Journal of Industrial Information Integration 38 (2024) 100575

Contents lists available at ScienceDirect

Journal of Industrial Information Integration

journal homepage: www.sciencedirect.com/journal/journal-of-industrial-information-integration

Full Length Article

# Ad-hoc collision avoidance system for Industrial IoT

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ARTICLE INFO

*Keywords:*
Industrial IoT
Bluetooth
ADAS
Safety and security
Location systems
Industry 4.0

ABSTRACT

Safety and security in the workplace are extremely important. In the industrial sector, with heavy machinery, an accident can have serious if not life-threatening consequences. In Industry 4.0 with the inclusion of paradigms such as the Industrial IoT, new technologies can help not only to improve the production process of a company but can also assist by improving the safety and security of industrial workers. Security is sometimes considered an add-on or something to be applied in the future, which could lead to very expensive or complex solutions. In this work, we deal with scenarios where heavy machinery and workers are in a common area. In these scenarios with heavy machinery, accidents can be caused by different factors. To aid in the avoidance of such incidents, we create a system that detects the presence of nearby workers by using Bluetooth devices. Using the signal emitted by these devices, the driver of the heavy machinery is warned through visual and haptic signals. The system is designed to capture the attention of drivers and their peripheral vision with very simple signals, easing the learning curve of the system. The contribution of this work also provides an implementation the system using Bluetooth for the emitters and the detectors, which are connected to a Raspberry Pi that manages the ADAS, evaluating the information about surrounding Bluetooth emitters, and triggering the different feedback mechanisms as required. Accuracy is a limitation of Bluetooth-based location systems. Nonetheless, the proposed system allows us to detect nearby workers relative to the heavy machinery, as opposed to pinpoint their location in a specific area. Furthermore, the system is very affordable and minimally intrusive compared with the use of cameras that require that the driver's attention is drawn away from the driving process. In this work, we design and provide the proof of concept of the complete collision avoidance system.

## 1. Introduction

The Internet of Things (IoT) has led to very interesting applications by connecting a myriad of devices to the Internet. Examples of these applications are Smart Buildings and Smart Cities, among others. IoT applied in the industry, also known as the Industrial Internet of Things (IIoT) also provides very promising applications. Not only is it expected to help improve the efficiency of the productive process of many industries, but it also provides advantages to important areas such as workplace safety and security [1].

In industry, some machines are quite heavy with additional loads to carry (e.g., forklifts, excavators, etc.), which makes driving alongside pedestrians/operators a dangerous activity if proper measures are not in place. In this work, we consider off-road, which are not expected to achieve the same speeds as normal vehicles do. Most of the work done by these machines, like forklifts and excavators, is to perform repetitive tasks, not for commuting. Some tasks may involve little movement from one place to another. These machines normally perform repetitive tasks such as moving cargo or digging trenches.

Different factors can contribute to a deterioration of the conditions for optimal performance and awareness of the workers such as poor illumination, hidden areas that create blind spots, moving obstacles that reduce visibility, noise typical in industrial areas, dust, etc. These are but a few of the different causes that may contribute to decreased awareness in drivers that may increase the probability of incidents. Accidents at work can be quite serious and even deadly.

There are numerous episodes in the news of accidents in an industry that in most cases could be avoided [2]. For instance, for excavators, the swinging of the excavator's boom or arm can strike workers or other objects. Additionally, workers can get caught between the excavator and

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https://doi.org/10.1016/j.jii.2024.100575

Available online 17 January 2024

a fixed object. In the case of forklifts, workers on foot can be struck by forklifts, especially in areas with poor visibility or if the forklift moving cargo in a repetitive task.

By leveraging the current technologies, we have available, we can contribute to a safer workplace, providing tools that enable drivers of heavy machinery to receive an early warning and improving the awareness of operators and drivers. The field of assisted driving is a very interesting research area more so in industrial scenarios where each context provides its complexities and challenges at different levels. Advanced Driver Assistance Systems (ADAS) provide interesting possibilities, but the nuances and the idiosyncrasies of the specific use case must be considered when designing a system that fulfills its needs. More concretely, we are dealing with a very specific driving experience that requires an extreme level of focus and accuracy from the driver. Hence, if we aim to assist the driver, it has to be designed in such a way that it will not require excessive mental processing that will deteriorate performance while operating heavy machinery. Hence, working with simple but effective feedback mechanisms for the driver is of paramount importance. Current solutions to aid drivers in increasing their awareness of nearby workers can be expensive, and they use feedback mechanisms that require a mental load that may not be compatible with long working hours like different monitors. Furthermore, location proposals are either based on a supporting infrastructure that aids in the location process, which may increase the cost of the solution, or use expensive technologies to implement the solution. There is only conceptual work surrounding the use of simple optical feedback to the drivers, by using red LEDs to warn the driver, and the current research work being done in the related area is either focused on developing a solution for the location of obstacles or workers, or for Human–Machine Interaction (HMI), but not an integration of both subsystems as a complete and standalone assistance system.

Therefore, the main contribution of this paper explores the use of new communication technologies to facilitate the integration of a location system for nearby workers that involves minimal setup for the off-road vehicle. The location system leverages the location capabilities of Bluetooth, concretely, but does it change the typical paradigm of location based on triangulation or trilateration, which require multiple beacons. The contribution of this paper opts for a simple proximity detection approach that eliminates the need for an infrastructure, that requires adequate beacon coverage to ensure precise location tracking. We design and build a proof-of-concept system to aid drivers of industrial off-road vehicles to locate nearby workers, which is low-cost, easy to set up, and with an easy learning curve while requiring low mental effort from the driver. The system is divided into two subsystems. The location subsystem and the driver feedback subsystem.

The HMI subsystem will interact with the driver through LED strips placed on both sides of the front and rear windows to engage the driver's peripheral vision, which has proven to be more effective than central vision by reducing the reaction time [3]. In addition, a haptic signal delivered by a vibrating mini-motor disk (similar to the ones in smartphones) will be sent through the safety belt. The system establishes two safety perimeters and warns the driver using a very simple color code (amber and red). The different LED strips will light up depending on the zone where already-known detected (front, back, left, or right). In the event the pedestrian is in the closest perimeter, the safety belt haptic feature is also activated. Drivers in dangerous scenarios can stop the machine, or at least be made aware of their surroundings [4]. When it comes to a feedback mechanism, a very simple system normally associated with specific behavior such as traffic lights, is luminous signaling which provides feedback to the driver prompting an immediate response, thanks to the already-known traffic light color association.

For the location subsystem, we leverage Bluetooth technology to provide drivers with location information about nearby operators/workers. The system will estimate their location and prompt a luminous signal to the driver who can act accordingly. The use of Bluetooth for indoor location systems is something that has been discussed in the literature [4]. Bluetooth as a technology has a set of advantages that encourage its consideration. The technology is very affordable and continues to be developed and improved. In addition, in terms of technology for location, it can be used leveraging signal strength to estimate the location, albeit not the most accurate, but sufficient to provide very simple information to the driver and what is most important without requiring installing a supporting infrastructure to get location information, allowing us to provide an ad-hoc system.

The rest of the paper is organized as follows: in Section 2 we discuss the background and state of the art. Section 3 presents the proposal, its architecture, and its design. In Section 4, we elaborate on the experimental setup and the proof-of-concept implementation. In Section 5 we provide some discussion on different aspects of the system. Lastly, Section 6 provides conclusions and future work.

## 2. Background and state of the art

Since the onset of the first Industrial Revolution, there has been significant evolution. As described by Karnik et al. [5], we have transitioned from purely mechanical production to the age of intelligent manufacturing, thanks to advancements in Cyber-Physical Systems, the Internet of Things, Big Data, Cyber Security, Cloud Computing, Additive Manufacturing, Advanced Robotics, Modeling, Simulation, and Augmented Virtual Reality. These innovations promote seamless integration and coordination across different processes and departments within an organization due to their real-time connectivity features. Such heightened connectivity offers benefits such as reduced development time, the ability for mass customization, and enhanced modularity and configurability. This among other things allows us to integrate the advances in different areas to fuel research innovation and provide solutions to new use cases in Industry 4.0.

Within the areas where the different advances can be of use is the area of workplace safety, where it comes to preventing accidents between co-workers and off-road heavy machinery used in industrial sites. We approach this by reviewing works in two distinct areas of research related to assisted driving in industrial environments: location for collision avoidance, and Human–Machine Interaction (HMI).

Before choosing a specific technology to develop a solution for location and collision avoidance, we reviewed different alternatives considered in the industry. We use as reference two works, one by Hayward et al. [6] provide a very comprehensive survey on the different indoor location Technologies, Techniques and Applications in Industry and the work of Cao et al. [7], where different location methods are reviewed that can be used to provide information to a forklift driver, and different assistance systems are analyzed. On the one hand Hayward et al. [6] identify *i*nertial systems, radio frequency systems*,* acoustic systems, *and* vision systems. On the other hand, Cao et al. [7] identify technologies such as radar, ultrasonic solutions, radio, and optical systems. We will follow on their footsteps to review the characteristics of some those technologies as well as specific contributions in those areas.

Inertial measurement units (IMUs) are capable of tracking location by referencing a predetermined point [8]. These devices combine accelerometers, gyroscopes, and often magnetometers to respectively measure an object's linear movements, angular velocity, and the intensity of magnetic fields in a local setting. Additionally, some IMUs are equipped with altimeters that measure external air pressure, offering nine degrees of freedom along with elevation data [9,10]. However, in indoor settings, relying on a magnetometer to ascertain magnetic north for directional orientation is not reliable due to potential interference from the surrounding infrastructure, which can result in heading errors [11].

Ultrasound technologies have come a long way from the early days when they presented poor performance, as expressed by Kelemen et al. [12], who recognized issues due to temperature and target angle having a significant impact on measurements. Nowadays, many solutions provide high-reliability location information based on ultrasound.

Filonenko et al. [13], propose an indoor positioning system using asynchronous Ultrasound Trilateration, relying on an infrastructure of four anchors to perform the estimation. Qi et al. [14], propose a high-accuracy ultrasound indoor positioning system based on a Wireless Sensor Network, relying on an infrastructure of anchors to perform the estimation. Other approaches that use ultrasound, such as the one proposed by Holm [15], with an ultrasound positioning system based on time-of-flight and signal strength, still rely on a basic infrastructure to support. Relying on infrastructure increases the cost and maintenance of the system, so we focus on solutions that will provide an affordable ad-hoc location system.

Radar or lidar-based solutions provide accurate and reliable information about the location of objects that can be applied to pedestrians in the vicinity of the industrial vehicle. The issue with these solutions is that they are far from inexpensive, and are limited by line-of-sight, which may be a deterrent when it comes to deploying them as part of a company's measures. Nonetheless, it is worth mentioning that with the increased interest in these technologies and their use in Intelligent Transport Systems (ITS) and IoT applications, their price is likely to fall in the future and be a welcome addition to complement a location system.

In the area of optical systems, Borstell et al. [16] provide a location system for forklifts using planar marker detection. A set of markers (like QR codes) are placed on top of each forklift and with the help of a set of cameras distributed around the warehouse where the forklifts are moving, their location and route can be determined. This solution requires a costly installation of support infrastructure to provide the necessary information about the location of the forklifts. Furthermore, they do not consider the movement and the location of nearby workers, which is pivotal in our proposal.

Sun et al. [17], discuss the advantages of Ultra-Wide Band (UWB) for indoor locations. They develop a forklift safety monitoring system using UWB technology, using the method of locating the time difference of arrival, to be able to locate forklifts in the warehouse. They rely on the infrastructure of base stations located in the warehouse to perform the location. As in the previous scenario, the focus of this work is not the interaction and pedestrian workers' safety. Similarly, in two works by Che et al. [18,19] use Machine Learning (ML) to improve the location of UWB indoor, where they use anchor-based location in a simulated environment. Although the work is interesting, their infrastructure-based approach is not aligned with the objectives of this work.

Lang et al. [20] developed a system that employs existing image processing techniques to avoid potential accidents by deploying cameras. The movement vectors of all items in the forklift's travel path are determined in this fashion, allowing for the prediction of possible collisions. A two-stage warning is also possible thanks to the additional detection of people. Collisions that may harm individuals can thus be anticipated. This approach is much closer to the objective of that proposed here. The downside of this approach is the cost of the equipment, infrastructure deployment, and the complexity of the image processing that must be carried out. Affordable solutions are important when it comes to security, to reduce as much as possible reluctance to adopt new safety mechanisms.

Tamara et al. [21] go one step further and study Automatic Guided Vehicles (AVG). Their focus is on providing accurate placement of the forklift by itself in a warehouse, to enable an automatic guidance system. Their focus is not on avoiding collisions with nearby workers or other vehicles.

Wang et al. [22] introduce a weighting scheme that adjusts mixing weights using a Boltzmann distribution analysis, focusing on maze-solving tasks, and examining how two metrics, pain-avoiding and goal-reaching, impact each other's learning behaviors. They developed a sensor fusion network that combines data from lidar and a monocular camera, simulating three varied complexity mazes.

Rohrig et al. [23], develop a localization system, called nanoLOC, instantiated with ISM 2.4 GHz with IEEE802.15.4. Proposed infrastructure by using 4 anchors, covering a square zone, the anchors being the four vertices of the square they rely on, to provide an accurate measurement of the positions of the different nodes. They then apply a set of algorithms to improve the location based on parameters such as the Time of Flight and Round-trip Time of Flight (RToF) and apply filters such as Kalman to minimize noise and errors in the estimations.

Bluetooth is another technology that is proposed for the indoor location. The typical proposal uses infrastructure-based indoor location systems such as those proposed by Faragher et al. [24] and Gonzalez-Castano et al. [25]. While infrastructure-based approaches help provide an absolute position, the use case where the absolute position is not needed, but rather a relative position to another target, remains uncovered. In this paper, we propose a solution that leverages Bluetooth to provide an infrastructure-less location service, which does not require absolute positioning information. This is, therefore, the technology that we will leverage to obtain an infrastructure less approach to a location system, that is both affordable and provides location capabilities.

On the other hand, we review related work regarding Human–Machine Interaction (HMI) in industry. These entail proposals to assist drivers of industrial vehicles, by giving them information about their surroundings to prevent accidents. These feedback systems need to be affordable in the implementation and deployment and must also be suitable for the specific use case. In this sense, there is no advantage in having several cameras and setting up monitors for the driver that results in complex dashboards. The feedback information must be interpreted by the driver in real-time, concurrently with a very attention-demanding task such as driving heavy machinery. To find a simile, complex feedback systems are akin to texting and driving for everyday drivers, which requires a driver to take their attention off the road, even for a few seconds, which could lead to a traffic accident.

Regarding HMI in industrial scenarios, several works contribute to the area. Most of the related work relies on visual feedback with an onboard monitor. The difference lies in the information given to the driver and the reported security issues.

In the work of Ludwig et al. [26], a system is developed to provide feedback to drivers about their work performance in a monitor installed on a heavy vehicle. In this setup, the company recorded no accidents during the study and the authors state that they continue to have one of the lowest accident rates. This gives us valuable information about the mental load a worker can handle without affecting the safety of the daily operation. Looking at the information on a monitor sporadically, every 5 or 10 min to check the current performance, is manageable for the driver and is not something that must be done concurrently while maneuvering the vehicle.

The next two instances rely on information from cameras relayed to the driver. Ulrich et al. [27], work on a system that aims to prevent accidents by giving the driver information directly from came infrastructure-based development of a novel collision warning system for mobile machinery in off-highway applications, to improve safety in scenarios where there is a significant chance of an accident. Their use case relies on a monitor and cameras that show the driver in a split-screen the rear and top view and add a trajectory overlay, like the typical rearview parking assistance systems in most modern cars. On the other hand, Wei-Hsiang Chung et al. [28], provide an AI-assisted system that overlays the captured image from cameras and provides information about the objects (e.g., employees, cargo, other trucks, etc.). This kind of solution improves the ability of drivers to see around them, but they do not provide a direct warning signal, as the driver has to remove their attention from the real view to look at the monitor and determine if there is any possible danger. To provide an easy and direct warning signal to the driver, we can rely on more straightforward approaches that facilitate the driver's response to a basic visual stimulus, such as a warning light.

Stein et al. [29], perform a study to show the use of peripheral vision

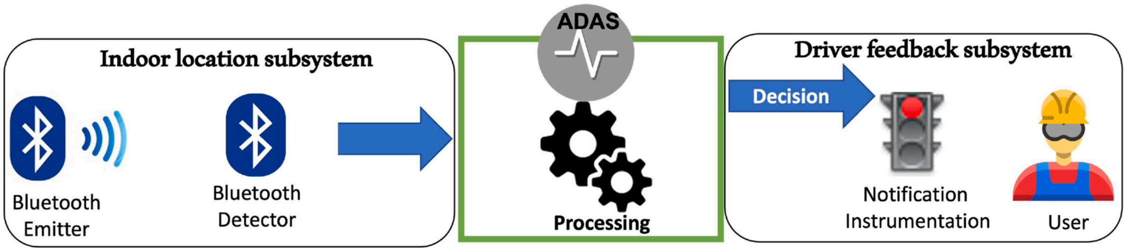


**Fig. 1.** Ad-hoc location system architecture.

to provide visual feedback to the driver. They use red LED strips placed horizontally and on the sides of the forklift frame. This work shows that simple visual feedback reduces reaction time, which is paramount when dealing with safety applications. This agrees with our approach, which follows the research by Adam Larson and Lester Loschky [30,31] conducted research on central and peripheral vision in 2009, and Loschky conducted even more research in 2019 [32]. Then he measured how long it took for the amygdala (the emotional part of the brain that responds to fearful images) to react. When the fearful object was shown in the central vision, it took from 140 to 190 ms for the amygdala to react. But when objects were shown in peripheral vision, it took only 80 ms for the amygdala to react.

In this work, we go further by applying additional but simple visual and haptic feedback. While we agree that very simple feedback that relies on peripheral vision improves the response time, we find that only one color (red) to show warning signals could trigger unnecessary responses if the situation does not prompt an immediate response. For instance, if there are workers nearby and the only aim is to let the driver know, more precautions could be taken without bringing the vehicle to a complete stop. We did not find studies that analyze the impact of using different color ranges for different warnings or other types of feedback mechanisms such as haptic responses. For these reasons, we build upon the related work to generate a system that not only focuses on one aspect of assisted driving but also brings location technology and HMI together, providing a comprehensive and cost-effective solution to improve safety and security in the workplace. Most reviewed solutions focus either on the system or technology for the location or the HMI side of the interaction with the user, but there is little work dedicated to uniting the two topics. The solutions that focus on location usually rely on infrastructure with anchors to provide accurate location information in a warehouse. While the anchor-based approach provides accurate information and the possibility of obtaining absolute location information, this work focuses on an integrated solution of an ad-hoc location-based subsystem that is integrated with an efficient driver feedback approach. This approach minimizes the cognitive load of the driver and provides different sources of sensory information, both visual and haptic, as well as providing additional information with different colors, not solely red, to reduce the number of abrupt responses from the driver, by giving information not only about possible emergencies but also through warning signs.

## 3. Advanced driver assistance system design

In this section, we present the design of the proposal for the collision avoidance system. It has been designed with an ad-hoc location information subsystem integrated with a feedback subsystem for drivers of heavy machinery. The solution increases safety in industrial environments by providing a standalone solution to increase the awareness of heavy machinery drivers. This proposal aims to provide information about their surroundings and nearby workers to drivers of machines such as forklifts, which operate in warehouses and similar indoor locations, where there is the movement of different machinery and workers on foot. In this way, the awareness of drivers to reduce incidents is increased.

The design of the system pursues the following characteristics: 1)

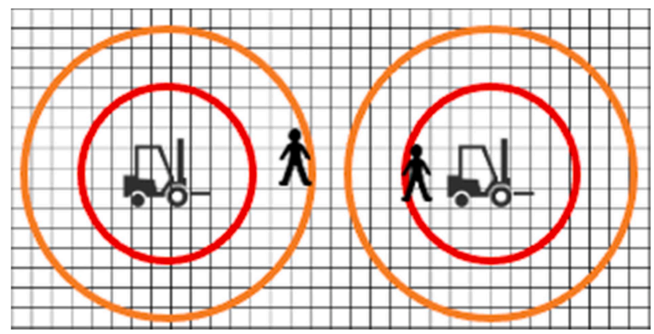

**Fig. 2.** Ad-hoc location system concept.

Affordable and scalable deployment, 2) a standalone solution, not dependent on a support infrastructure for location, 3) a simple yet meaningful feedback system, and 4) a reduction of the cognitive load of the driver. The design of this proposal is divided into two main parts that are integrated: the ad-hoc location subsystem and the driver feedback subsystem that provides feedback to the driver.

The four elements of the architecture of the proposal can be seen in Fig. 1. These elements are 1) the beacon emitters, 2) the detectors, 3) the ADAS engine, and 4) the Informational elements of the feedback system, which are the LED strips and haptic feedback system.

The beacon emitters are set up and programmed to send these messages at a given frequency, so the detector can gather the information necessary to make a prediction. The beacon detector setup will be described in Section 4. Related work reviewed in Section 2 shows that using Kalman filters can improve the prediction of users' location. We can use Kalman filters to process and combine two different RSSI (Received Signal Strength Indicator) readings from Bluetooth devices to achieve a more accurate estimate. If we have two different readings of the same RSSI value (for example, from two different receivers or sensors picking up the same Bluetooth device), using a Kalman filter can help combine and refine these measurements for a more accurate estimate. The idea is to treat each RSSI reading as an individual measurement of the same underlying state (the "true" RSSI value). The Kalman filter can then be used to fuse these measurements, considering the uncertainties associated with each reading [33–35]. This information is then processed by the ADAS system, which performs the estimation of the data received by the beacons and delivers, according to the prediction, what the driver feedback subsystem needs to indicate to the driver.

### 3.1. Ad-hoc indoor location subsystem

In the field of location systems, there are solutions for global positioning systems (GPSs), and local positioning systems (LPS). For the latter, active target remote positioning allows finding the relative position of other nodes. The concept is illustrated in Fig. 1, and the objective is to determine if there are nearby users at a safe distance (outside of the amber circle), nearby (between the red and amber), or too close inside the red circle). Using beacon signaling emitted by the users that are on foot, the ad-hoc location system installed in the vehicle can determine

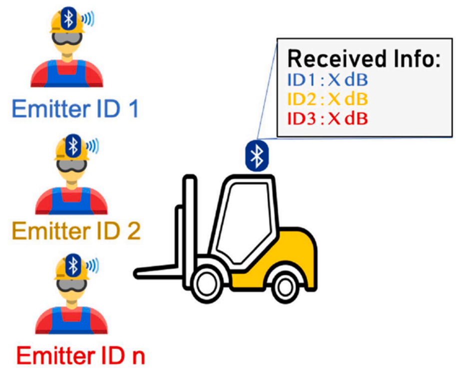


**Fig. 3.** Ad-hoc location system representation.

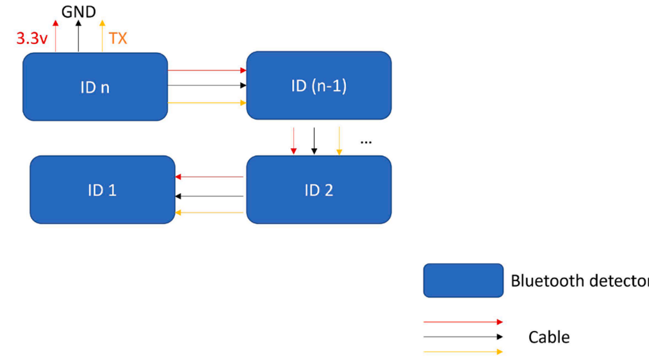


**Fig. 4.** Schematic of arrangement of detectors in series.

the relative position of workers and provide feedback to the driver (Fig. 2).

We have chosen Bluetooth technology for the design. As reviewed in Section 2, Bluetooth is identified in [7], among the technologies and approaches that can be used for locating purposes. In this paper, we use a method that pertains to this positioning system, using the Received Signal Strength-Based Positioning (RSSI). There are numerous contributions regarding the use of Bluetooth and RSSI to provide location information [36,37]. We have chosen this technology because of its reliability and affordability, and because it is continually being improved with new characteristics. On its own, in terms of accuracy, this method does not provide the best results. Related work shows that using Kalman filters can improve the prediction of user location using RSSI [33,35,38]. For our use case, the precision of Bluetooth with the use of filters is sufficient to provide information about the nearby workers in an area that can be considered dangerous or only prompts for a warning indication. Once the data about the signal strength is received and filtered, the approximate distance in meters can be calculated, as detailed in Section 4.1.

Next, we describe the design of the proposal for location, to comply with the requirements and specifications of the previous section. The location system has two entities: the emitter and the receiver. The mapping between the Bluetooth entities and the warehouse workers is illustrated in Fig. 3. The nearby workers carry the Bluetooth emitters working in advertising mode. The Bluetooth receivers working in observing mode are located on the forklift. This way, any forklift can receive beacons from any number of workers, process the data, and feed it to the ADAS engine in the forklift, so it can generate the necessary information to interact with the driver feedback subsystem.

By using Bluetooth beacons, we implement an ad-hoc system. The accuracy of the location of each worker is not high, but for this use case, it is more important to issue a warning about a nearby worker than to pinpoint the exact location of each worker in the warehouse. This approach is scalable, in the sense that with the same setup, we can add a Bluetooth receiver to each forklift which will receive the beacons from any nearby workers. If one worker happens to be close to two forklifts, both forklifts will receive the beacon from the worker and process it accordingly. Furthermore, each beacon carries a specific ID, that can be used to distinguish between different emitters.

For the design of the location subsystem, we aim to provide an infrastructure-less system for locating nearby workers, without having to rely on fixed infrastructure or anchors. This approach allows us to have an n-to-n relationship between workers who are expected to be detected and the drivers of heavy machinery, making it scalable. That is, every worker is detectable by every driver if they are within range. Furthermore, the location information received by the location system is relative to the position of the driver and the worker. Not having to rely on infrastructure anchors to obtain location information about a specific reference frame simplifies the calculations and the location procedure. For this to work, the proposal requires specific equipment for the forklift and nearby workers.

Every worker needs to carry a device that emits beacons whilst they are in the warehouse. The device can be placed on the hard hat, for instance. The beacon is received by Bluetooth detectors, which are installed in every heavy machine. Every machine will have two detectors placed, one on each side to infer the relative position of the workers and the distance. The equipment in the forklift will gather the information from the beacons, evaluate it from every nearby worker, and provide feedback to the driver, which is the second part of the system, that is, the driver feedback subsystem.

### 3.2. Driver feedback subsystem

In this article, we go beyond the state of the art in industrial vehicles HMI [29], where they base the feedback to the driver on two long, red LED strips placed vertically on the sides of the vehicle frame, plus one LED light in the center. In the proposal of this article, the information for the driver will be simple, using LED strips in two colors, amber and red. The amber strip will warn drivers that they should maximize precautions as there are workers nearby, while the red will indicate to drivers that there are workers too close to continue moving, so they should stop if they are unaware of said workers. Coupled with the red LED lights, drivers receive haptic feedback. Vibrations are produced by the seatbelt to improve the reaction time of drivers as re-enforcement to red LEDs.

Each worker carries an emitter Bluetooth device sending regular beacon messages. These beacons are received by Bluetooth detector systems installed on the forklift. This information is gathered by an ADAS (Advanced Driver Assistance Systems), which estimates the distance of the workers and emits a red LED light if the zone where the worker is predicted to be is dangerous, prompting the driver to stop and making sure the surrounding area is safe, or amber if the workers are predicted to be close to the vehicle, inviting the driver to slow down and making him or her aware of the surroundings. The HMI system considers the following building principles as part of the interaction with the user. Simple light signals with colors such as those that all drivers are familiar with (red and amber) provide a very intuitive and easy learning process to interact with the system. Additionally, we provide haptic feedback, producing vibrations in the seatbelt to reinforce the feedback of the red LED light.

## 4. Experimental setup

In this section, we implement a proof of concept of the proposed ad-hoc location and HMI feedback system for drivers of heavy machinery in the industry. This proof of concept uses Bluetooth LE devices. On the one hand, we use Bluetooth emitters [39] that send beacons, and these are received by the Bluetooth detectors, which, in turn, send the information to the ADAS. The ADAS, a Raspberry PI 3 where all the Bluetooth detectors are connected, gathers all the data from the detectors and

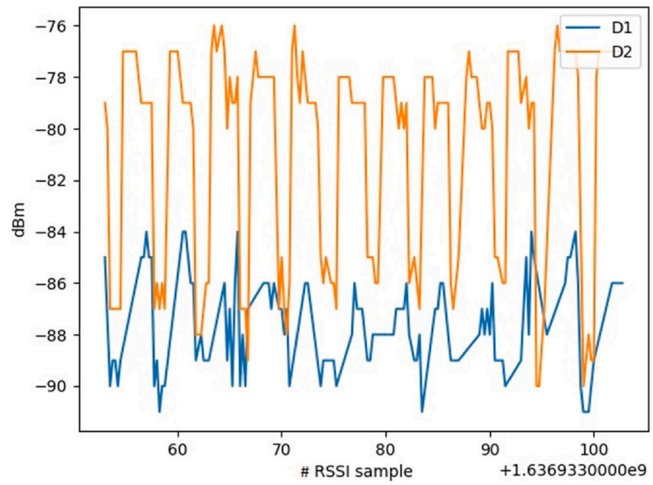


**Fig. 5.** Oscillation of two nearby detectors.

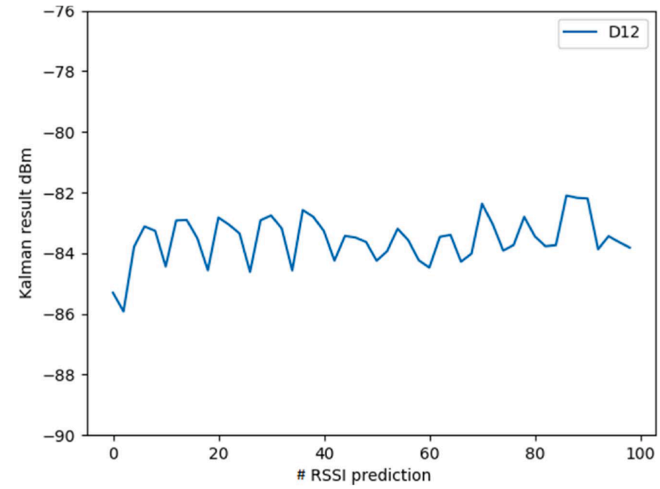


**Fig. 6.** Detectors 1 and 2 after applying the Kalman filter.

processes it to provide information to the driver. The radiofrequency of Bluetooth is not altered. To enable the detection system, we change the frequency at which the beacon messages are sent from the emitters to a specific number of messages per second. This value can be altered depending on the demand of the system. The antennas in both receiver and transmitter, are omnidirectional with 0dBi gain. The Bluetooth detectors are all connected in series, following the schematic shown in Fig. 4. After processing, the ADAS estimates the relative position of the Bluetooth emitters in close range, so the HMI system can be activated accordingly.

### 4.1. Bluetooth-based location subsystem

As an initial contact with the technology, we saw how a real system behaved in a very simple setup. When using only one emitter and one detector on each side of a large table to emulate a real forklift (4 detectors in total). In this design and the proof-of-concept, the emitter sends an identification message according to Bluetooth specifications. The signal can be considered in fact as a pulsed signal. We noticed that for an emitter that is not moving, the value of RSSI detected oscillates and that the amplitude of the oscillation is not the same for two very close detectors.

This is shown in Fig. 5, where we can see that two detectors that are right next to each other (blue D1 and orange D2) give RSSI values of the same Bluetooth emitter, and those values oscillate and differ considerably. It is worth noting that both detectors present a similar oscillation in RSSI values, so it is fair to think that this oscillation is probably due to electromagnetic boundary conditions, which slightly modify the electromagnetic channel and produce losses depending on time. Nonetheless, as the distance between the emitter and the detector increases, the RSSI values decrease as expected. Furthermore, we noticed that due to the proximity of the detectors at each side of the table, and given the oscillations of the signal, sometimes the detector given the highest RSSI value was not the expected one (an adjacent detector). To minimize this effect, we experimented with shielding the signal with a metallic grid, which improved the results considerably. This is due to the modification of the radiation pattern of the Bluetooth antennas when including this shield, this increases the gain of the antenna and reduces the impact of the boundary-changing conditions of the electromagnetic channel. In addition, to avoid reading in a specific instant from two detectors on adjacent sides, which could lead to an incorrect prediction, we can also increase the reliability of the prediction by placing two detectors on each side, to smooth the prediction. This is the same principle of the MIMO (Multiple Input, Multiple Output) antennas, widely used in electromagnetic communications. Given the variability of the RSSI readings of Bluetooth, the question then arises: How can we establish a correspondence between a set of RSSI readings and the position of the emitter? To tackle this issue, we follow the procedure already proposed in related work, which is to use a Kalman filter to smooth the values and generate a prediction. These values need to be adjusted depending on the specific configuration of the Bluetooth emitter, the specific SoC used, etc. Röbesaat et al. [35] provide such an approach to using Bluetooth and RSSI for location.

With the aforementioned information on how the Bluetooth hardware was used for the experiments, we decided to use a window of accumulated readings upon which we predict applying the Kalman filter. The results of the application of the filter can be seen in Fig. 6.

After we obtain the smoothed signal, we proceed to translate that into a distance in meters from the detectors. The log shadowing model can be used to compute the distance in free space, and Eq. 1, can be deduced from this model:

$$d[m] = 10\,\frac{RSSI[dBm] - RSSIref[dBm]}{10 * n}$$

where:

| | |
|---|---|
| $d$ | distance in meters |
| RSSI | the RSSI value detected from an emitter. |
| $RSSI_{ref}$ | RSSI of reference |
| $n$ | environment parameter ($n = 2$ in free space) |

To calculate $RSSI_{ref}$ we take samples at 1 m to establish a baseline of the measurement. We determine the different zones that are considered for a warning amber light or an alert with a red light and haptic feedback. For the proof of concept, we can establish that for a value of 3 m or less, we will provide an alert, and for a value between 3 and 5 m, we issue only a warning. The authors would like to note that the values used here are only for the proof of concept and in no way reflect the real values of the warnings or alerts to be issued in a real deployment. The definition of the specific configuration of the different zones falls outside the scope of this paper, as it should be part of a study on safety policies.

### 4.2. Driver feedback subsystem

The feedback system in this proposal goes further than that proposed in related work, where the improvement of elongated peripheral warnings is analyzed, using long LED strips placed in the center over short LED strips, only in red. We go further than the current state of the art [29], by adding another color (amber) which allows us to distinguish between an alarm and a warning. Previous work only using red LEDs may limit the feedback when a dangerous situation is ongoing. We provide a simple sensory feedback system that does not require the

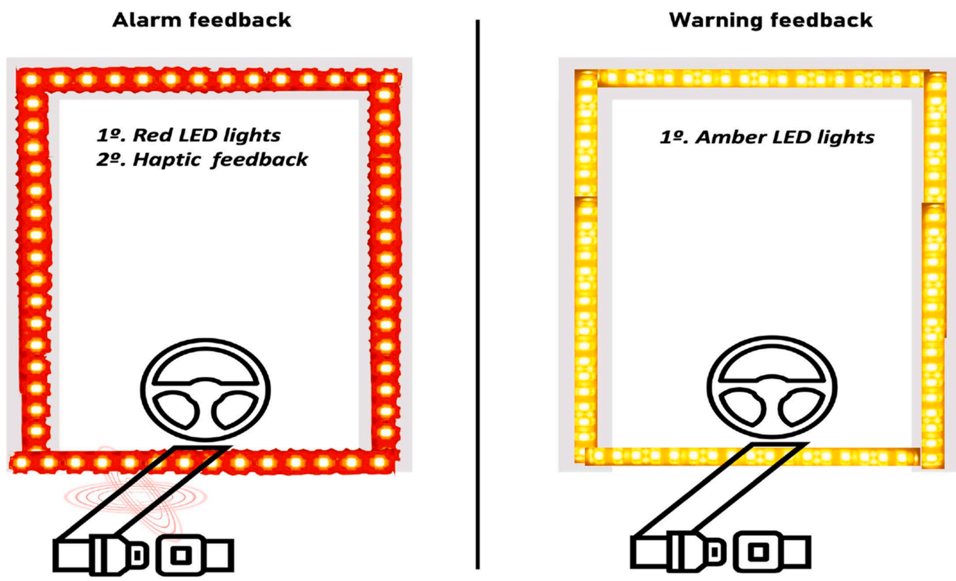


**Fig. 7.** Human–machine interaction (HMI) system.


**Fig. 8.** Example of HMI system.

driver to perform demanding cognitive tasks to evaluate the information. This is the case as the color code used is very intuitive to the driver as it is akin to that used in traffic lights. Furthermore, we added a haptic feedback system, with vibrations in the seatbelt that will complement the alarm indication (red LED) to improve the driver's reaction time. The feedback system for the visual part divides a multi-color LED strip into 4 distinct groups, which are mapped to different zones. They will light up independently, depending on the information received from the detectors on each side. An illustration of this system is shown in Fig. 7. The group of LEDs installed on the top of the frame will light up if the detection is ahead. If the detection is done behind the heavy vehicle, this will cause the lower LED strip to light up, and finally, right, and left detection will light up the respective strip. Fig. 8 shows an example where there are workers detected in proximity ahead (red light), and nearby on the left side (amber light). In addition to this, to reinforce the feedback system in an alert situation, we introduce the haptic feedback system, which will also act as a fallback system in case the red LED is not detected as quickly as expected.

We restrict the feedback system to the most restrictive prediction. Thus, if there is an alert and a warning detected on the same side, the vehicle must be stopped immediately.

### 4.3. Experimental results

The delay time between the detection of the worker, processing of the data, and the feedback to the driver is very important, to show that the delay does not preclude the user from having a good reaction time. In this section, we show the time between the detection of the worker, processing of the data, and feedback to the driver. In this sense, we have divided the complete process into three different subprocesses: 1) Reading Detectors, 2) Generating prediction and 3) Activate user Feedback mechanisms. The summary of the times that each subprocess takes is shown in Fig. 9. It is worth noting that the Bluetooth emitter is sending beacons at a predefined frequency, we then can get a reading from the Bluetooth detectors approximately every 78 ms. We have then a pool of readings from all the detectors that can be used to generate a prediction of the location and the zone where the user is located. This prediction takes about 20 ms. If the prediction estimates that the user is in a warning or dangerous zone, then we proceed to activate the user feedback mechanisms. Activating the feedback mechanisms takes about 25 ms. If we account for the whole process to provide a more complete view of the system, our proof-of-concept completes the whole process in about 164 ms. This allows us to generate alerts 6 times per second if needed.

### 4.4. Proof-of-concept implementation

In this section, we describe the experiments carried out to provide proof of concept with real machinery. We set up the system in a TAKEUCHI TB219 Compact Hydraulic Excavator,[1] as shown in Fig. 10.

[1] https://www.takeuchiglobal.com/compact-excavators/tb219-compact-excavator

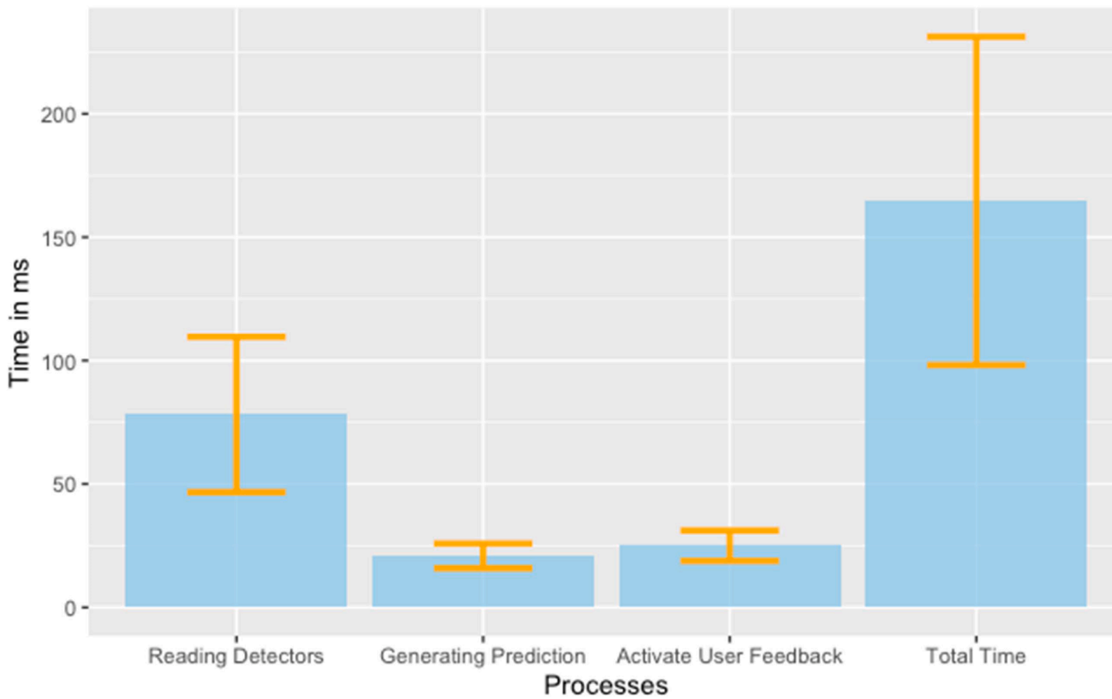


**Fig. 9.** Time in ms of the different processes.

**Fig. 10.** Excavator used in the proof-of-concept.

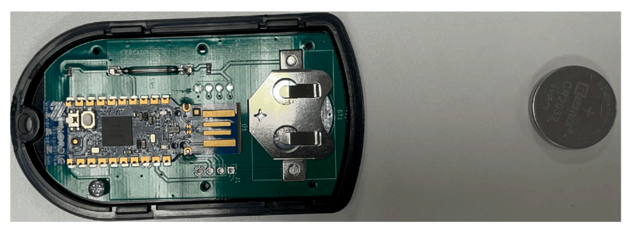

**Fig. 11.** Emitter device.

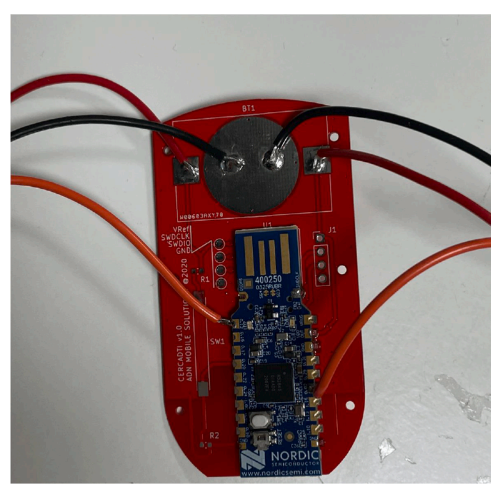

**Fig. 12.** Detector device.

The main height of the users that tested the system was 175 cm, and they had the Bluetooth emitter in their hard hats.

We used multi-color LED strips and a vibrating device connected to a Raspberry Pi 3 where the ADAS has been implemented. All devices are connected to the GPIO of the Raspberry Pi.

We also connected 8 Bluetooth detectors in series to the RPI, two per each side of the vehicle. The information from the detectors is received at a specified frequency, which can be parameterized, giving us the possibility of obtaining a greater number of samples if needed.

The Bluetooth detectors and emitters use the Nordic nRF5340 SoC,[2] as shown in Figs. 11 and 12. The emitter is attached to a hard hat, as the worker moves through, the system can detect where the worker is and issue a warning as shown in Fig. 13 or an alarm as shown in Fig. 14.

## 5. Discussion

In this section, we comment on some additional points that we

[2] www.nordicsemi.com/Products/Bluetooth-Low-Energy

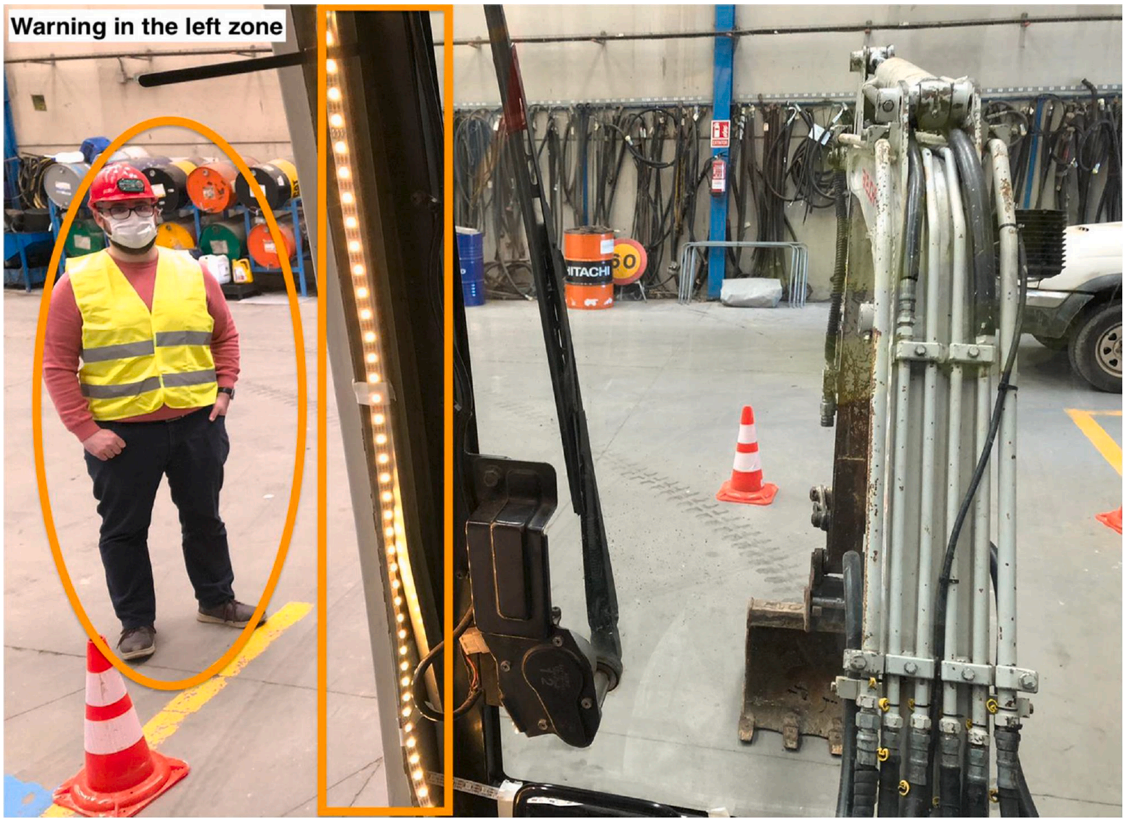


**Fig. 13.** Warning sign with amber LED.


**Fig. 14.** Alert sign with red LED and haptic feedback.

believe require further consideration. Given the results of the proof-of-concept, we have a clear baseline on how the system would perform. In this sense, with the hardware used, we can generate 6 complete estimations per second. Whether this frequency has to be augmented, has to be done with a specific use case, depending on the industrial vehicle and its characteristics. For an excavator, that is expected to be static most of the time, with a specific maximum radius of motion, the system has demonstrated good behavior, when warning the users. For other industrial vehicles such as forklifts, we have to account for the maximum velocity of the vehicle and adjust the zones to be able to warn the driver well in advance.

### 5.1. Deployment considerations for detectors

Regarding the detector placement, there is a lesson learned from the laboratory experiments, which is the distance between the detectors is of great importance. Due to the variability in the RSSI parameter, if the detectors are placed less than a meter apart, some readings may get the prediction that the user is close to an adjacent detector, not the expected one. Hence, it is important to account for this parameter when constructing the setup. Another issue can be raised regarding the battery of the emitter devices. As the distance is calculated based on signal strength, maintenance of the battery system of the beacons is needed and should be considered in real deployments.

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### 5.2. Real-time considerations

Another interesting point to raise is the issue of how many times per second the emitters send information to be able to prevent an incident, considering that heavy machinery does not move in the same way as a commercial car. In this sense, off-road vehicles such as forklifts and excavators are not used for commuting. Their use is mostly focused on, for example in the case of the excavator, performing works with the excavator's boom or arm while it is stopped at a specific location. Similarly, the forklift can be moving cargo from one place to another in a repetitive manner. As nearby workers approach the off-road vehicle, it is enough to gather information about the broad area surrounding the vehicle, and whether someone is approaching to trigger the alert or warning to the driver. In Section 4.3 we have provided data that shows that in this proof-of-concept we can go up to 6 predictions per second. Nonetheless, the real value must be parameterized and adapted according to the specifics of each use case and machinery used.

## 6. Conclusions and future work

In this work, we provide a system to help improve safety in industrial environments with heavy machinery where accidents can have severe if not fatal consequences. We propose a very affordable system that uses Bluetooth as a technology to infer the proximity of a worker to heavy machinery, to warn the driver by prompting with a feedback mechanism, and LED lights in our proof of concept, but that could be adapted to other feedback systems. A limitation of the current system is that it does not provide an accurate location over a predefined mapped area, rather it provides an approximation of the relative location of the pedestrians or nearby workers to the industrial vehicle. Regardless of the accuracy issues of Bluetooth, the technology shows good performance to indicate if a nearby worker is in a dangerous zone. If the worker is too close, the driver needs to slow the vehicle and take precautions. If the signal is weak, the user is safe. A specific configuration or calibration must be done for the equipment used. The process can be customized to the specific requirements of the use case.

This work provides the basis and a platform for very interesting research work that can be done in terms of the location and the driver feedback subsystems.

For the location system, future work is planned to use one of the new characteristics of Bluetooth 5, the Angle of Arrival (AoA), by which we may improve the results of the location while maintaining a cost-effective proposal. Additional future work is planned to analyze how the ranges established as red or amber can be dynamically modified as the vehicle moves, so as the vehicle increases speed, both the warning (amber) range and the dangerous (red) zone might be widened. Further future work can also be aimed at researching the adaptability of the system as the vehicle moves, to dynamically increase the warning and alert areas as the velocity of the heavy vehicle increases. A broader view could also be achieved by using Bluetooth mesh communications and Bluetooth performance [40]. In terms of driver feedback, additional work can be carried out to study the reaction of drivers to different kinds of visual and haptic stimuli. In this sense, we can provide more complex information by using LED matrices, progressions, blinking lights, different intensities, etc. to convey more information and evaluate the response and cognitive load of the driver.

## Author contribution

All the authors contributed equally to this article.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

## Acknowledgments

This work was possible partially thanks the project TED2021-130919B-I00 funded by MCIN/AEI/10.13039/501100011033, and by the European Union NextGenerationEU/ PRTR, and partially by the project SV-22-GIJON-1-01 of the Instituto Universitario de Tecnología Industrial de Asturias (IUTA). We want to give special thanks to EXCADE S.L., which provided the real excavator machine to undertake the proof of concept.

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