According to the estimated proximity values and the exposure time, a finite state machine will alarm when the worker receives the maximum dose defined by health authorities. The proposed system can be applied to prevent any risk that can be eliminated or reduced controlling distances and/or exposition time of the worker to the occupational risk. The proposal is robust, is inexpensive, and respects the privacy of workers, and its accuracy is higher than that of existing smartphone applications. In future pandemic situations, the system can be easily updated to the safety distance and viral particle dose related with the new risk agent. The system can protect from additional risk incorporating beacons on the extra risk identified such as thermal, noise, or radiation.

1. Introduction

Due to the worldwide spread of COVID-19, there is a public health concern about people's exposure to the virus. Since the initial report from Wuhan, China, during December 2019, until the beginning of July 2021, more than 188 million cases and 4 million deaths caused by the virus were officially reported in most of the countries of the world [1]. Several medical experts, scientists, and organizations are working on the development of medicines and vaccines, but they are not the only alternatives to prevent the spread of the virus. In previous research, social distance was revealed as one of the mitigation measures that may be recommended during pandemic situations because of their effectiveness to reduce infection rate [2, 3]. In the particular case of COVID-19, many infected people cannot present symptoms but they can spread the disease [4]. The combination of a lack of effective medicines and a high number of infected people caused the lockdown of many countries to keep social distance and to control the pandemic, but socioeconomic consequences of cited lockdown will be difficult to solve in short and medium term [5].

In some countries, leaders support lockdown with tighter restrictions, while in other countries they sustain a more gradual lockdown [6], but essential workers in the health sector or logistics industries are necessary under any circumstance.

Then, they should be protected with the most effective preventive measures, and their use of personal protective equipment should be rational [7].

WHO protocols recommend maintaining a distance of at least 1 meter to follow a minimum safety social distance [7]. In Spain, this safety distance was increased until 2 meters by the Spanish government recommendations [8].

It is important to bear in mind that in the workplace some factors such as interaction with customers, suppliers, patients, or other workers can increase the transmission of the disease [9].

While the risk of COVID-19 is a new occupational issue, the problem of controlling safe distances between workers and their occupational hazards, such as noise, electromagnetic radiation, thermal radiation, heavy equipment, biological risks, or other workers, is a known problem, and its management is not easy to carry on, especially in dynamic environments [10–12].

In order to control the negative consequences of the exposure of the workers to some of the aforementioned hazards, it is common to define a maximum dose allowed to protect the workers' health and to limit their exposure to the risks. The dose values are calculated considering the concentration of the agent in particles received per minute, and the exposure time of the worker in minutes is shown in

$$\text{Dose} = \text{concentration} \times \text{exposure}. \tag{1}$$

In the case of biological agents, the level of dose dangerous for workers' health can be defined as minimum infective dose (MID) or the minimum amount of biological agent that has to penetrate the host to produce the disease. Infectious dose may vary by biological agent, the route of entry, and host resistance [13]. Determining the MID that can initiate infection and the factors influencing this dose is important for the development of risk assessment models [14]. Droplets are produced during all expiration in healthy and ill subjects with wide disparities between individuals; if droplets are inhaled, the minimal infectious dose must be reached [15].

In the particular case of COVID, some authors estimated that as few as 1000 SARS-CoV-2 infectious viral particles are all that will be needed [16, 17], and concentration can be estimated in around 33 viral particles per minute in a single breath [17].

Then, if MID and concentration are known and variable exposure depends on distance from worker to the risks, occupational risks can be controlled controlling relative distances and location of workers. Existing technology-based solutions addressed the location problem at workplace using different real-time location systems (RTLS) based on ultra-wideband (UWB) [18, 19], radio frequency ID (RFID) [20, 21], GPS [22, 23], computer vision [24, 25], and BLE beacons [26].

Several examples of RTLS can be found in different working environments (Table 1).

For instance, in the construction sector, many avoidance systems have been proposed using various technologies such as RFID [35, 36] or UWB [18, 37] to prevent occupational accidents. Localization and tracking technologies have been applied in office facilities too. Recently, researchers determined whether an RTLS can measure and spatially locate the nonstationary and stationary behaviors of adults working in an office work environment [38]. Similarly, BLE beacons combined with accelerometer's proximity features were tested to determine where office workers spend time at work [39]. Aligned with that, some authors developed and implemented an algorithm to determine where physical activity occurs using proximity sensors coupled with a widely used physical activity monitor [40]. Further than occupational safety issues, other researchers applied RTLS for tracking patients' flows in hospital [41] and to map social interactions of students in schools [42]. Additionally, other authors discussed the impact of workers' responses to proximity warning in real workplaces [43, 44].

Some specific systems based on BLE beacons to prevent the spread of COVID-19 have been found in the literature [45, 46]; however, the systems only considered social distancing, and they did not include relevant aspects about the viral load.

Therefore, the aim of the current paper is to develop a proposal for a dosimeter to monitor and control of the distance between workers based on BLE beacon technology considering viral load.

The rest of the paper is structured as follows: Section 2 describes the relative technology and the state of the art about beacons. Section 3 describes all components of the system proposed, the filtering method, and the state machine for detecting the status of the worker. Finally, in Section 4, conclusions and future works are described.

2. Related Works

Technologies capable of sensing and warning workers when hazardous proximity issues exist are needed in risky workplaces [47]. Aligned with this problem, RTLS have been revealed as an effective way to identify and track the location of an object or person in indoor and outdoor workplaces [27]. Current RTLS use different localization technologies, such as radio frequency, UWB, GPS, or vision analysis, but many of them present some important limitations as low accuracy, inconsistency, or unreliability [48, 49].

Radio frequency is an extended strategy for location purpose [20, 21, 28–30]. The use of RFID is common in complex indoor workplaces such as offices and hospitals, and it provides a flexible approach to identify workers and devices [27], although its accuracy is low [47]. In contrast, cost associated to use is high in comparison with other technologies [47].

UWB is another extended technology that belongs to radiofrequency position family, with better results in indoor environments, although its accuracy decreases in large areas and with the presence of obstacles [19, 31, 32]. Another remarkable limitation of UWB systems is the requirement of connection of a local area network (LAN), which is not available at every workplace [50].

As an alternative to cited technologies, GPS is commonly used to obtain the position from objects or people located in

Table 1: Comparison of real-time location system (adapted from Li et al. [27]).

Function	Technology	Author	Accuracy	Calibration	Monitoring	Indoor/outdoor
Proximity location	RFID	[21]	3.7–1.1 m	None	No	Outdoor
Localization performance	RFID	[28]	86.5–63.62 cm	None	No	Indoor
Monitoring occupancy	RFID	[29]	1.42–0.49 cm	None	Yes	Indoor
Localization jobsite	RFID	[30]	1.22–2.58 m	None	Yes	Indoor
Position tracking	UWB	[31]	10–50 cm	High	Yes	Indoor
Material and activity tracking	UWB	[19]	60 cm	High	Yes	Indoor (obstacles)
Tracking static resources	UWB	[32]	20 cm	High	Yes	Indoor (obstacles)
Tracking equipment	GPS	[22]	2.15 m	None	Yes	Outdoor
Tracking material	GPS	[33]	3.22 m	None	Yes	Outdoor
Capture unsafe behavior	Vision	[34]	88%	High	Yes	Indoor
Social distance	YOLO	[25]	Person detection	High	Yes	Both

outdoor environments [51]. Previous applications tracked location of the equipment or material with a reported accuracy lower than 4 m [22, 33]. However, it is recommended to combine GPS with RFID to increase its accuracy [52]. Vision analysis systems can be used to detect unsafe workers' behaviors [34]. More recently, some authors applied vision analysis to detect the proximity of people to maintain social distance [25], but this only detects people and does not monitor the distance or exposure time.

More recently, safety systems based on BLE have been demonstrated as an effective tool to manage distances from worker to the occupational risk. In a previous research, an approach to measure and evaluate the proper use of harnesses at construction sites based on BLE was developed [26]. In the cited system, the distances from worker to potential risky zone were estimated according to the BLE signals. Similarly, these authors developed a system of virtual fences based on BLE to avoid intrusions [53]. Other authors proposed a smart glasses-based personnel proximity warning system based on BLE [54]. Additionally, BLE systems can be improved adding complementary technologies [55]. An example of this can be found in the proposal of a BLE system with fuzzy technology integrated [56].

Despite accuracy being a very relevant factor in RTLS, other additional characteristics are important to be evaluated in these systems. Size and weight of the device, power or source, storage, cost and maintenance, social issues, data processing, transmission, or the integration with other systems should be considered to choose the most appropriate technology [47].

According to Figure 1, BLE devices are cheap when they are compared with the rest of current technologies. Their size and weight are low, and batteries can run for more than a year. Their data can be easily transmitted, and they can be integrated with other technologies. In regard to social issues such as privacy and legal issues, the system provides a less invasive approach than a smartphone because you only monitor data related with occupational health and safety from a receptor. The receptor is associated with an ID of the worker and traceability is possible, but data can be evaluated anonymously, especially when there are no safety warnings. In addition, the device is only used at the workplace; then, your privacy when you are not working is not invaded.

3. Proposed Approach

The developed mobile proximity and warning system is based on BLE communication protocols (Figure 2).

The system can be applied in a group of workers. The only necessary condition is that the worker carries the receiver and a transmitter beacon. In this section, we describe the proposed solution, including its electronic devices and the behavior of the RSSI signal.

The distances between workers are estimated from BLE beacon signals. The beacon signals are sent from each worker and are received by the workers' receiver. Then, the signal received is filtered by a proximity detection filter, and based on the filtering process, the worker status can be estimated. The filter provides closeness detection in the form of probability, and worker status can be modeled as a finite state machine. While the worker is not keeping the safety distance, exposure time is recorded by the system. Once the exposure time is close to the maximum exposure allowed, the worker will be alerted by the system (red led). The system is also capable of alerting the worker if he is below the safety distance (yellow led). The basic description of the proposed system is shown in Figure 2.

Each worker has attached a BLE beacon receiver (Br) with a programmable microcontroller and a BLE transmitter (Bt). The BLE transmitters were enabled using a fast connection and low power. The spectrum for BLE was composed by 40 channels separated by 2 MHz, and only three of them were used for sending advertisement packets.

A random delay to reduce the collision probabilities from different BLE devices was configured. Beaconing devices (Be) were based on Texas instrument cc2551.

They provide configurable parameters, and they can operate more than one year with only a coin battery configuring their advertising rate.

The BLE receiver is based on ESP32 designed for Internet of Things applications Figure 3. The device features a Wi-Fi and Bluetooth Chip ESP32 with RF components and power modules. The BLE receiver provided RSSI values from

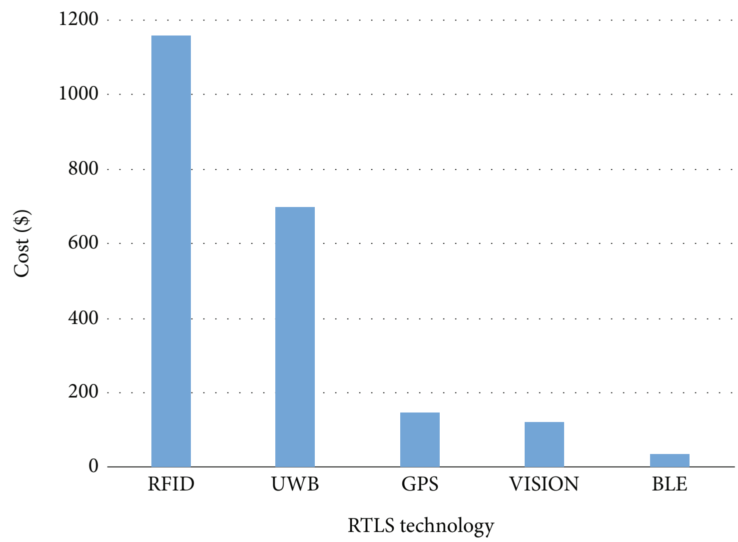

FIGURE 1: Cost of technologies adapted from Awolusi et al. [47].

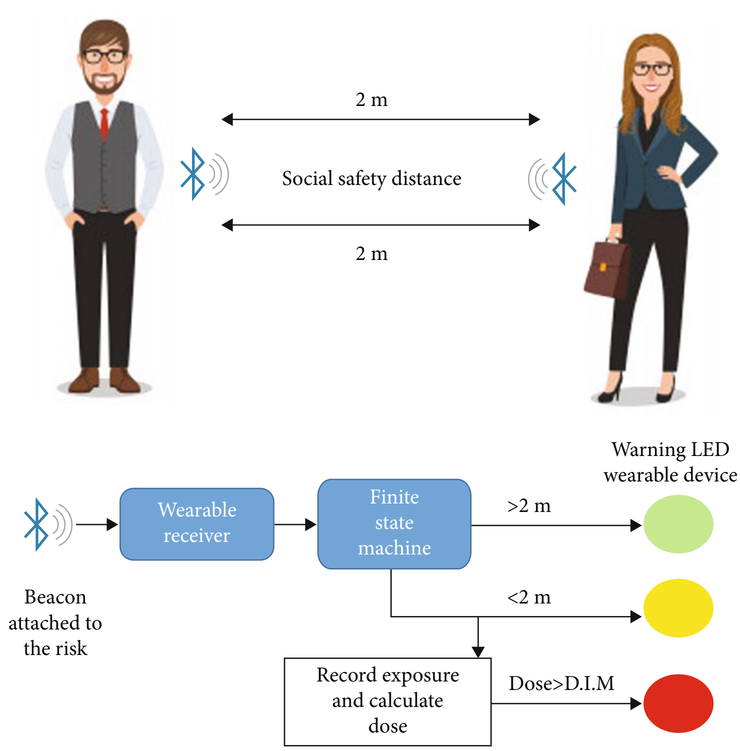

FIGURE 2: System description.

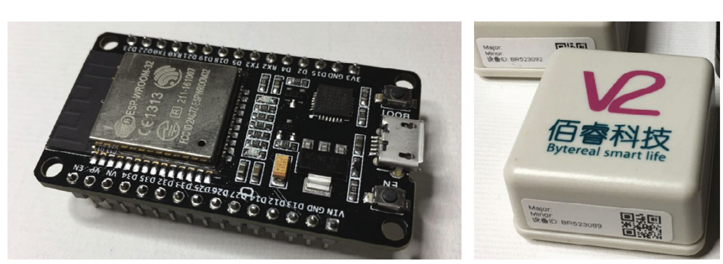

FIGURE 3: BLE devices: ESP32 and cc2541 from Bytereal Telecommunications International limited.

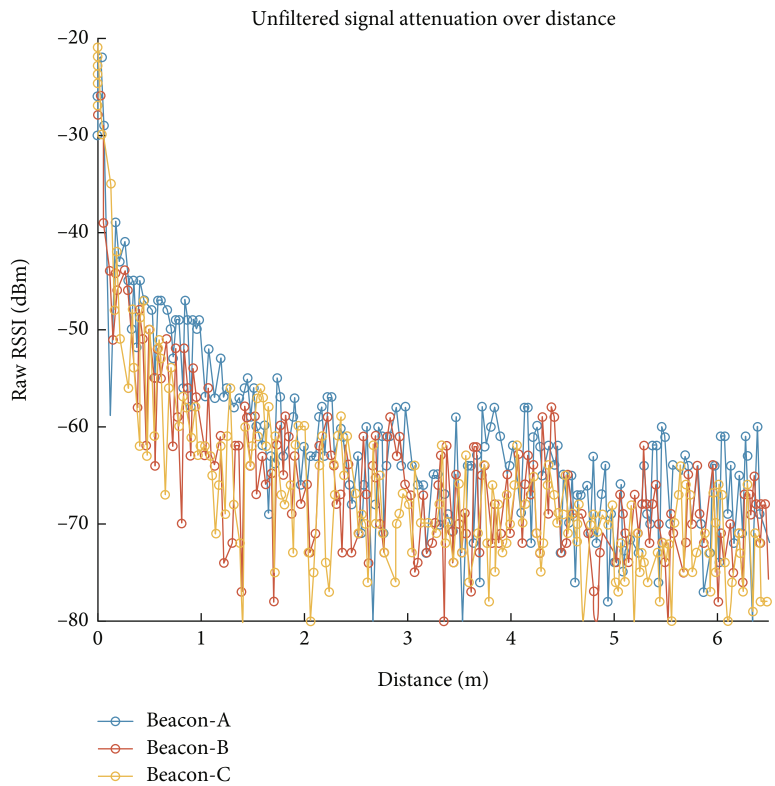

Figure 4: RSSI vs. ground trough distances. Unfiltered signal with three different beacons (A, B, and C).

the advertising messages received. ESP32 were configured to scan signals and storing them into a FIFO buffer.

RSSI values are noisy and can be influenced by objects or electromagnetic interferences. In Figure 4, RSSI values gathered from 3 different beacons at distances from 0 to 5 m were plotted. It can be observed that filtering of the signal is necessary. In consequence, a proximity detection filter was applied. A double filter composed by a Gaussian filter and extended Kalman filter (EKF) was selected. This solution was applied successfully in a previous research [26]. The Gaussian filter estimates distances using observations, while the EKF is a discrete filter that uses the results of the first stage to estimate our final distance. More details of the filters can be found in cited research. Based on the filtering process, it can be estimated by the dose received by the worker. The location of the worker with respect to the source of risk is estimated based on the proximity filters previously described. The worker dose can be modeled as a finite state machine (Figure 5). The detector has three states. In the first state, worker is not receiving any dose because he is keeping a safety distance to the risk. In the second one, worker is exposed to the risk because his safety distance is lower, but the dose received is not higher than the threshold value recommended. In the third one, the worker has received the maximum dose allowed. A time counter records the exposure time of each worker. When the exposure accumulated reaches the maximum level programmed, the system will warn the worker about this situation. Then, the worker should be placed in a safety distance from the rest of the workers.

Accuracy of system is higher than other wearable devices. For example, a wrist wearable can vary about more the 50 cm only with the natural movement of the human arm. Proposed system parameters can be updated according to the future exposure thresholds studied. The system can be extended to any occupational risk, in which distance and/or exposure time are influence variables to prevent the possible damage to the worker (thermal radiation, machinery in movement, falls, cuts, etc.). Only with the addition of beacons on the risk focus and entering the necessary safety distance for the additional risk and maximum exposure time allowed for monitored risk.

4. Results and Experiments

A real scenario has been tested to validate our proposal. Two healthy workers were selected, and one of them was supposed as a source of COVID-19. They were placed in an office. One of them was in a static position wearing a BLE receiver, and the second one was moving around the first one wearing a BLE beacon. They started together without any safety distance between them, and the second one was moving away until a distance of 2 meters for the first one. Then, the worker stopped and spent 100 seconds keeping the same distance. Afterward, he walked to a distance of 4 meters and stopped there for 60 seconds. Finally, he walked and moved back to a distance of 2.30 meters. Beacon RSSI readings and ground truth distance are showed in Figure 6. As it can be observed in the results from Figure 6, raw RSSI data were not enough to determine distances; then, it was

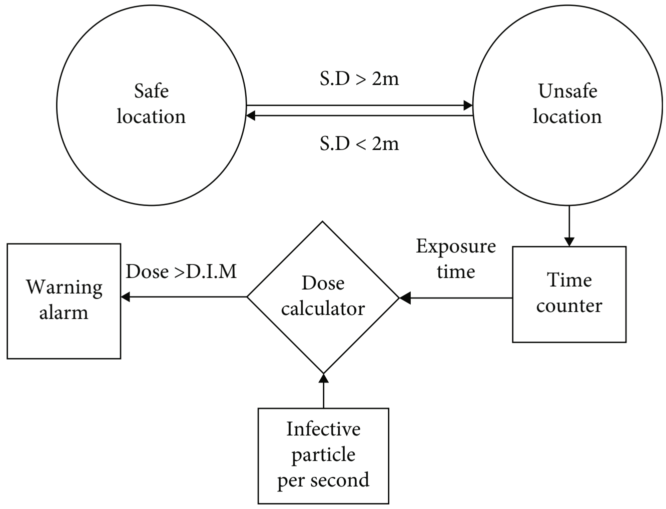

FIGURE 5: State diagram for worker status.

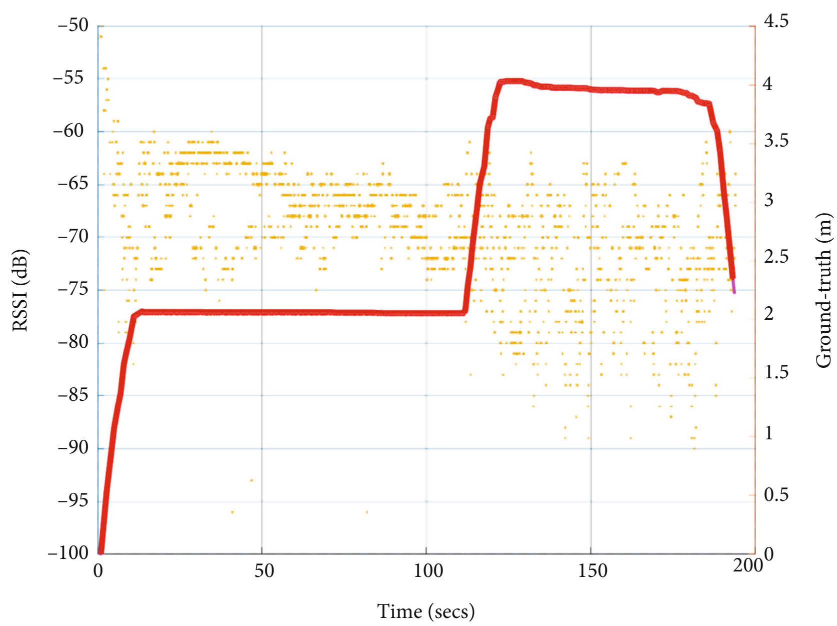

FIGURE 6: Workers' experiment values. RSSI vs. ground truth distances obtained.

necessary to apply the proposed proximity filter. Results obtained after the application of the filter and finite state machine are shown in Figure 7. The time plot showed the following values: beacon distance estimation, beacon ground truth, and closeness status. Due to the possible estimation error, conservative criteria were used, and the safety distance was set up in 3 meters. Despite signal filtering, the high uncertainty in the beacon's signal could not be completely removed. However, the accuracy of results estimated is close to real values obtained by the ground truth. The distribution of the errors calculated can be observed in Figure 8, and the expected error was 27 cm. It is remarkable that the threshold limit value chosen could be extended or reduced in our system according to the medical recommendations and safety procedures.

Finally, the dose estimated was calculated by the system using the exposure time estimated by closeness detection and considering that the SARS-COV-2 concentration can be estimated in around 33 viral particles a minute in a single breath [17]. The formula is detailed in

$$\begin{aligned} \text{Dose estimated} &= 0.55(\text{viral particles a second}) \times 88(\text{seconds}) \\ &= 48.4 \text{ viral particles received.} \end{aligned} \tag{2}$$

Some authors estimated that as few as 1000 SARS-CoV-2 infectious viral particles are all that will be needed [16, 17]. While the dose estimation does not reach the cited value, the worker will be considered safe. It is remarkable that cited

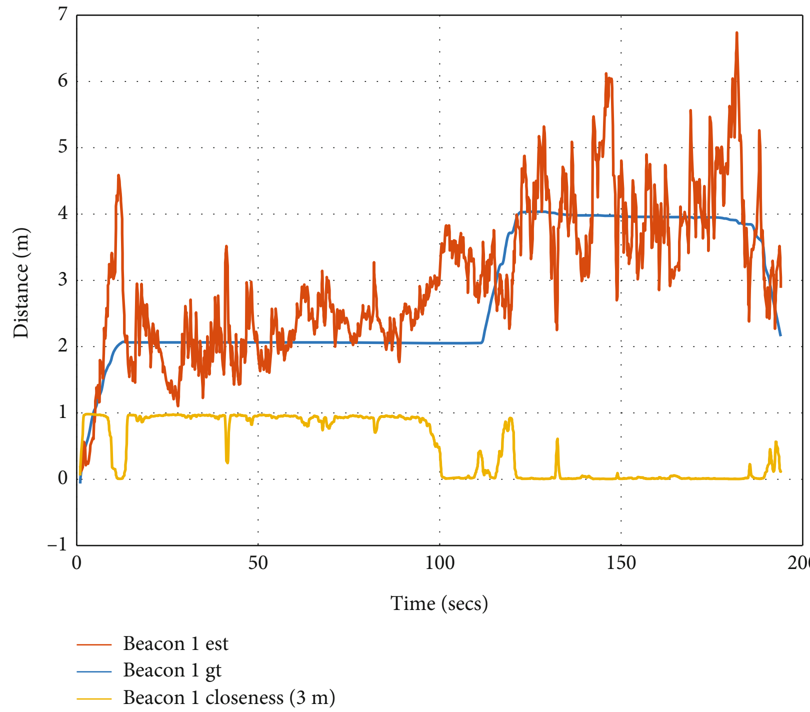

FIGURE 7: Estimation of beacon 1 after sign filtering vs. ground truth and closeness detection status for a safety distance of 3 meters.

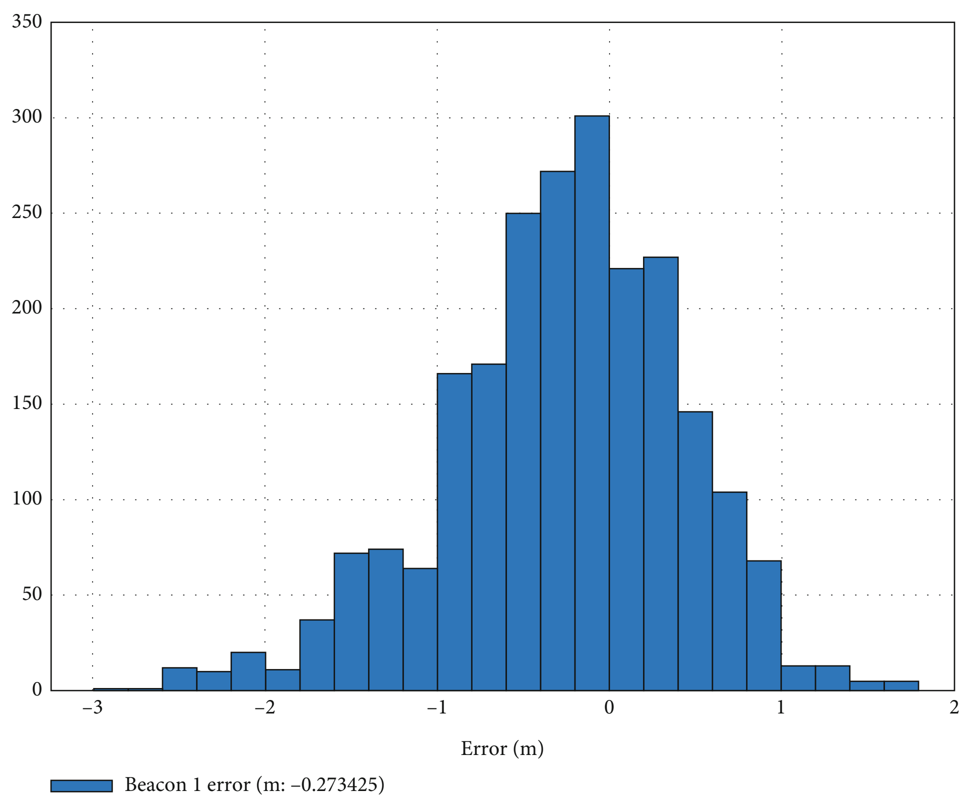

FIGURE 8: Error estimation in distances estimated.

limit can be updated according to new findings in the body of knowledge about the disease, and it could be adapted to other similar diseases. Additionally, to increase safety conditions of the workers, the limit could be reduced by a safety factor.

5. Conclusions and Future Research

The proposed system based on BLE beacons to monitor exposure to COVID-19 has been demonstrated as an efficient and robust tool to control the safety social distance and to reduce the exposure to a possible infection. The key novelty of the system is the combination of the safety distance with viral load to estimate the dose received, including a Gaussian extended Kalman filter. An inexpensive set of BLE beacons and receiver was configured to monitoring workers and to keep their safety distances in the workplace. Although previous research studies identified the problem, the majority of them proposed complex solutions based on alternative technologies linked to complex installation, low accuracy, and difficult calibration. The system created was tested in an office. Two workers wore BLE beacon and the receiver and one of them was moving around the other one. Accuracy and stability of the results obtained in the experiment can be considered acceptable for the aim of the system. The developed process demonstrated the potential to address the control of safety distance at an indoor or outdoor workplace.

In addition, the system designed can be adopted to prevent other safety or hygienic risks in which distance from worker to the risk was a critical variable as struck against objects, thermal radiation, or fall from heights. Only with the use of a beacon per each additional risk to control and establishing the minimum safety distance required the system will monitor the risk, and it will warn the worker in case of violation of the safety risk.

In the future, if medical researchers about COVID-19 obtained new data about the safety distance or number or particle necessary to be infected, updating of cited parameters will be easy to be updated in the current system.

Additionally, the system is cheap, easy to configure, and robust. Data can be recorded and transmitted for further analysis, and they can help to manage the workplace conditions and task distribution, in order to improve health, safety, and productivity of workers.

Last but not least, the privacy of workers is more protected in comparison with smartphones or similar devices frequently used out of the workplace.

5.1. Limitations of the Study. The main limitation of the systems is linked to the possible variability in the strength received from RSSI signals in the presence of some obstacles. However, in the majority of cases as windows, panels, doors, or columns, the obstacle would attenuate the signal and would reduce or eliminate the infective dose received by the worker.

5.2. Future Research. Integration of the current system with additional technology or extra controls in order to check the proper use of personal protective equipment would improve OHS conditions at the workplace.

Other warning signals such as vibration, sounds, or text messages could be included and tested in the current system to check the effectiveness of the system in the worker perception with different warning methodologies.

The addition of a logging feature could allow the system to track potential infected people. However, some important issues about privacy of the workers should be addressed before the implementation of this function in the system.

Data Availability

Access to data is restricted because we are working on the development of future commercial applications.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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