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An IoT-Aware Smart System Exploiting the Electromagnetic Behavior of UHF-RFID Tags to Improve Worker Safety in Outdoor Environments

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Abstract: Recently, different solutions leveraging Internet of Things (IoT) technologies have been adopted to avoid accidents in agricultural working environments. As an example, heavy vehicles, e.g., tractors or excavators, have been upgraded with remote controls. Nonetheless, the community continues to encourage discussions on safety issues. In this framework, a localization system installed on remote-controlled farm machines (RCFM) can help in preventing fatal accidents and reduce collision risks. This paper presents an innovative system that exploits passive UHF-RFID technology supported by commercial BLE Beacons for monitoring and preventing accidents that may occur when ground-workers in RCFM collaborate in outdoor agricultural working areas. To this aim, a modular architecture is proposed to locate workers, obstacles and machines and guarantees the security of RCFM movements by using specific notifications for ground-workers prompt interventions. Its main characteristics are presented with its main positioning features based on passive UHF-RFID technology. An experimental campaign discusses its performance and determines the best configuration of the UHF-RFID tags installed on workers and obstacles. Finally, system validation demonstrates the reliability of the main components and the usefulness of the proposed architecture for worker safety.

Keywords: worker safety; working environment; IoT; UHF-RFID localization; BLE; beacon

1. Introduction

The need of guaranteeing worker safety both in indoor [1] and outdoor scenarios has been gaining interest in recent years due to its social relevance [2–4]. In fact, as declared by Stefana et al. [5] and Bitar et al. [6], "organisations face a range of ongoing safety-related challenges in order to protect the occupational safety of workers from harm and injuries and to prevent process safety events resulting in adverse effects on workers, local communities, and the environment".

In addition, the interest in such a field has grown also due to the requirements and restrictions imposed by institutions to protect workers' health and safety. The different obstacles and dangerous situations faced by workers every day, indeed, impose the respect of a lot of rules defined by institutions to reduce and, if it is possible, completely prevent risks to which they are exposed in their common actions and routines.

Nonetheless, with the aim of guaranteeing safety of workers in their daily duties, different technologies and methodologies have been introduced. In agricultural working environments, for instance, heavy vehicles, such as tractors, have been recently upgraded to be remotely controlled with the main aim of avoiding accidents such as roll-overs, which can be fatal to workers.

However, as it often happens when new solutions are adopted, the introduced innovation could bring new risks to be monitored and mitigated. In fact, the remote control of machines can cause other safety issues; as an example, a distracted ground-pilot (also called driver or ground-driver in the following) or those with poor visibility can continue to drive machinery by provoking collisions that could involve other machines, or human operators, in the worst case [2,3].

In such scenarios, smart solutions could be introduced to mitigate or completely avoid dangerous situations. An example could be a localization system installed on remote-controlled farm machinery (RCFM) to track human workers with respect to RCFM, thus preventing fatal accidents and reducing the risk of collision occurrence.

In this framework, this paper proposes an innovative smart system designed within the SMARTGRID Project [7,8] and developed in collaboration with the Italian National Institute for Insurance against Accidents at Work (INAIL) that exploits passive Ultra High Frequency-Radio Frequency Identification (UHF-RFID) technology supported by commercial Bluetooth Low Energy (BLE) Beacons for monitoring and preventing possible accidents that may occur when ground-workers of RCFM collaborate in outdoor agricultural working areas. The proposed system leverages the possibility offered by the modern technologies to localize and track workers, obstacles and machines in an area of interest to secure their movements and actions. Commercial UHF-RFID and BLE systems simultaneously operate to guarantee the workers' safety through redundancy. The paper proposes a modular architecture to merge such technologies in a smart environment able to expose useful services for the different kind of workers that could be present in agricultural working environments. The architecture is designed to monitor the described dangerous situations through the localization of all the stakeholders. Then, alarm signals are sent to site personnel by means of smartphone notifications to suggest intervention or automatic stops of RCFM in the event of potential collisions. The implementation details of each technology are reported to show the feasibility and usefulness of the proposed smart system in the presented context. Specifically, the goal of this paper is to describe the system architecture and provide a first Proof-of-Concept (PoC) demonstration of the UHF-RFID tracking system, which is the most innovative component.

The paper is organized as follows. Section 2 analyzes related works, while Section 3 reports a descriptive scenario used in Section 4 to define the requirements of the system and to design the system's architecture. Section 5 describes the main characteristics and the implementation details of the main components of the proposed architecture by focusing on the UHF-RFID tracking system and the optimal tag configuration with respect to its position on the worker body. Then, Section 6 reports the experimental results gathered with a PoC of the UHF-RFID tracking system and a first functional validation of the proposed solution. Finally, Section 7 concludes the paper and sketches future works.

2. Related Works

Real Time Locating Systems (RTLSs) can be implemented through various technologies, and their applicability for safety management on construction sites or other work scenarios has been studied over the years [1–3]. The real-time localization of human personnel, machines and obstacles is vital, in fact, for the prevention of the risks of dangerous collisions both among vehicles and among vehicles and humans [4].

Multiple solutions to implement RTLS systems exist and, in almost all the cases, the only monitoring of the location and the direction of on-site resources, particularly workers and equipment, is enough to prevent exposure to hazards and potential accidents. Essentially, two main architectures can be found in the literature and on the market:

- Localization systems with external infrastructure: a fixed infrastructure allows determining the position of all agents present on the site, such as operators, machines and obstacles, according to a common reference frame. A central system manages the generation of alarms based on a set of pre-established criteria, for example, the excessive proximity between an operator and a machine, or the proximity of a person or object to a hazard (e.g., fall, gas leak, etc.).
- Localization or proximity detection systems with internal infrastructure: machines, and possibly also the operators, have a local system that measures the relative distance of operators and obstacles, or simply detects their presence (proximity systems), and possibly generates an alert signal based on pre-established criteria.

In general, both these systems involve two types of components:

- Equipment Protection Unit (EPU), consisting of the equipment installed on the RCFM;
- Personal Protection Unit (PPU), consisting of devices provided to the worker.

Another possible classification takes into account the nature of the signals used for localization; thus, we can distinguish radio technologies and other technologies. Some of them are more suitable for the implementation of systems equipped with external infrastructure, while others are more appropriate for the implementation of relative localization or proximity detection systems equipped with internal infrastructure. The main radio technologies are as follows: Global Navigation by Satellite System (GNSS), including Global Positioning System (GPS) [9], Ultra-Wide Band (UWB), ZigBee and Wireless Sensor Networks WSNs [10]; including those based on Long Range (LoRa) technology [11], UHF RFID [12], BLE [13] and, to a lesser extent, Wi-Fi [14] and radar systems [15]. Among the non-radio ones, the most popular are Computer Vision [16], Infrared [17] and Ultrasound [18].

Table 1 summarizes the main characteristics of these technologies when adopted for RTLSs with the aim of improving safety on agricultural and construction sites.

Radio frequency (RF) technologies present different techniques to perform localization, depending also on the available service bandwidth. Typically, a fixed infrastructure of powered devices is required. They are able, by measuring the distance, to detect the position of the device by using radiogoniometry methods such as multilateration [19]. The device is generally powered by batteries and is in motion in the scenario. If the system's bandwidth is very high, as in UWB systems or WSNs based on chirp spread spectrum communications, the distance is measured by leveraging time-of-flight measurements so that localization accuracy can reach satisfying levels for safety purposes [20], despite high infrastructural cost. When the available bandwidth is low, such as in Wi-Fi systems, an attempt is made to retrieve the signal power measurement with the distance measurement by using path-loss models [21]. However, signal strength is strongly affected by multipath and by the relative orientation of the transmitter and receiver antennas; therefore, path-loss models often result in overly coarse localization. Wi-Fi fingerprinting techniques can be used to circumvent this problem, but the map acquisition process is too time consuming in outdoor environments [22]. Moreover, a localization error of 1–2 m can be achieved with this approach, which may not be sufficient for safety applications.

Systems based on non-radio technologies present several disadvantages. The performance of computer vision systems is highly dependent on weather and lighting conditions. Infrared laser systems are very susceptible to steep terrain, while ultrasonic-based systems can suffer from the problem of loud noises generated by farm machinery, chainsaws or other sources. Based on such comments and observations, for the purposes of this paper, only radio technologies have been considered for the implementation of the SMARTGRID system.

Within agricultural areas, the development of an external infrastructure could be hard to deploy and maintain; thus, a simpler solution is desirable. For this reason, the passive UHF-RFID system represents a good candidate. Indeed, it is possible to realize a system with internal infrastructure, where the power supply of the reader is managed entirely by the vehicle. Moreover, the exploitation of passive tags, without battery supply, facilitates system installation and maintenance. In addition, novel Bluetooth Low Energy (BLE) technology, characterized by low power consumption, can be adopted by bringing numerous advantages in terms of security system reliability, versatility and speed in data and information exchange. For these reasons, for the purpose of the SMARTGRID project, passive UHF-RFID and the BLE technologies have been primarily evaluated among all the available radio-frequency technologies for localization. It is noteworthy that the limited range of passive UHF-RFID systems, up to 10–15 m, represents an optimal distance for our purposes; indeed, the ground-operator cannot be too far from the RCFM for correct piloting.

Table 1. Comparison among the various technologies available for RTLS for safety.

Technology	Main Technology	Advantages	Limitations	Suitability
Wireless Sensor Networks/Zigbee/LoRa	Radio	Low battery consumption	Good accuracy only with Spread Spectrum Systems	External infrastructure
Ultra-Wide Band (UWB)	Radio	High accuracy	Bad tolerance to metallic obstacles	External infrastructure
Bluetooth Low Energy (BLE)	Radio	Wide market penetration	Poor accuracy and battery life	Both external and internal infrasrtucture
GNSS	Radio	Pre-existing infrastructure for outdoor scenarios	Poor accuracy	External infrastructure
Wi-Fi	Radio	Pre-existing infrastructure for indoor scenarios	Poor accuracy	External infrastructure
Radar	Radio	No device on worker (PPU)	Only for proximity localization, low market penetration, target identification not allowed	Internal infrastructure
Passive UHF-RFID	Radio	No battery, no maintenance cost, 10–15 m reading range, false-alarm rate reduction	Only for proximity localization	Internal infrastructure
Computer Vision	Computer Vision	No device on worker (PPU)	Needs for optical line of sight, susceptibility to weather conditions	Both external and internal infrastructure
Ultrasounds	Ultrasounds	No device on worker (PPU)	Only for proximity localization, target identification not allowed	Internal infrastructure
Infrared	Infrared	No device on worker (PPU)	Only for proximity localization, only only distinction among inanimate objects and people	Internal infrastructure

2.1. Rfid-Based RTLS For Safety

In the present paragraph some literature solutions aiming at the generation of alert signals in case of dangerous situations revealed by proximity systems based on RFID technology are discussed. In these kinds of systems, the EPU usually consists of the RFID reader and the corresponding connected antennas, whereas PPUs consist of RFID tags worn by workers.

In the literature, both solutions based on active [23,24] and passive [12,25] RFID systems appear.

Within the solutions based on active RFID technology, a system operating in the 700 MHz band was presented by Marks et al. in [23]. In this case, the alert signal was generated upon tag detection, and a the calibration based on the desired safety distance was, hence, necessary. The goal is to maintain a high distance (even greater than 10 m) between operators and machines. In only in 2 cases out of 432 overall tests, the alert was not triggered, and the minimum range of signal generation was 5 m. The system proposed by Chae et al. [24] instead aimed at exploiting active RFID technology at a frequency of 315 MHz to prevent collisions between people and work machines that can be simultaneously operating in a construction site. Such a system foresees RFID tags worn by operators or placed on machines and RFID readers used where safety hazards for workers existed. The proposed system was tested through the exploitation of 12 readers and 27 tags placed on a site of approximately 1722 m^2. A crawler crane with a clamshell bucket, a medium-sized hydraulic excavator and two compact hydraulic excavators have been used during the tests, demonstrating the system's ability to generate alerts in correct situations, i.e., when the tags were detected by the reader. Finally, the work proposed by Kanan et al. [17] presented a solution in which RFID technology was combined with the ultrasonic one for similar reasons.

On the other hand, several other works based on passive RFID technology have been proposed. One of them was proposed by Teizer et al. [12], it exploits a passive UHF-RFID proximity sensing/alert system within a construction site to provide real-time warning when heavy equipment and workers are too close to each other. PPU is implemented by using an ad hoc RFID tag equipped with an horizontally polarized crossed-dipole to be installed in the worker's helmet. An acoustic alert signal is generated by the tag itself when the electromagnetic power achieved by the device overpasses a given threshold, i.e., $\sim$3 m, set after a proper calibration. In addition, Jo et al. [25] presented an alerting system implemented by using passive RFID technology. Operators are equipped with a helmet with passive RFID tags, while an excavator is equipped with an RFID reader and antenna. The excavator is designed to automatically stop its movement in case of an alert signal generation. The signal is emitted when the reader installed on the vehicle detects the RFID tag. The obtained reading distance was around 5 m for moving operators; thus, it was possible to emit the alert signal when the operator reached 5 m away from the excavator.

2.2. Ble-Based RTLS for Safety

In the present paragraph, some literature solutions aiming at the generation of alert signals in case of dangerous situations revealed by proximity systems based on BLE Beacon technology are discussed. In their work, Lim et al. [13] proposed a BLE-based system capable of operating in both indoor and outdoor environments to monitor the location and movement of multiple workers in real time. Since a conventional BLE system using Received Signal Strength (RSS) typically has a high error, the safety devices are integrated with an accelerometer. This guarantees the receipt of notifications in cases of worker access into previously marked danger zones. The results showed that the combination of an accelerometer and BLE can be used as an effective sensor to detect the movement of moving workers with an average error of 0.32 m.

Instead, Yusheng et al. [26] proposed an alert system composed by a fixed infrastructure with four poles equipped with an antenna, nine Bluetooth sensors and some cameras (only to evaluate the system performance). In addition, at about 100 m, there was a Site Office with its own antenna and that was capable of maintaining a database of occurred events. When the operator enters the unsafe zone, he/she receives a vibration on a wristband. At the same time, the event with information about the identification of the involved operator is notified for the Site Office, together with the time and position at which the alert occurred. The experiments were conducted in a 110 × 70 m^2 test area inside a power plant construction site. The used Bluetooth sensors, provided by Quuppa [27], guaranteed an error of the order of one meter in a range of 150 m.

There are also Bluetooth-based solutions applied to proximity localization, such as the system proposed in [28,29]. Park et al. [28], in fact, presented a proximity detection and alert system that, by exploiting Bluetooth sensing technology, is able to detect hazardous proximity situations between pedestrian workers and construction equipment in roadway work zones at grade. The system was tested in various interaction scenarios between pedestrian workers and construction equipment to demonstrate the reliability of the created Bluetooth infrastructure. It guaranteed a high level of simplicity, minimized infrastructure, ease of calibration, and ease of installation.

In addition, Baek et al. [30] proposed a Bluetooth beacon-based Proximity Warning System (PWS) capable of preventing collisions inside underground tunnels among pieces of equipment as well as among equipment and workers. The proposed system exploits Bluetooth Beacons attached to the mine-worker's body and/or equipment. Such beacons are detected by the smartphones installed on the vehicles and provide drivers with primary (caution) and secondary (warning) alerts when an "obstacle" is going to be reached. Authors demonstrated the effectiveness of the proposed PWS in preventing collisions inside underground tunnels.

Finally, Baek et al. [29] presented a further solution based on wearable personnel PWS with smart-glasses for pedestrian safety in construction and mining sites. In this case, beacons are attached to heavy equipment or vehicles, while smart glasses are used to warn their closeness through a visual alert displayed on glasses themselves. The main objective of the work is to demonstrate that the mental, temporal and physical stresses are minimized when workers use the smart glasses-based PWS. Despite the objective being substantially different, such work inspired the present paper for demonstrating the importance of pedestrian safety for pedestrian safety in construction and mining sites.

2.3. Combination of RFID and BLE

To the best of our knowledge, the literature lacks solutions exploiting a passive UHF-RFID system supported by BLE beacons. Therefore, the present work proposes an architectural solution for tracking and localizing workers, obstacles and machines, which is based on the exploitation of both technologies. The main advantages of such combinations are summarized as follows:

- Passive UHF-RFID tags can achieve up to a 10 m read range by easily avoiding false alarms. They are low cost, e.g., a few cents per tag, easy to install and maintain and, therefore, they represent a very attractive technological solution. In addition, reduced tag sizes allow deploying several tagged PPUs on each worker by enhancing reliability through redundancy. More details about this technology will be given in Section 5.1.1.
- BLE technology is well consolidated on the market, with many commercially available solutions adaptable to any situations. Thanks to a fast data-rate exchange of information, it represents a good candidate as a side solution to the passive UHF-RFID system for guaranteeing system reliability, which is essential in worker safety applications.

3. Operating Scenario

The design and implementation of the solution proposed in this paper were guided by the operating scenario presented in Figure 1, which graphically represents the agricultural working environment in which the proposed system is supposed to operate. The agricultural area is appropriate for piloting remote-controlled farm machinery since obstacles are typically not present or confined at the edges of the area.

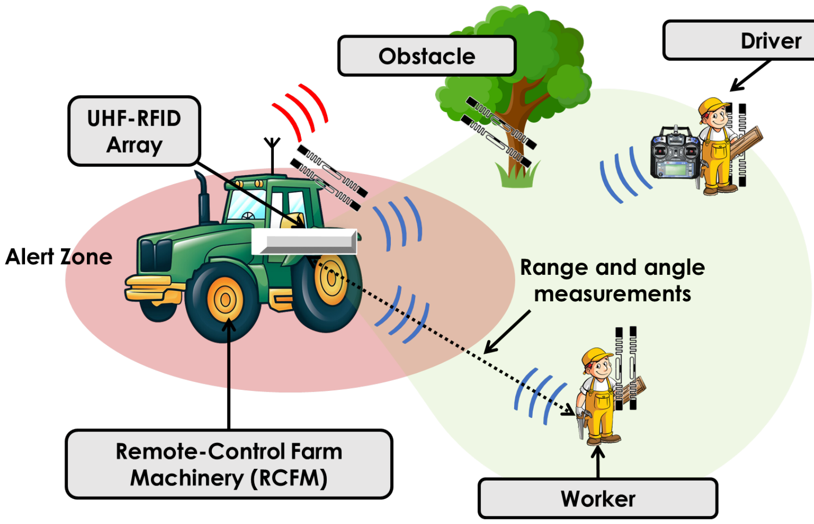


Figure 1. Operating outdoor scenario of the SMARTGRID Project.

RCFM operates in an environment where, in addition to the ground-pilot, which is the employee responsible for movements and actions of the machinery, other different workers could be present. Furthermore, the presence of obstacles, such as trees or pins, should be considered when operating with RCFM.

For this reason, with the aim of facilitating operations and guaranteeing the safety of all the stakeholders involved in the scenario, at the same time, an "Alert Zone" has been defined around the machinery, e.g., the red area in the Figure 1. In such an area, no one can be located while the machinery is working.

To support such a scenario and guarantee safety and security of both workers and machines, different technologies and solutions can be adopted, as demonstrated by the state of the art. However, in our opinion, the most important feature to be exploited by an innovative system capable of supporting it is to track and locate each stakeholder (i.e., workers, machines and obstacles), to calculate the relative distance among them, to warn each user if necessary and to stop machinery on time before accidents, if it is the case.

To this aim, the next sections will present the high-level architecture of the proposed solution to then discuss the possible technologies that can be exploited for tracking users, machines and obstacles and, therefore, guaranteeing safety in the agricultural environment.

4. System Architecture

4.1. Requirements

With the aim of designing a modular architecture suitable for the discussed context, four different stakeholders have been identified as possible users of the system with respect to an RCFM: (a) the Generic Worker, (b) the RCFM Driver, (c) the Security/Safety Manager, also called "Health, Safety & Environment" (HSE) Supervisor and (d) the system Administrator. Each stakeholder must accomplish different duties that are mainly summarized in the following paragraphs.

The first user involved in the system is the Generic Worker, a worker without responsibility with respect to the machinery but who is near the area in which it operates. Hence, he should (a) be tracked by the localization system and (b) receive a notification in cases of dangerous situations that could involve him.

Then, the second user is the RCFM Driver, who is in charge of controlling the machinery with a remote controller. Such a user should (a) be tracked by the localization system, (b) receive a notification in case of possible dangerous situations that the machinery could cause to himself or to another worker in the area, (c) receive a notification if the machinery is reaching an obstacle and, finally, (d) receive notifications about warnings caused by dangerous situations related to other machines.

Another important stakeholder of the system is the HSE Supervisor who is responsible for monitoring safety in the working environment. HSE should (a) access the history of all the warning situations occurring in the working environment and (b) consult statistics about all monitored workers and machines.

The last user is the Administrator who manages the entire system, checks that everything is working properly and provides instructions to new workers. Therefore, he is responsible for (a) managing authorizations and authentications of different users through a dedicated Graphical User Interface (GUI), (b) inserting new devices into the system and associate them to the user workers, e.g., a smartwatch for receiving notifications, (c) registering machines and obstacles present in the working environment, (d) associating each machinery to devices used for tracking and, finally, (e) accessing the same interfaces provided to HSE Supervisors to know the history of all the occurred warning situations and to consult statistics about all the monitored workers and machines.

Finally, it is essential to highlight the most important requirement that is behind all reported needs, namely, the necessity of guaranteeing safety and security of either workers and machines in agricultural working environments. In this work, the latter is addressed through the redundancy guaranteed by BLE technology.

4.2. System Architecture Design

The scenario presented in Section 3 and the requirements reported in the previous paragraph inspired the design of the high-level architecture shown in Figure 2.

As already mentioned, the system has been designed as a modular architecture in which two or more technologies can be used in parallel to guarantee redundancy in assuring safety and security. Specifically, the consolidated BLE technology has been selected as the redundant trusted technology to support UHF-RFID, one which is in its infancy as a safety-enabling technology.

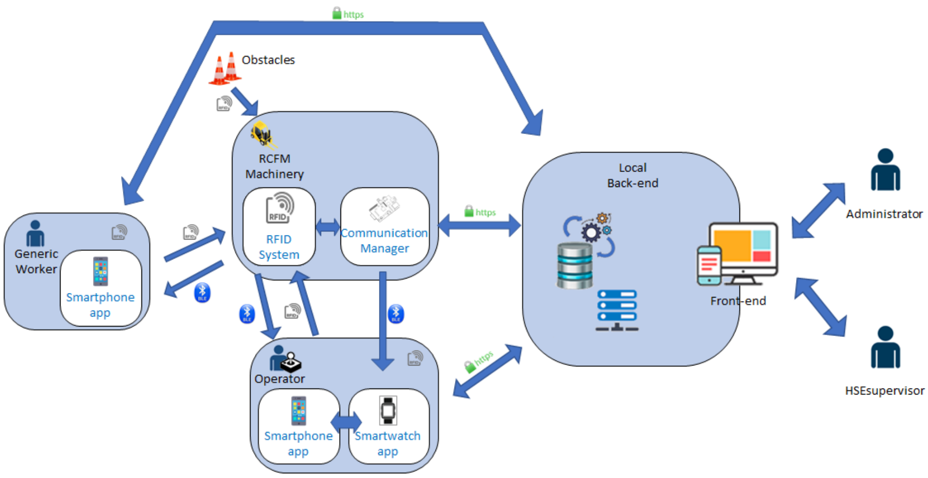


Figure 2. High-level SMARTGRID system architecture.

Therefore, the architecture is organized to serve both systems. On the one hand, the UHF-RFID system revolves around the RCFM that contains the two most important blocks with respect to its functionalities. The RFID System block is responsible for detecting the relative location of the machinery and the workers/obstacles (e.g., pins and barriers) present in the working area in order to, then, inform the Communication Manager in cases of high vicinity. In addition, the Communication Manager is responsible for all communications among the RFID system and the other system components needed to both communicate warnings and alerts to the involved users and also to share the data with the Local Back-end responsible for its storage. After the detection of all RFID tags present on obstacles and worn by workers, the RFID System block calculates the distance among stakeholders from the estimated relative coordinates.

On the other hand, the BLE beacon system does not have a central component such as UHF-RFID and leverages the smartphone device provided to each worker. Specifically, the smartphone detects the distance among the owner and the machinery and communicates with the local backend to both share stored data and notify alerts and warning. In addition to the blocks specifically dedicated to the localization related technologies, the other two main components of the system are the Local Back-end and the Front-end. The Back-end is mainly responsible for exposing Application Programming Interfaces (APIs) needed by the other components to share stored data and to notify warnings/alerts. Moreover, it provides all infrastructure needed to expose Front-end application, e.g., database, authentication and authorization system. The latter is the GUI that Administrators and HSE Supervisors can use to accomplish their duties, such as (a) managing authorizations and authentication of different users of the system, (b) insert new devices into the system and associate them to the workers, e.g., a smartwatch for receiving notifications, (c) register machines and obstacles present in the working environment, (d) access the history of all warning situations occuring in the working environment and (e) consult statistics about all the monitored workers and machines. As shown in the Figure 1, all interactions among system components are secured by an Hypertext Transfer Protocol Secure (HTTPS) connection.

5. Materials and Methods

As already depicted in the Section 4, the architecture of the system is composed of different modules that cooperate to expose various services to the workers. Therefore, the following section reports the description of each component by differentiating the main roles needed to localize users, machines and obstacles. As already stated, in this paper, passive UHF-RFID technology is supported by commercial BLE Beacons as a redundancy technology for safety reasons to localize workers, machines and obstacles. For this reason, the following paragraphs present details on both technologies.

5.1. UHF-RFID Localization

Currently, many types of RFID systems are commercially available. One popular version of the technology involves low-frequency (LF) systems at 125 kHz and high-frequency (HF) systems at 13.56 MHz. Both systems require almost close contact between the reader and tag, as they are based on the principle of inductive coupling, especially LF systems. For this reason, they cannot be employed for localization purpose. HF tags are readable from a few centimeters distance and have been used for indoor localization of robots [31] using the principle of proximity localization. This kind of approach is obviously unfeasible in an outdoor environment and requires high infrastructural cost and maintenance.

UHF systems work at 433 MHz, 860–960 MHz and 2.4 GHz. UHF tags can be detected through the transmission of an electromagnetic signal and guarantee their detection at greater distances. The detection distance depends on the chip's sensitivity, the tag antenna and, above all, on battery presence on the device. In fact, active tags equipped with a battery can reach distances of tenths of meters, but the power source presence is a great drawback in terms of maintenance and costs.

Of greater interest for this work, instead, are passive UHF-RFID tags (860–960 MHz), which communicate through the principle of modulated backscattering [32,33]. In fact, thanks to modern chips and antenna designs, up to 10 m read range can be achieved. Moreover, due to their low cost (a few cents per tag) and ease of installation and maintenance, passive UHF-RFID tags represent a very attractive technological solution for localization and safety systems. In addition to its lost cost, the low sizes of tags allow deploying several PPUs on each worker to create useful redundancy that enhances the worker's safety.

5.1.1. Positioning Algorithms with the UHF-RFID Technology

In addition to tag identification data, i.e., the Electronic Product Code (EPC), commercial UHF-RFID readers almost always provide useful information about the signal's power through the Received Signal Strength Indicator (RSSI) and the phase of the backscattered signal [33], which can be used for localization purposes [34,35]. Although phase-based algorithms show very good performance thanks to the high sensitivity of the phase parameter, their application in outdoor environments has not been deeply explored yet. However, the usage of RSSI might be preferred for safety purposes.

The received power can be expressed as follow [33]:

$$P_{RX} = P_{TX} G_R^2 G_T^2 \chi^2 K \left(\frac{\lambda}{4\pi d}\right)^4 |H|^4 \tag{1}$$

where P_{RX} is the received power at the reader side, G_R and G_T are the reader and tag antenna gains, respectively, χ is the depolarization coefficient which accounts for the polarization mismatch between reader and tag antennas, λ is the electromagnetic signal carrier wavelength, d is the distance between reader and tag antennas and K is the "backscatter gain" parameter, accounting for the amount of incident power that is backscattered into a useful signal by the tag. H represents the complex factor, which describes channel response. For a line-of-sight (LOS) scenario, $H = 1$, the presence of the backscattering gain term K and the effects of an unknown communication channel prevent the reader-tag distance from being directly derived from the received power.

In this paper, to establish the position of workers and obstacles with respect to the RCFM by circumventing the aforementioned issues, we rely on the system described in [7,8]. This system, briefly described below, is able to achieve a complete knowledge about the coordinates of the worker/obstacle with respect to RCFM by measuring the 2D distance, ρ_k, and the Direction of Arrival (DoA), θ_k, to obtain the pair ρ_k, θ_k. The 2D distance ρ_k is intended as the projection on the ground plane of the distance between reader and tag. To perform DoA measurements, we need an antenna array that is able to electronically scan the beam in the surrounding environment. The array may cover 360° or only a part of it so that multiple arrays are needed. Their radiating volumes can be either partially overlapping to create redundancy or not.

In an agricultural environment, it is quite typical that, in the case of an absence of other nearby machines, the electromagnetic propagation channel linking the vehicle side reader antenna and the tag is approximated to a two-ray channel with an LoS path and the ground reflection path. This characteristic allows us to make some assumptions about parameter H. Moreover, the system requires that each worker, obstacle or driver itself must be equipped with at least two RFID tags with the same model and orientation at different heights. By exploiting the tag diversity, backscattering gain term K can be canceled out and the measurement of ρ_k becomes feasible with available RSSI data without any previous offline calibration stage.

The measurement of DoA θ_k, on the other hand, can be performed by a simple beamforming algorithm that allows, through the diversity reception of the array, understanding which antenna beam the tag resides.

The measured polar coordinates ρ_k, θ_k are then used as input parameters for an Unscented Kalman Filter (UKF) [36] designed to continuously track the relative Cartesian position and velocity of the worker/obstacle with respect to the vehicle over time $\hat{s}_k = [\hat{x}_k, \hat{v}_{x_k}, \hat{y}_k, \hat{v}_{y_k}]^T$ [8]. The advantage of a tracking system over a simple positioning system in which the position is estimated at each step, without any kind of memory of previous states, lies first and foremost in better accuracy, but more importantly in the ability to assess whether the track is lost. In the case where the worker is in unsafe locations, or if the driver is not visible, the alarm procedure is started.

Several criteria have been investigated in order to find the best configuration of geometrical parameters of the system [7]. In particular, in order to maximize tracking performance, placing the two tags as far apart as possible is required. This also brings advantages because it reduces the electromagnetic coupling between the two tags.

The experimental analysis, which will be presented in detail, involves an RFID array: the Impinj xArray device [37]. xArray is not equipped with multiple RF frontends and only allows for sequential electronic beam scanning. It is, therefore, not possible to apply common beamforming techniques by using it. However, it is possible to measure the DoA, θ_k, of the tag by analyzing the RSSI response of each beam. Most likely, the beam that collects data with the highest RSSI value will identify the direction in which the tag is located.

5.2. Ble Localization

Bluetooth is a widely used short-range wireless standard that uses UHF radio waves for exchanging data between devices over short distances. It operates at 2.4 GHz and has evolved over the years to accomplish new trends and needs. Its more recent versions, such as the BLE, have been introduced to allow low-powered device to consume as little power as possible for communications. One of the most appreciated usages of BLE technology is related the possibility of using it as a device-positioning technology. Thanks to the exploitation of some anchors called "beacons" distributed at known hot positions, the standard allows the detection of the current position of a device supporting the technology. For instance, by using four beacons, it is possible to cover a reading range pf up to 100 m. From the signal power measurement received from three or four beacons, the mobile node typically manages such signals for self-location with an accuracy on the order of a meter [13,26]. Furthermore, due to its diffusion for such purposes, in the new BLE 5.1 version, some localization-related features have been introduced. Thanks to the use of "special" beacons containing arrays of antennas, indeed, it is now capable of measuring the Angle of Arrival (AoA) and the Angle of Departure (AoD) with good accuracy [38]. In addition, the new version also improves performance and enables the applicability of technology for signaling systems. Nonetheless, to the best of our knowledge, the new version is not yet completely supported by commercial solutions and only a few devices support it, e.g., the device launched in the market before the release of the new Bluetooth 5.1 standard implemented by Quuppa [27].

5.2.1. Positioning Algorithms with the Beacon BLE Technology

As stated, although the new version of BLE 5.1 has introduced new features that are more similar to the ones used with UHF-RFID technology, e.g., AoA and AoD, by considering that Beacon BLE technology has been selected as a redundant support for the UHF-RFID one, in the present paper, BLE 4.2 version is used as the more reliable one than the new 5.1 one for guaranteeing worker safety and security.

As already discussed in one of our previous works [39] and as shown in Figure 3, BLE Beacon technology usually leverages on two main components: the BLE Beacons and one or more monitoring devices, typically, smartphones or smartwatches. Therefore, normally, some beacons are installed in strategic well-mapped points of the monitored area. They are cost-effective small radio transmitters available in different sizes and shapes and continuously send signals to be revealed within a few meters.

Specifically, at setup phase, every association between a beacon, i.e., its MAC address and its location, i.e., the coordinates, is stored in a database. The latter can be saved on the monitoring device itself or on a server that supports the monitoring device in both storing and calculating the inferred information needed to establish its position. Therefore, when the system is activated, the monitoring device periodically scans for all beacon signals available in the area and filters them by only considering the beacons stored in the database. Finally, by knowing the exact position of the beacons, the transmission power used by each one and obviously the RSSI itself, it is possible to calculate the corresponding position of the monitoring device. In the present work, the selected monitoring devices are smartphones owned by workers running a specially designed and implemented application.

Although the details of the exact formulas used to calculate the distance are out of the scope of this paper, the summarizing formula used to calculate the distance among the monitoring device and each beacon is reported in the following formula:

$$Distance = 10^{(calibratedRSSI - RSSI)/(10 \, * \, pathLossParameter)} \tag{2}$$

where the $calibratedRSSI$ parameter is the RSSI of the Beacon measured at 1 m distance, $RSSI$ is instead the currently measured RSSI and $pathLossParameter$ is the path-loss adjustment parameter. More details about such parameters and how it is calculated can be found in our previous works [39].

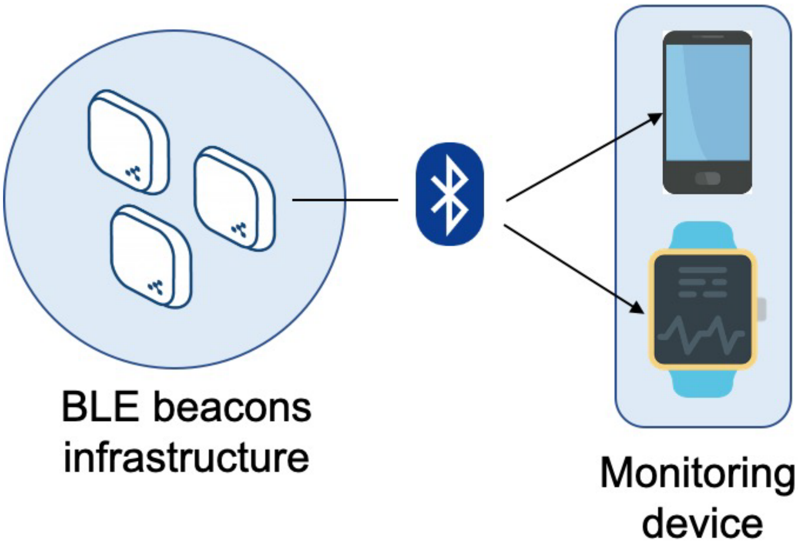


Figure 3. Main components of a BLE system.

5.3. Local Back-End

As depicted in the previous Sections, the Back-end is the central system of the entire architecture that exposes two main subsystems: the REpresentational State Transfer (REST) APIs to accept input requests from all the other components involved in the architecture and the Front-end application, a web-based dashboard to support HSE managers and the system administrator in their duties.

5.3.1. Rest Apis

The Back-end software is developed by using the Spring-Boot framework [40] and, thus, by using Java Programming Language. It exposes the APIs presented in Table 2.

Table 2. APIs exposed by the Back-end.

Action	Method	Path	Input Parameters
Notify a dangerous situation	POST	http://::/smartgrid/api/v1/machine/:id/alert	id: unique identifier of the machinery
Obtain the list of registered UHF-RFID tags with the corresponding associated information	GET	http://::/smartgrid/api/v1/machine/:id/info	id: unique identifier of the machinery
Update the status of a machinery	PUT	http://::/smartgrid/api/v1/machine/:id/up	id: unique identifier of the machinery
Obtain the list of registered beacons with their associated information	GET	http://::/smartgrid/api/v1/beacon/info	-
Send a notification related to a user	POST	http://::/smartgrid/api/v1/user/:id/alert	id: unique identifier of the user that generated the notification

Through such APIs, each component of the system can interact with the Back-end to send notifications about dangerous situations, i.e., notifications sent by the UHF-RFID system or by the smartphone that acts as a monitoring device in Figure 3, but it can also obtain the list of registered UHF-RFID tags with the corresponding associated information, update the status of a machinery and finally, obtain the list of registered beacons with their association information.

Within the present work, the fast-prototyping Raspberry Pi 4 [41] board has been selected to implement the Local Back-end.

5.3.2. Front-End

In addition to REST APIs, the Local Back-end exposes also a web-based dashboard to support the HSE manager and the system administrator in their duties.

The following list summarizes the requirements of such a web-based application. Each line is preceded by the letter: (A) when the requirement is related to the Administrators, (R) when the requirement is related to the HSE Supervisor and (AR) when the requirement is related to both the Administrator and the HSE Supervisor.

(R1) (AR) Access the login page;
(R2) (AR) Perform predefined queries on the data stored in the database and view the results in the dashboard, e.g., "in the last six months what are the dangerous situations to which the operators have been exposed";
(R3) (AR) Access historical data related to generated notifications;
(R4) (AR) View and modify worker own personal data;
(R5) (A) Insert, modify or delete workers from the system;
(R6) (A) Insert, modify or delete HSE Supervisors from the system;
(R7) (A) Insert, modify or delete Administrators from the system;
(R8) (A) Register the devices associated to each worker;
(R9) (A) Register, modify or delete the machines present in the monitored area;
(R10) (A) Register, modify or delete each single obstacle, e.g., pin;
(R11) (A) Associate an RFID tag to each machinery, obstacle or worker;
(R12) (A) Associate a Beacon to each machinery;
(R13) (A) Define safety zone sizes.

Within the present work, the dashboard was implemented by exploiting features exposed by the Spring-Boot framework [40] and, therefore, by using the Java Programming Language, the JavaScript Angular 9 framework [42], Ionic [43] and finally the MySQL database [44].

6. Experiments and Results

Different experiments have been conducted with the aim of demonstrating the reliability of the main system components. In particular, a first Proof-of-Concept (PoC) demonstration of the UHF-RFID tracking module is here presented to show the feasibility and usefulness of the proposed architecture in the presented context.

Therefore, the first two paragraphs present the specific experiments conducted on the UHF-RFID tracking system, while the final paragraph presents the functional validation of the overall architecture.

6.1. Optimal Tag Placement

As already stated, the targets of the localization procedure are part of a heterogeneous set that includes the following, among others: static obstacles, e.g., holes in the ground, trees, etc., other machines and, obviously, workers. The performed analysis procedure had the goal to identify the better configuration of cost-effective label-type tags focusing on the most challenging of those targets, which are the workers. The difficulties related with that type of target depend on different factors such as the closeness of tags with the human body, with a consequent drop of the RFID tag performance and the difficulty to select proper location of the tags to ensure the needed redundancy and the mandatory comfort of the workers during motion at the same time.

To fulfill these needs, in the first step, a measurement analysis of a large set of different UHF-RFID tags was carried out by using the lab-made characterization system, for which its realization and test are described in [14]. After this preliminary analysis, some tags ensuring better on-air performance were selected for further analysis on the human body. Among the others, two well-performing tags were LabID UH107, mounting IC NXP UCode8, and the Tageos EOS500, mounting IC Impinj Monza R6.

Once the preliminary analysis has been completed, the problem of the correct location of the tags on the workers was faced up by choosing to place them onto worker PPEs. The PPEs that better satisfy the need of space and stability to host the tags were the helmet and the jacket. For this reason, different configurations of four tags for each PPEs were analyzed and tested by measuring the RSSI of each tag when PPE was equipped and for eight different angles of the source positioning at a fixed distance of 2.6 m. The most promising configurations resulted to be the ones with all four tags set up vertically, such as those shown in Figure 4 and summarized in Figure 5, where the RSSI measurements are shown. Without a loss of generality, the measurements were performed by using the EOS500 tag.

It is noteworthy how the readings of the helmet tag are more stable due to the higher stiffness of PPEs. Moreover, jacket readings can suffer from the presence of arms obscuring the LoS between the reader antenna and tag. Nevertheless, the jacket would be the preferred PPE for where to locate the tags because it is mandatory for workers, which is different from helmets. For this reason, the possibility to use a linearly polarized reader antenna, instead of a circularly polarized one, to improve overall performance was considered. Some results are shown in Figure 6 where, without a loss of generality, a set of measured RSSI for only one of the four tags on the jacket is shown as an example of the achievable improvements.

Other approaches to further improve the performance of the tags onto the jacket, involving the use of electromagnetically transparent substrates to enlarge their distance from the human body whilst stiffening them at the same time, will be explored in future activities.

Figure 4. UHF-RFID tags vertically installed on a helmet and numerical model of tags installed on a jacket.

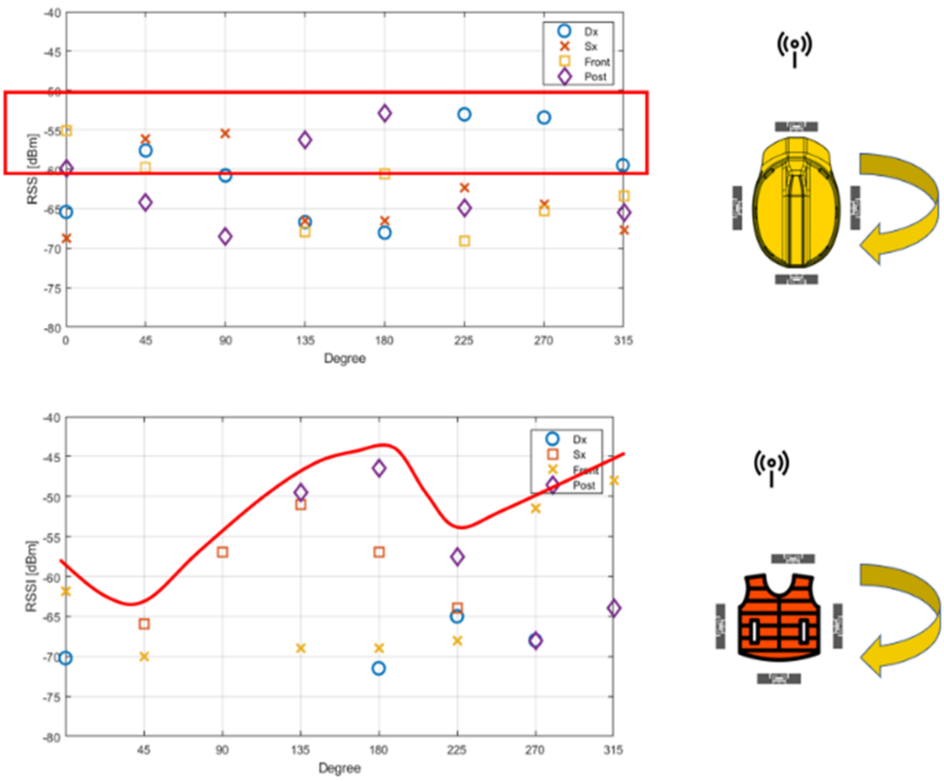


Figure 5. Measured RSSI for both tag configurations, when varying the source angle.

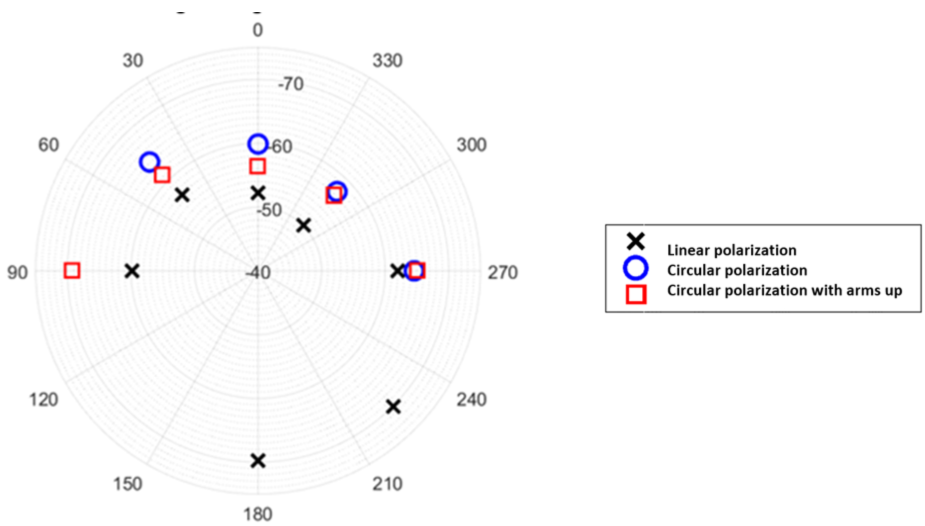


Figure 6. Comparison of measured RSSI values for the tag set in frontal position onto the jacket and read by varying the source angle.

6.2. Validation of the Tracking System

With the objective of determining the relative location of the worker with respect to RCFM, a configuration with a static array and a moving tagged-equipped person was set for the experiments of a first measurement campaign. A UHF-RFID commercial system formed by an RFID reader and the antenna array Impinj xArray, [37] was brought in the courtyard of the Department of Information Engineering at University of Pisa, Italy. The geometrical barycenter of the antenna was installed at the coordinates $[x, y, z]^T = [0, 0, 1.5]$ m. The radiated power was set to $P_{TX} = 28$ dBm and the operating frequency was set at $f = 865.7$ MHz. xArray was placed on a pole and kept static during the tests as shown in Figure 7. A human operator wore a reflective jacket equipped with four LAB-ID UH107

RFID tags placed vertically at $h_2 = 1.37$ m and $h_1 = 1.07$ m, respectively, heights optimized for the xArray radiation pattern. The data collected from the two pairs of tags serve to collect more data at the same time.

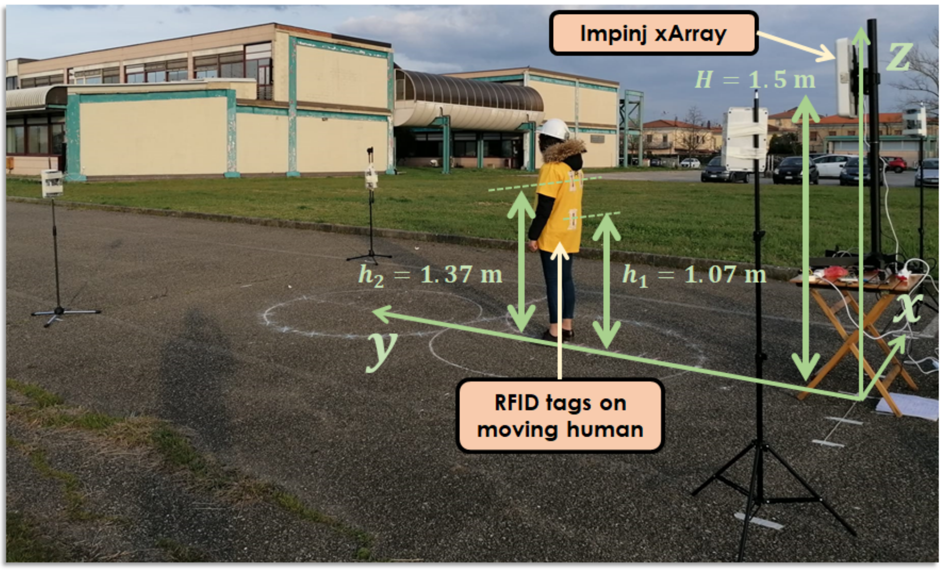


Figure 7. Measurement setup for the validation of the tracking system.

xArray is capable of generating 52 beams in dual polarization divided into nine angular sectors. For each beam, the reader dedicates one time slot to vertical polarization transmission and one slot to horizontal polarization transmission in order to maximize the probability of detecting all tags in the field of view. In addition, it has incorporated an RFID reader inside, the Impinj Speedway Revolution R420 [45]. For our purposes, the device was configured to only scan on the horizontal plane with vertical polarization. With this configuration, it is possible to cover an angular sector of 120°, (±60°) with respect to the frontal direction; thus, multiple xArrays will be required on RCFM to cover all directions, namely 360°. The spacing among beams is 10°. However, the directivity of each beam is not very high, also because of the object sizes, i.e., 45.7 cm × 45.7 cm × 6.35 cm, which are comparable with those of the wavelength, i.e., 34 cm. Therefore, each tag is detected by several beams. By using the algorithm briefly described in Section 5.2.1, it is possible to determine the DoA.

The worker performed two types of trajectories with different shapes with respect to xArray: (i) a rectilinear 5 m long path and (ii) a smooth "L-shaped" trajectory with a total path-length of 3.46 m, with starting point in $[x, y]^T = [0, 0.5]^T$ m and ending point in $[x, y]^T = [2, 3]^T$m. In both cases, the worker's speed never exceeded 0.3 m/s. The ground truth paths were acquired by using a video-camera. The results of the UKF tracking algorithm for two sample trajectories are reported in Figure 8. It is apparent that after an initial transient behaviour, the tracking algorithm converges on the right path. Moreover, the error slightly increases when the worker approaches locations very lateral to the frontal direction of the array. For the two aforementioned sample trajectories, the DoA estimation errors are reported in Figure 9.

The global performance of the system may be validated by analyzing the error histograms. In particular, the performances of six rectilinear trajectories and six L-shaped trajectories were gathered to reach a total of 726 points for rectilinear trajectories and 668 points for L-shaped trajectories, respectively. Figure 10 shows the histogram of the measured DoA error. DoA is better estimated for the rectilinear trajectories than L-shaped trajectories, and the higher values are associated to lateral positions of the worker with respect to the xArray. This effect is mainly due to the weakness of the received signal which affects the reliability of the angle measurements for very lateral directions. However, for both cases, the error is bounded to ±10°. It is worth mentioning that, in the final prototype, multiple xArrays will be installed on the RCFM to cover 360°. Consequently, this can also help to mitigate the above-mentioned issue by exploiting redundancy during the handover between two different coverage areas. Figure 11 shows the histogram of the 2D localization error, defined as $\epsilon_{d_k} = \sqrt{(x_k - \hat{x}_k)^2 + (y_k - \hat{y}_k)^2}$.

On average, the L-shaped trajectories are better processed by UKF, but some outliers appear due to the error increasing phenomena when the tag is far from the frontal direction of the xArray. However, the localization error never exceeds half a meter all along the trajectories.

The mean localization errors along the x-coordinate ($\bar{\epsilon}_x$), y-coordinate ($\bar{\epsilon}_y$) and combined 2D distance error ($\bar{\epsilon}_d$) all over the entire dataset are resumed in Table 3. We can conclude that the tag tracking is performed with a localization error in the order of a few tens of centimeters and it is therefore feasible for the safety system. Although such experiments have been carried out in a controlled environment, the obtained success demonstrates the feasibility of the proposed solution to track the worker's position with respect to machinery. The implementation of the UHF-RFID localization system on a tractor is under development to asses the system's functionality in real agricultural scenarios.

Table 3. Global Performance of the UHF-RFID tracking system in terms of mean localization error on the x-coordinate ($\bar{\epsilon}_x$), y-coordinate ($\bar{\epsilon}_y$) and 2D distance error ($\bar{\epsilon}_d$).

Trajectory	$\bar{\epsilon}_x$ (cm)	$\bar{\epsilon}_y$ (cm)	$\bar{\epsilon}_d$ (cm)
Rectilinear	1	−7	14
L-shaped	−1	2	10

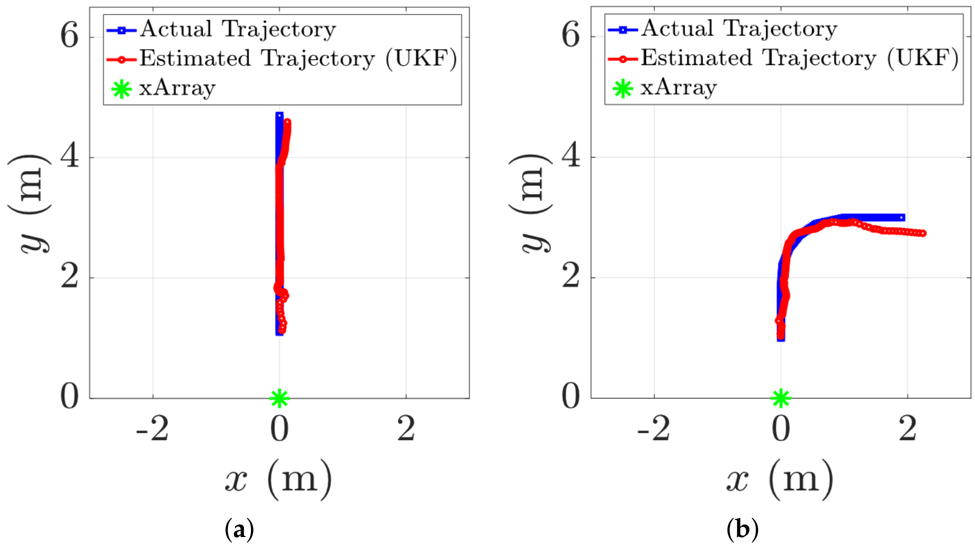
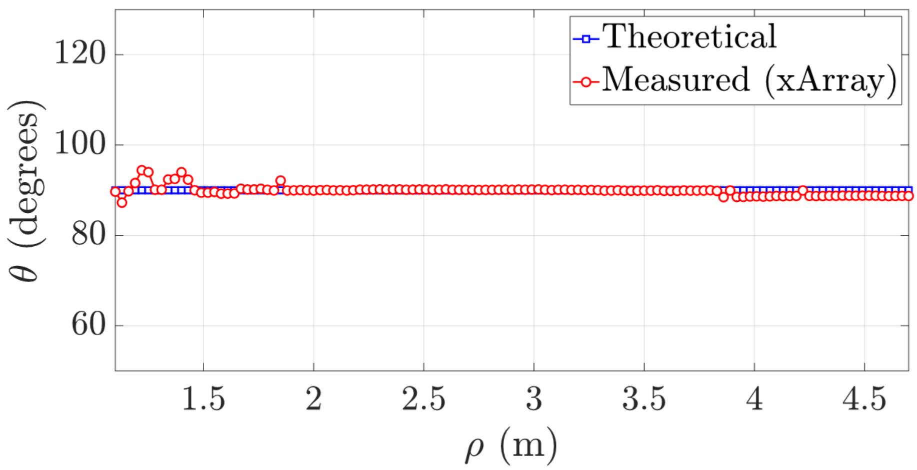
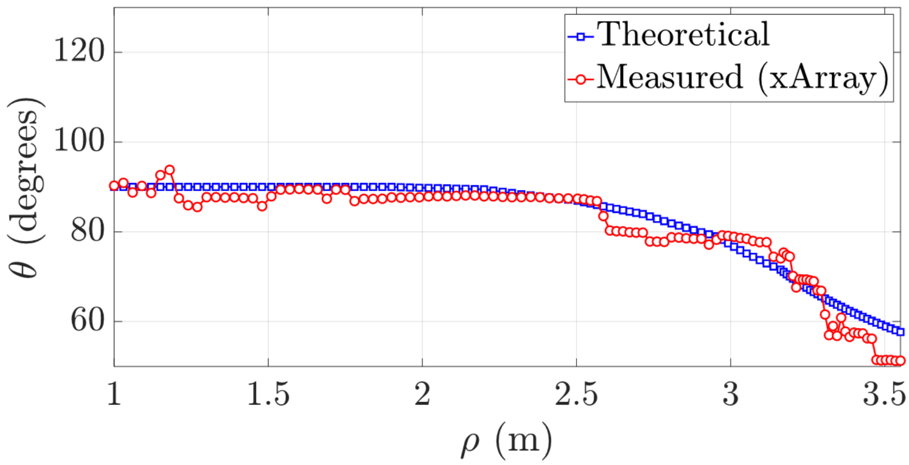


Figure 8. Actual (blue squared markers) and estimated (red circular markers) trajectories when the tagged person moves according to the following: (**a**) a sample of a straight path and (**b**) a sample of an L-shaped trajectory. xArray is represented with a green star marker.



(**a**)



(**b**)

Figure 9. Actual (blue squared markers) and estimated (red circular markers) Direction of Arrivals when the tagged person moves according to the following: (**a**) a sample of a straight path and (**b**) a sample of an L-shaped trajectory.

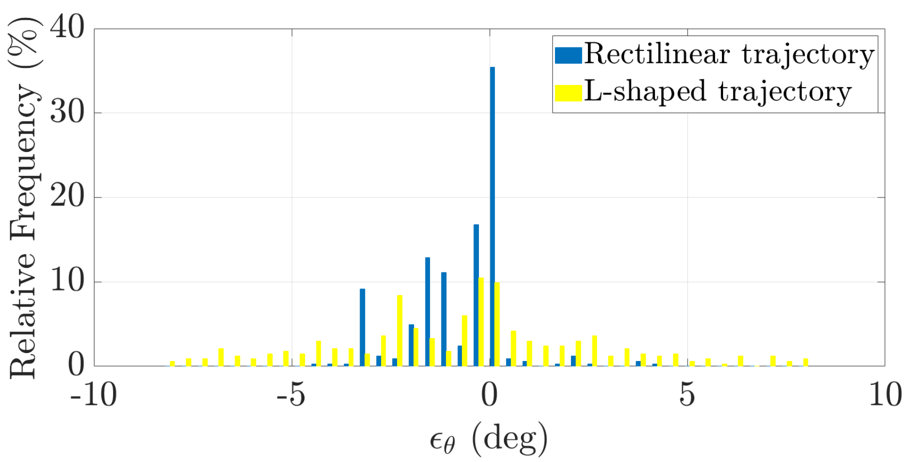


Figure 10. Histograms of the measured DoA error. Blue bars refer to rectilinear trajectories (726 sample points), whereas yellow bars refer to L-shaped trajectories (668 sample points).

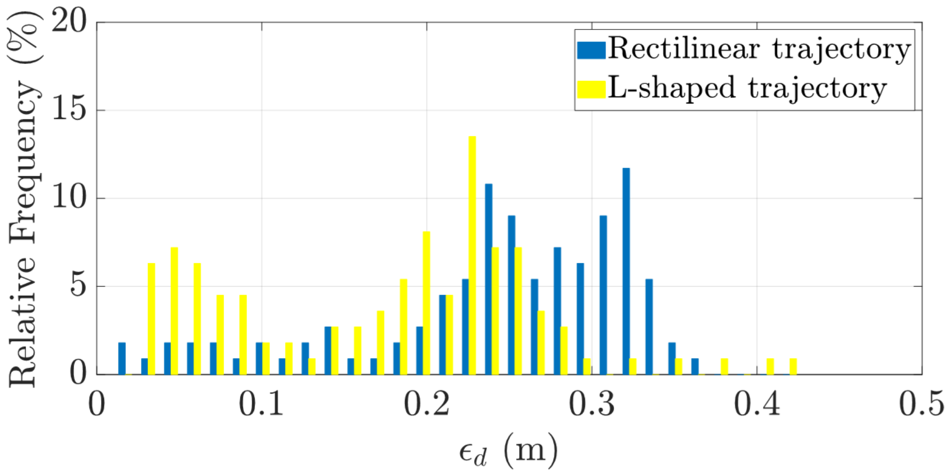


Figure 11. Histograms of the 2D localization error. Blue bars refer to rectilinear trajectories (726 sample points), whereas yellow bars to L-shaped trajectories (668 sample points).

6.3. Functional Validation of the Architecture

To validate the overall developed system, a functional validation has been performed with the aim of demonstrating the feasibility of the system and the satisfaction of all identified requirements reported in the previous sections as the functionalities to be provided to each user. The performed validation consisted in monitoring the system while the behavior of each identified stakeholder of the system was emulated. Therefore, considering that the Front-end application is actually the main interface for every user of the system, it was used as the main valuable outcome of the system and considered for such a validation to demonstrate the fulfillment of all requirements. Figures 12–14 report the screenshots of the most important components of the web-based Front-end application used for the evaluation. Considering that the HSE Supervisor can access the same tabs of the Administrator, apart from some specific dedicated functionalities, as reported in the dedicated section of this paper, only Administrator tabs are shown. Obviously, the ones that are also accessible by the HSE Supervisor have exactly the same content and graphic organization. Specifically, Figure 12 shows the tab dedicated to the login. It allows authenticating and authorizing each user who can also differentiate the available functionalities. This satisfies requirement R1 allowing both Administrators and HSE Supervisor to access the application.

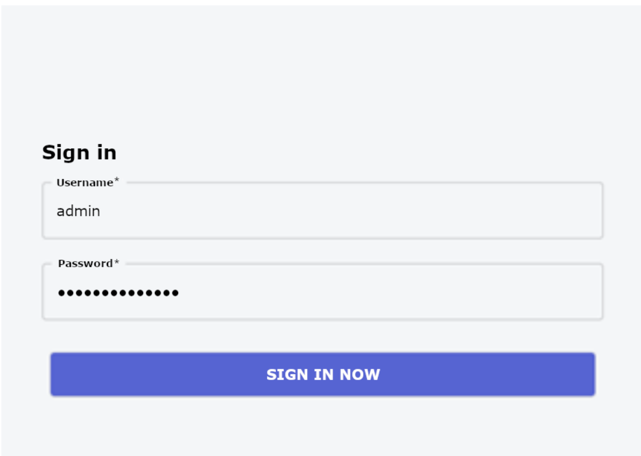


Figure 12. Login tab of the Front-end application.

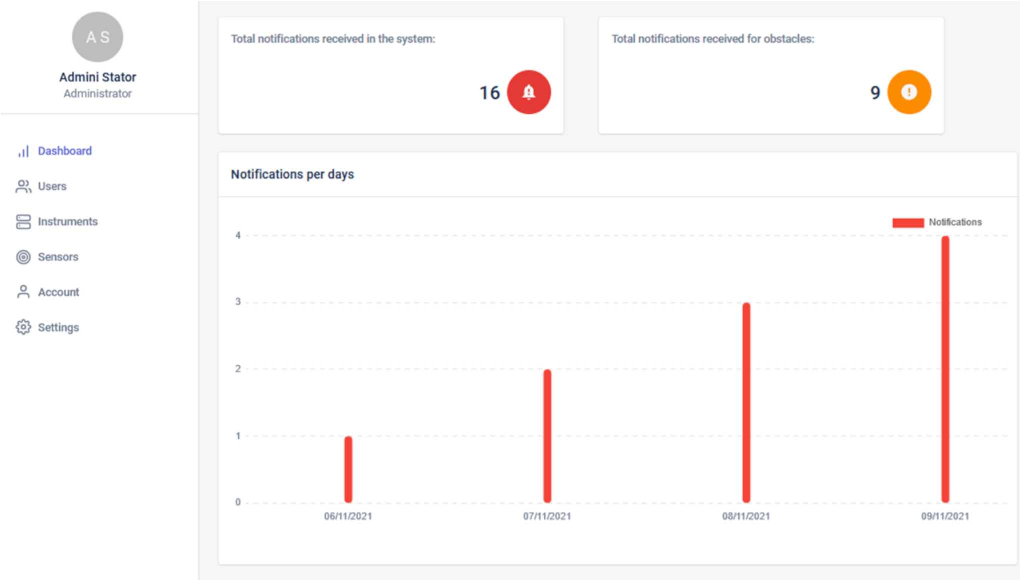


Figure 13. Statistical information shown in the Front-end application.

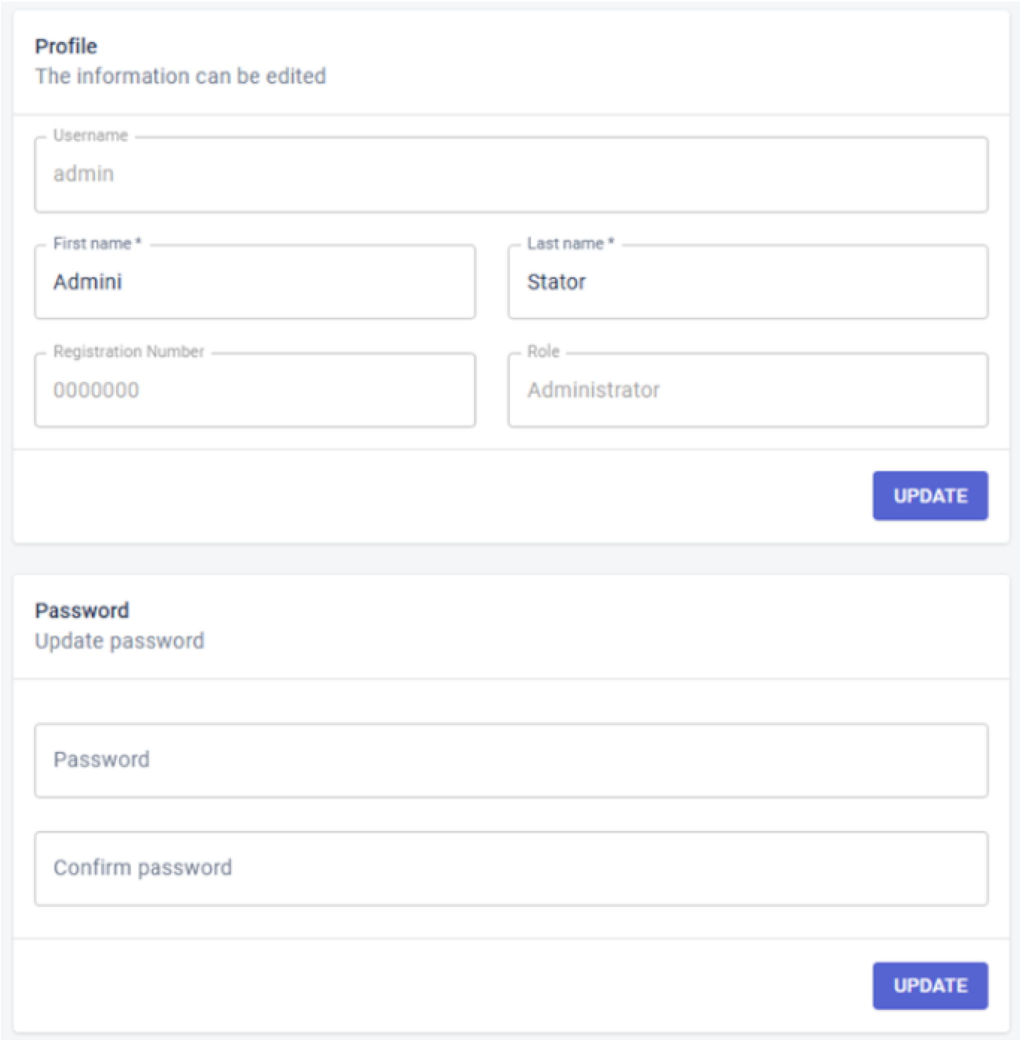


Figure 14. Personal-information tab of the Front-end application.

Then, Figure 13 reports the tab responsible for showing the statistical information about each generated alarm. It allows the filtration of data with respect to the user, the devices and the machines, thus satisfying requirements R2 and R3.

Figure 14 shows the tab that allows each user to visualize their own personal information and they can modify them. It was used to test all functionalities related to requirement R4.

Figure 15 reports the tab showing all users of the system with details related to their role (Administrator, HSE Supervisor, etc.). In this section, the functionalities related to requirements R5, R6 and R7 were tested. Considering that the HSE Supervisor can observe a reduced list of users, i.e., the administrators have not been shown, the tab was tested with both the user types to be sure that every user is able to access and use the functionalities dedicated to him.

Figure 16, instead, shows the tab in which the user can visualize, modify and delete machines and obstacles. In addition, in this tab, it is possible to assign a user, e.g., the RCFM Driver, for instance, for the movements of the machinery to each "instrument" to control. This tab allowed testing the satisfaction of requirements R8, R9 and R10.

In addition, Figure 17 shows the tab in which all sensors, namely UHF-RFID tags and Beacons, are listed. In this part of the application, the administrator can insert new sensors, assign a sensor to an instrument, e.g., machinery, and modify existing sensors and settings. It satisfied requirements R11 and R12.

Finally, Figure 18 shows the tab dedicated to all settings of the entire system. In such a tab, it is possible to set the dimension of the safety areas within which an alarm is generated when a worker, obstacle or other machinery are detected. It satisfies the last requirement, R13.

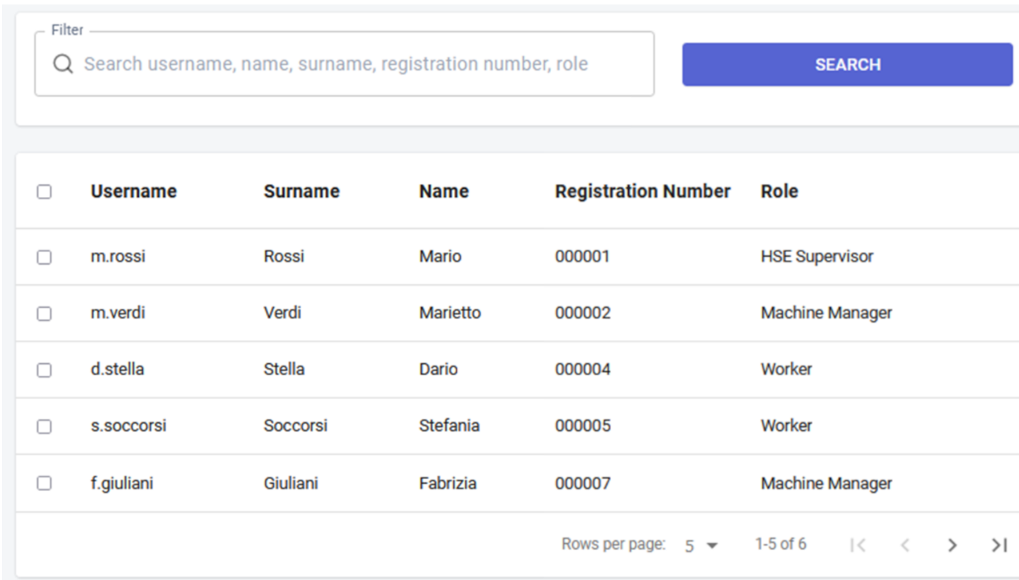


Figure 15. User tab of the Front-end application.

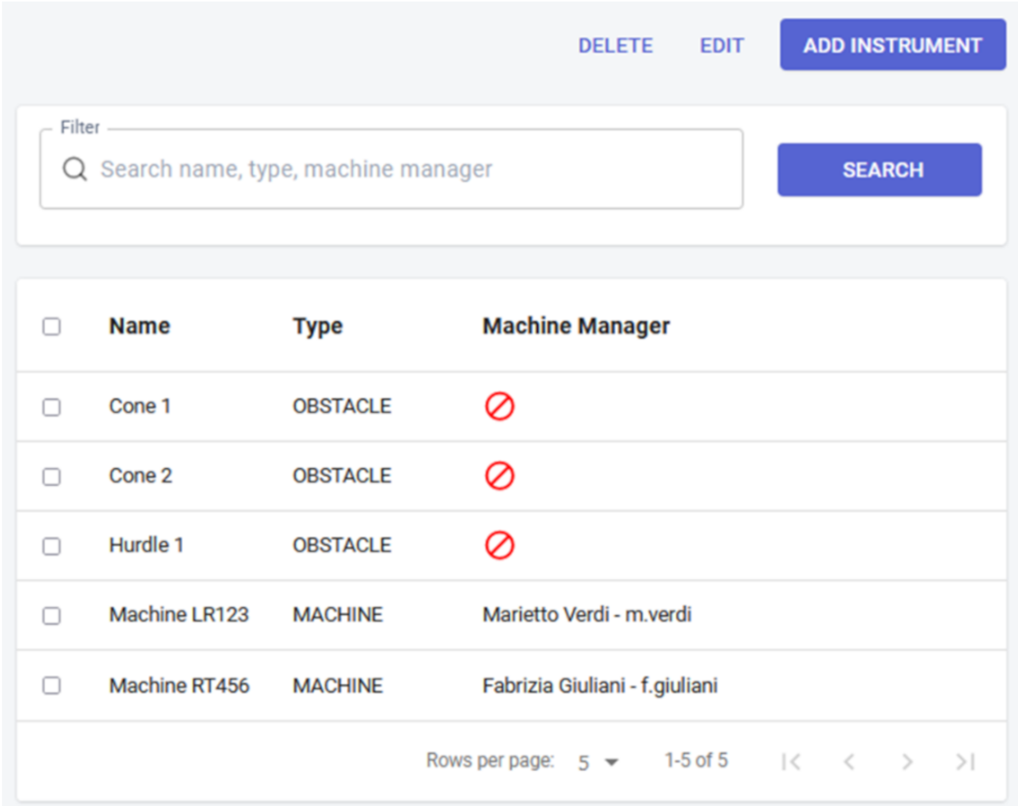


Figure 16. Instrument tab of the Front-end application.

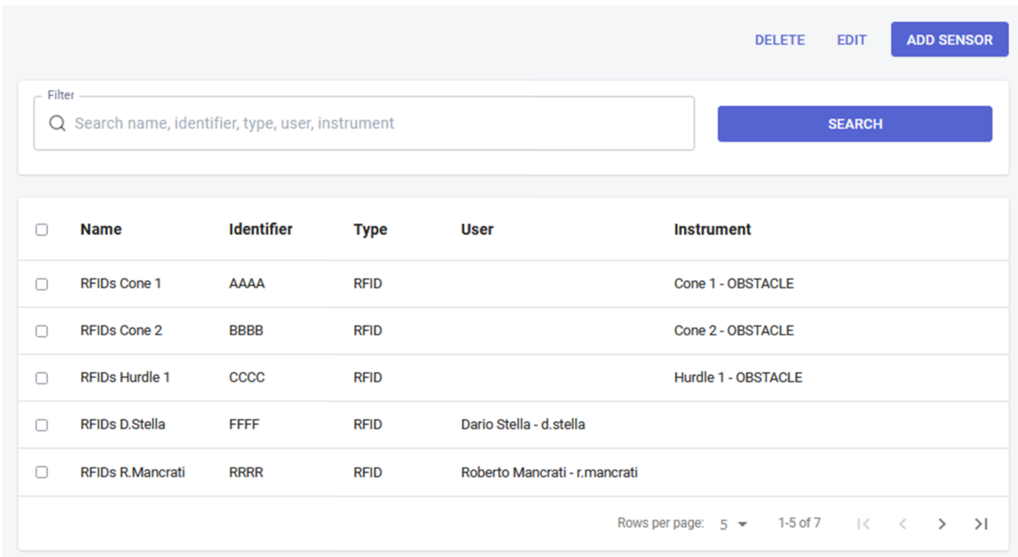


Figure 17. Sensors tab of the Front-end application.

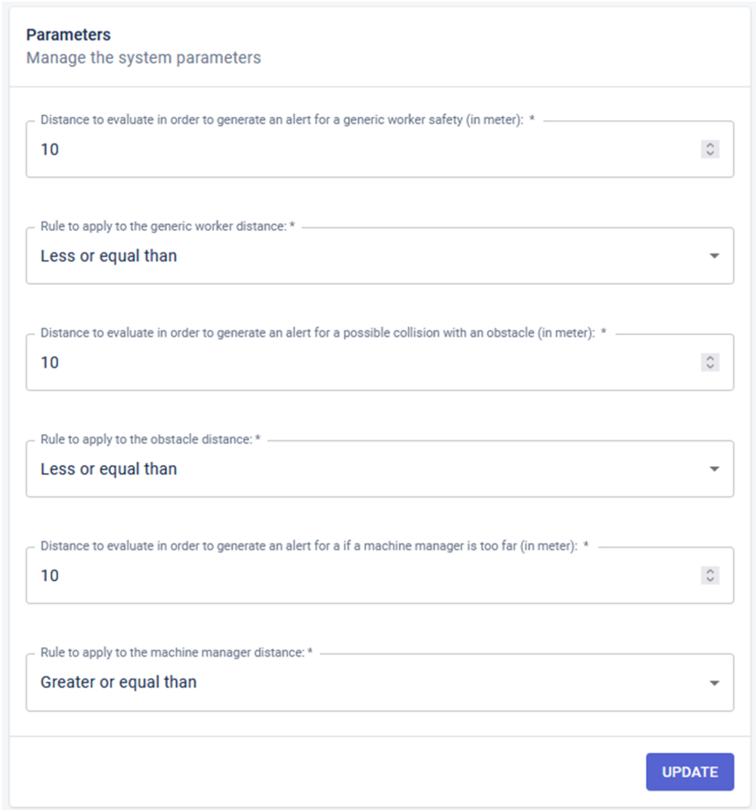


Figure 18. Settings tab of the Front-end application.

7. Conclusions

One of the most challenging requirements to be satisfied in work environments is worker safety.

One of the sectors interested by such needs is the agricultural work, where heavy vehicles, such as tractors, have been recently upgraded to be remotely controlled in order to avoid accidents such as roll-overs, which can be fatal to workers.

Therefore, with the aim of guaranteeing the safety of agricultural workers, an innovative system has been proposed in the present paper. The system has been designed in the framework of the SMARTGRID Project and developed in collaboration with the INAIL Italian Institute to exploit passive UHF-RFID techonology in addition to the BLE one for monitoring and preventing possible accidents that may occur when ground-worker RCFMs collaborate in outdoor agricultural working areas.

The proposed system leverages the possibility offered by modern technologies to localize and track workers, obstacles and machines in an area of interest to secure their movements and actions. The localization performed through a passive UHF-RFID system is supported by commercial BLE Beacons to create a redundancy for security/safety reasons and, therefore, guaranteeing the worker safety.

The paper proposed a modular architecture to incorporate such technologies in a smart environment able to expose useful services for the different kind of workers that could be involved in agricultural working environments. Different experiments were conducted and demonstrated the reliability of all main system components and, in addition, the feasibility and usefulness of the proposed architecture in the presented context.

The proposed architecture can inspire future works in the field aimed at, for instance, the integration of further technologies for the localization of all involved stakeholders. In addition, thanks to modular architecture, other tests could be conducted in parallel to compare different techniques and methodologies for guaranteeing safety in agricultural working areas.

Finally, authors will evaluate the possibility of conducting more experiments with the new 5.1 Bluetooth version to further enhance both the system itself and to improve safety in working environments.

Author Contributions: All authors equally contributed to the research design and realization of this study. All authors, in fact, formulated the idea and identified research requirements and objectives. T.M., I.S. and L.P. designed the software architecture and the components and conceived the system's functional validation. A.M., A.B. and P.N. designed and characterized the RFID-based tracking system and the related experimental analysis. L.C., F.P.C. and R.C. designed, implemented and tested the UHF-RFID system by carrying out the related reported experiments. In addition, P.N., L.P., L.C. and M.P. collaborated by also leading the activities and contributing to the design, the implementation and the execution of all experiments and validation phases. Finally, all authors prepared the manuscript, critically edited it and approved the final draft. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Landi, L.; Buffi, A.; Stecconi, A.; Marracci, M.; Di Leone, P.; Bernardini, F.; Di Donato, L. Localization systems for Safety Applications in Industrial Scenarios. In Proceedings of the 2021 31th European Safety and Reliability Conference (ESLER), Angers, France, 19–23 September 2021.
2. Pirozzi, M.; Donato, L.D.; Tomassini, L.; Ferraro, A. Possible innovative technical measures for risk prevention during the use of mobile machines with remote guide/control. *Procedia Manuf.* **2020**, *42*, 457–461. [CrossRef]
3. Arboleya, A.; Laviada, J.; Álvarez López, Y.; Las-Heras, F. Real-Time Tracking System Based on RFID to Prevent Worker–Vehicle Accidents. *IEEE Antennas Wirel. Propag. Lett.* **2021**, *20*, 1794–1798. [CrossRef]
4. Soltanmohammadlou, N.; Sadeghi, S.; Hon, C.K.; Mokhtarpour-Khanghah, F. Real-time locating systems and safety in construction sites: A literature review. *Saf. Sci.* **2019**, *117*, 229–242. [CrossRef]
5. Stefana, E.; Ustolin, F.; Paltrinieri, N. IMPROSafety: A risk-based framework to integrate occupational and process safety. *J. Loss Prev. Process Ind.* **2022**, *75*, 104698. [CrossRef]
6. Bitar, F.K.; Chadwick-Jones, D.; Lawrie, M.; Nazaruk, M.; Boodhai, C. Empirical validation of operating discipline as a leading indicator of safety outputs and plant performance. *Saf. Sci.* **2018**, *104*, 144–156. [CrossRef]
7. Motroni, A.; Rosati, F.; Nepa, P.; Buffi, A.; Pirozzi, M.; Di Donato, L.; Tomassini, L.; Ferraro, A. An RFID-based Ranging System for Worker Safety in Agricultural Working Areas. In Proceedings of the 2021 6th International Conference on Smart and Sustainable Technologies (SpliTech), Bol and Split, Croatia, 8–11 September 2021; pp. 1–6. [CrossRef]
8. Motroni, A.; Rosati, F.; Nepa, P.; Buffi, A.; Pirozzi, M.; Di Donato, L.; Tomassini, L.; Ferraro, A. An RFID Tracking System for Agricultural Safety. In Proceedings of the 2021 IEEE International Conference on RFID Technology and Applications (RFID-TA), Delhi, India, 6–8 October 2021; pp. 28–31. [CrossRef]
9. Wang, J.; Razavi, S.N. Low False Alarm Rate Model for Unsafe-Proximity Detection in Construction. *J. Comput. Civ. Eng.* **2016**, *30*, 04015005. [CrossRef]
10. Naticchia, B.; Vaccarini, M.; Carbonari, A. A monitoring system for real-time interference control on large construction sites. *Autom. Constr.* **2013**, *29*, 148–160. [CrossRef]
11. Li, H.; Chan, G.; Huang, T.; Skitmore, M.; Tao, T.Y.; Luo, E.; Chung, J.; Chan, X.; Li, Y. Chirp-spread-spectrum-based real time location system for construction safety management: A case study. *Autom. Constr.* **2015**, *55*, 58–65. [CrossRef]
12. Teizer, J.; Cheng, T. Proximity hazard indicator for workers-on-foot near miss interactions with construction equipment and geo-referenced hazard areas. *Autom. Constr.* **2015**, *60*, 58–73. [CrossRef]
13. Lim, J.S.; Song, K.I.; Lee, H.L. Real-Time Location Tracking of Multiple Construction Laborers. *Sensors* **2016**, *16*. [CrossRef]
14. Edrei, T.; Isaac, S. Construction site safety control with medium-accuracy location data. *J. Civ. Eng. Manag.* **2017**, *23*, 384–392. [CrossRef]
15. Choe, S.; Leite, F.; Seedah, D.; Caldas, C. Evaluation of sensing technology for the prevention of backover accidents in construction work zones. *J. Inf. Technol. Constr.* **2014**, *19*, 1–19.
16. Park, M.W.; Brilakis, I. Continuous localization of construction workers via integration of detection and tracking. *Autom. Constr.* **2016**, *72*, 129–142. [CrossRef]
17. Kanan, R.; Elhassan, O.; Bensalem, R. An IoT-based autonomous system for workers' safety in construction sites with real-time alarming, monitoring, and positioning strategies. *Autom. Constr.* **2018**, *88*, 73–86. [CrossRef]

18. Lee, U.K.; Kim, J.H.; Cho, H.; Kang, K.I. Development of a mobile safety monitoring system for construction sites. *Autom. Constr.* **2009**, *18*, 258–264. [CrossRef]
19. Rezazadeh, J.; Moradi, M.; Ismail, A.S.; Dutkiewicz, E. Superior Path Planning Mechanism for Mobile Beacon-Assisted Localization in Wireless Sensor Networks. *IEEE Sens. J.* **2014**, *14*, 3052–3064. [CrossRef]
20. Arthaber, H.; Faseth, T.; Galler, F. Spread-Spectrum Based Ranging of Passive UHF EPC RFID Tags. *IEEE Commun. Lett.* **2015**, *19*, 1734–1737. [CrossRef]
21. Mazuelas, S.; Bahillo, A.; Lorenzo, R.M.; Fernandez, P.; Lago, F.A.; Garcia, E.; Blas, J.; Abril, E.J. Robust Indoor Positioning Provided by Real-Time RSSI Values in Unmodified WLAN Networks. *IEEE J. Sel. Top. Signal Process.* **2009**, *3*, 821–831. [CrossRef]
22. Biswas, J.; Veloso, M. WiFi localization and navigation for autonomous indoor mobile robots. In Proceedings of the 2010 IEEE International Conference on Robotics and Automation, Anchorage, Alaska, 3–8 May 2010; pp. 4379–4384. [CrossRef]
23. Marks, E.D.; Teizer, J. Method for testing proximity detection and alert technology for safe construction equipment operation. *Constr. Manag. Econ.* **2013**, *31*, 636–646. [CrossRef]
24. Chae, S.; Yoshida, T. Application of RFID technology to prevention of collision accident with heavy equipment. *Autom. Constr.* **2010**, *19*, 368–374. [CrossRef]
25. Jo, B.W.; Lee, Y.S.; Kim, J.H.; Kim, D.K.; Choi, P.H. Proximity Warning and Excavator Control System for Prevention of Collision Accidents. *Sustainability* **2017**, *9*, 1488. [CrossRef]
26. Yusheng, H.; Amin, H.; Zhenhua, Z. Providing Proximity Safety Alerts to Workers on Construction Sites Using Bluetooth Low Energy RTLS. In Proceedings of the Creative Construction e-Conference 2020, Opatija, Croatia, 28 June–1 July 2020.
27. Quuppa Localization System. Available online: https://quuppa.com/ (accessed on 8 January 2022).
28. Park, J.; Marks, E.; Cho, Y.; Suryanto, W. Performance test of wireless technologies for personnel and equipment proximity sensing in work zones. *J. Constr. Eng. Manag.* **2016**, *142*, 04015049. [CrossRef]
29. Baek, J.; Choi, Y. Smart Glasses-Based Personnel Proximity Warning System for Improving Pedestrian Safety in Construction and Mining Sites. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1422. [CrossRef]
30. Baek, J.; Choi, Y. Bluetooth-Beacon-Based Underground Proximity Warning System for Preventing Collisions inside Tunnels. *Appl. Sci.* **2018**, *8*, 2271. [CrossRef]
31. Nikitin, P.V.; Rao, K.V.S. Antennas and Propagation in UHF RFID Systems. In Proceedings of the 2008 IEEE International Conference on RFID, Las Vegas, NV, USA, 16–17 April 2008; pp. 277–288. [CrossRef]
32. RFID Handbook: Radio-Frequency Identification Fundamentals and Applications. In *RFID Handbook: Radio-Frequency Identification Fundamentals and Applications*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2003. [CrossRef]
33. Nikitin, P.V.; Martinez, R.; Ramamurthy, S.; Leland, H.; Spiess, G.; Rao, K.V.S. Phase based spatial identification of UHF RFID tags. In Proceedings of the 2010 IEEE International Conference on RFID (IEEE RFID 2010), Guangzhou, China, 17–19 June 2010; pp. 102–109. [CrossRef]
34. Koch, A.; Zell, A. RFID-enabled location fingerprinting based on similarity models from probabilistic similarity measures. In Proceedings of the 2016 IEEE International Conference on Robotics and Automation (ICRA), Stockholm, Sweden, 16–21 May 2016; pp. 4557–4563. [CrossRef]
35. Motroni, A.; Buffi, A.; Nepa, P. A Survey on Indoor Vehicle Localization Through RFID Technology. *IEEE Access* **2021**, *9*, 17921–17942. [CrossRef]
36. Wan, E.; Van Der Merwe, R. The unscented Kalman filter for nonlinear estimation. In Proceedings of the IEEE 2000 Adaptive Systems for Signal Processing, Communications, and Control Symposium (Cat. No.00EX373), Lake Louise, AB, Canada, 4 October 2000; pp. 153–158. [CrossRef]
37. Impinj xArray Product Brief. Available online: https://support.impinj.com/hc/en-us/articles/202755688-xArray-Gateway-Product-Brief-Datasheet (accessed on 8 January 2022).
38. Angle of Arrival with BLE 5.1 Beacons. Available online: https://www.silabs.com/whitepapers/bluetooth-angle-estimation-for-real-time-locationing (accessed on 8 January 2022).
39. Bilbao-Jayo, A.; Almeida, A.; Sergi, I.; Montanaro, T.; Fasano, L.; Emaldi, M.; Patrono, L. Behavior Modeling for a Beacon-Based Indoor Location System. *Sensors* **2021**, *21*, 4839. [CrossRef]
40. Spring Boot Official Website. Available online: https://spring.io/projects/spring-boot (accessed on 8 January 2022).
41. Raspberry Pi Official Website. Available online: https://www.raspberrypi.org (accessed on 8 January 2022).
42. Angular. Available online: https://angular.io/ (accessed on 8 January 2022).
43. Ionic Framework. Available online: https://ionicframework.com (accessed on 8 January 2022).
44. MySQL Database. Available online: https://www.mysql.com/it/ (accessed on 8 January 2022).
45. Impinj Speedway Revolution UHF-RFID Readers. Available online: https://www.impinj.com/products/readers/impinj-speedway (accessed on 8 January 2022).