URSI-B EMTS 2025, Bologna, 23–27 June

Position and Attitude/Orientation sensing with UHF RFID systems and array antennas

Emanuele Tavanti(1), Andrea Motroni(1), Paolo Nepa(1), Roberto Gabbrielli(2), Marco Pirozzi(3)
(1) Department of Information Engineering, University of Pisa, Italy, 56122
(2) Department of Civil and Industrial Engineering, University of Pisa, 56122 Pisa, Italy
(3) Department of Technological Innovations and Safety of Plants, Products and Human Settlements, INAIL, 00143 Rome, Italy

Abstract

Workplace safety is a critical challenge requiring qualified personnel and can benefit from automatized monitoring systems. To mitigate these risks, we propose AISAFETY, an intelligent system that integrates passive Ultra High-Frequency (UHF) Radio Frequency Identification (RFID), Computer Vision (CV), and Artificial Intelligence (AI). This paper deals with the RFID module, designed to measure workers and objects location, as well as the orientation of critical system safety components through acceleration sensors integrated on the tags circuitry. Tests in a real multipath-affected laboratory environment including large metallic machinery are presented to verify the effectiveness of the installed system.

1. Introduction

Workplaces are called to face critical safety challenges, such as overcrowding in hazardous areas, interference with machine safety devices, equipment failures, and human errors [1]. These factors increase the risk of accidents and threat workplace safety.

Addressing these risks requires strict supervision and proper machine maintenance by qualified personnel following guidelines and ad-hoc workflows. To enhance safety, a smart monitoring system using passive Radio Frequency IDentification (RFID) technology at Ultra High-Frequency (UHF) band, Computer Vision (CV), and Artificial Intelligence (AI) algorithms name AISAFETY was proposed [2]. This system aims at stopping hazardous operations and alerts workers about dangerous situations. A multi-modal sensing approach has been adopted in AISAFETY, namely employing both RFID, which is based on radio waves, and CV, which works in the optical domain. This choice has been driven by the complementarity of these technologies [6]. Indeed, the CV cannot obviously handle cases where objects of interest are not visible to the employed cameras (i.e., the Line of Sight, LoS, condition is needed), and the identities of objects with similar appearance cannot be distinguished. RFID does not necessarily need the LoS condition, and the identification capability is intrinsic to this technology. Regrettably, RFID suffers from multipath phenomena. The severe multi-bounce reflections of the radio waves that happen in an indoor environment are a hard challenge for the RFID-

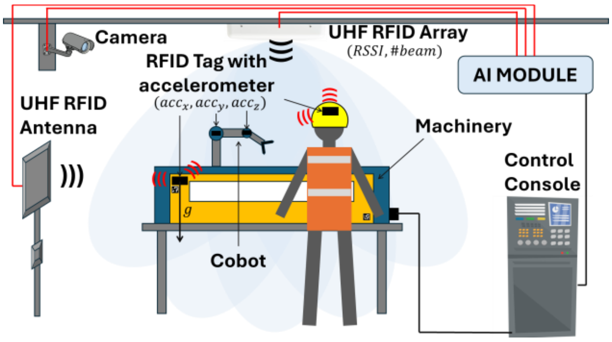


Figure 1. Schematic representation of the AISAFETY system architecture.

based localization algorithms, especially when many large metallic structures are present (as often happens in the industrial setting). On the other hand, CV is immune to any multipath phenomena, since it does not rely on radio waves. Therefore, the synergy of these two technologies allows to cope with the drawbacks of the single ones, to enrich the features of the system and increase the situational awareness.

In this work we present the RFID module, in charge of tracking workers locations, verifying the usage of the Personal Protective Equipment (PPE), and monitoring fixed/mobile safety guards of the machinery and tools. The RFID labels, lightweight and flexible, can be easily integrated into PPEs, and enable unique and remote identification of people and objects. When equipped with sensors, additional information such as their orientation measured through on-board accelerometers can be retrieved. RFID tags are also useful as they can be installed on metallic surfaces through proper antenna design and tag encapsulation, being suitable for metallic machinery.

Recently, the localization of tagged entities has been deeply explored with fixed structures, synthetic or physical arrays [3]-[5]. System location-awareness could be beneficial to increase the workplace safety.

In the AISAFETY architecture, RFID desktop readers and RFID gateway arrays (i.e., devices comprising a desktop reader and an array antenna at RFID band) are used to extract position and orientation of tags to monitor the activity in proximity to an industrial machinery.

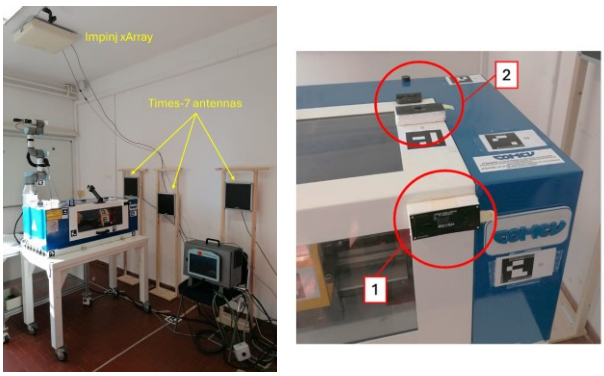
For effective activity control, the RFID module communicates with the AI module. The AI module processes these inputs combined with CV-generated inputs to make decisions and prevent hazardous situations. The AISAFETY system aims at monitoring human and cobot activity around machinery, as shown in Figure 1, by using passive RFID tags and passive RFID sensor tags with accelerometers.

2. Experimental Activity with the RFID module

The RFID module includes a desktop reader connected to multiple fixed antennas and a UHF RFID gateway array installed at the ceiling. The RFID module software consists of two independent processes running in parallel and performed by the desktop reader (Impinj R720) and the ceiling-mounted array (Impinj xArray), respectively: (i) monitoring the status of the cobot and the fixed/mobile guards of the lathe. This is done through passive sensor tags with embedded acceleration sensors; (ii) worker localization and monitoring the presence of tool holders.
Two readers are required since the UHF RFID gateway array software does not support simultaneous localization and reading of acceleration data, stored in the memory of the sensor tags.
The test setup was prepared in a real laboratory environment including large metallic lathe and a cobot as test machinery, to verify the effectiveness of the installed system in critical conditions. The setup is shown Figure 2a.

2.1 Attitude measurements with acceleration data

Asygn tags with single-axis accelerometer AS3213C.4 are used to monitor the inclination of the lathe fixed/mobile guards and of the cobot joints. When the lathe fixed/mobile guards and the cobot joints are in a "rest" state (i.e., when the guards are closed, and the cobot is in standby mode), the accelerometers measure an acceleration magnitude of $g = 9.81\ m/s^2$. When a tag reports an acceleration deviating from such value, the state becomes "non-rest", and a notification is sent to the AI module. This could happen when the cobot starts moving, the lathe door being open, or a fixed/mobile guard tampered or removed.



(a) (b)

Figure 2. (a) System setup with antenna array and lateral antennas; (b) sensor tags with accelerometer.

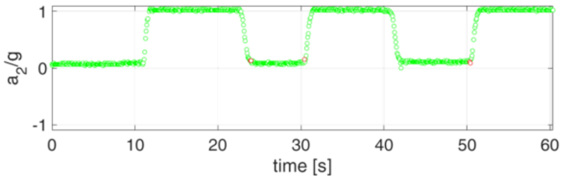
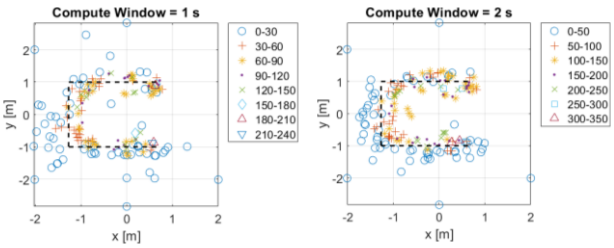


Figure 3. Sample acceleration data from an Asygn sensor tag installed at the lathe frontal door (Tag 2 in Figure 2b).

Acceleration data are read through the desktop reader connected to three Times-7 A4030C antennas with circular polarization and 6.5 dB gain, installed at lateral location with respect to the lathe with heights between 1 m and 1.5 m. An example of acceleration data gathered from a tag on the lathe frontal door (Tag 2 in Figure 2b) is represented in Figure 3, where "rest" (lathe door closed) and "non-rest" (lathe door open) states are clearly visible.

2.2 Position estimation with UHF RFID array

The positions of the tags, mainly attached to workers, estimated by the Impinj xArray gateway [7] determine the number of workers present in various key areas that could be allowed or not allowed depending on the work process being conducted. The Impinj xArray has three main embedded components: an array of antennas, a UHF RFID reader, and a mini-PC to control the operations of the whole device, to process the acquired data, and to transfer them to external devices. The array is capable of electronic beam switching: 52 beams can be sequentially activated, each one with a different pointing direction and a Half Power Beamwidth (HPBW) equal to 30°. Thanks to this set of beams, xArray has a global HPBW of 120°. When a beam is activated, the horizontal and vertical polarizations are sequentially irradiated, to mitigate issues of polarization mismatch with linearly polarized antenna tag. xArray is endowed with a proprietary and closed-source localization algorithm. It leverages RSSI (Received Signal Strength Indicator) of each tag reply and the known pointing directions of the beams that collected the tag replies to estimate the positions $[x, y]^T$ at ground level for each detected tag. The algorithm requires to average consecutive tag reading replies to reach proper localization accuracy. The consequence is that it is necessary to set a parameter, called "compute window" that determines for how long the array gathers raw data before calculating the output tag location. The longer the duration of the "compute window", the lower the localization error at the expense of increased latency in position updates and lower capability to track fast moving targets. The overall RFID monitoring system uses the locations provided by the xArray to determine in which area among those envisioned by the system administrator the person or object to be monitored is located. The tags installed at each worker are five: one on the helmet and four embedded in the vest. Asygn tags with accelerometer have been used to enable man-down detection to promptly identify workers who have fallen and are unable to get up.



(a) (b)

Figure 4. Outputs of the localization algorithm with the UHF RFID Array. Compute window (a) 1 s; (b) 2 s.

Two examples of algorithm output when a worker moves around the lathe are shown in Figure 4, considering "compute window" equal to 1 s (Figure 4a) and 2 s (Figure 4b). The trajectory of the worker is the dashed black line. The diversified markers consider an important parameter, namely the number of tag readings. The greater the number of readings, the better the position estimation. For this reason, a larger "compute window" improves the estimated position as it allows more reads per tag. However, we verified that if the "compute window" is set to values higher than 2 s, the localization is no more reliable, since the target's movement is too wide inside this temporal window. Finally, if multiple tags are placed on the worker, it is possible to combine their data to obtain more accurate trajectories.

3. Conclusion and Future Works

In this paper we have shown a system called AISAFETY combining UHF-RFID, CV and AI for improving worker safety in indoor industrial settings. The paper focuses on the RFID module, which is composed of a RFID antenna array with integrated reader and a conventional desktop reader connected to RFID patch antennas. The array monitors the workers or other object location around the test machinery by leveraging the received signal power at different angles through electronic beam scanning. The reported experimental data shown that the localization can reach noteworthy accuracy in a realistic experimental setup, as long as the key parameter required by the Impinj localization algorithm is properly set, accounting for the movements of the monitored target. The desktop reader extract acceleration data from passive RFID sensor tags delivering useful information about tampering or removal of fixed/moving guards of the machinery. As shown in Section 2.1, the RFID sensor tags can successfully wirelessly monitor the state of industrial machinery, such as the frontal door of a lathe, by exploiting the component of the gravity vector sensed by the onboard accelerometer. Future developments include the testing of all the system functions within realistic conditions, and the integration together with the AI and CV modules into a local network capable of managing the information and alert messages.

4. Acknowledgements

This work was supported in part by the Italian National Institute for Insurance Against Accidents at Work (INAIL) (Italy) under the Project AISAFETY through the fund "Bando BRiC-Call for Collaborative Research under Grant BRiC–2022"; in part by the PNRR Smart Mobility Project under Grant CUP I53C22000720001; and in part by the Italian Ministry of Education and Research (MIUR) in the Framework of the CrossLab and FoReLab Projects (Departments of Excellence).

References

[1] M. Braglia, L. Di Donato, R. Gabbrielli, and L. Marrazzini, "The house of safety: A novel method for risk assessment including human misbehaviour," *Safety Science*, vol. 110, pp. 249–264, Dec. 2018, doi: 10.1016/j.ssci.2018.08.015.

[2] R. Gabbrielli et al., "Development Of Novel Integrated Smart System Based On Artificial Intelligence For Management Of Operator Safety In Production Processes," in *Advances in reliability, safety and security, ESREL 2024, pt. 5 Human factors in system reliability, safety and security & occupational safety*, K. T. Kosmowski and K. Kołowrocki, Eds. Gdynia: Polish Safety and Reliability Association, 2024.

[3] A. Motroni et al., "Advanced RFID-Robot with Rotating Antennas for Smart Inventory in High-Density Shelving Systems," *IEEE J. Radio Freq. Identif.*, vol. 8, pp. 559–570, 2024, doi: 10.1109/JRFID.2024.3369470.

[4] A. Motroni, F. Bernardini, A. Buffi, P. Nepa, and B. Tellini, "A UHF-RFID Multi-Antenna Sensor Fusion Enables Item and Robot Localization," *IEEE J. Radio Freq. Identif.*, vol. 6, pp. 456–466, 2022, doi: 10.1109/JRFID.2022.3166354.

[5] P. Tripicchio et al., "A Synthetic Aperture UHF RFID Localization Method by Phase Unwrapping and Hyperbolic Intersection," *IEEE Trans. Automat. Sci. Eng.*, vol. 19, no. 2, pp. 933–945, Apr. 2022, doi: 10.1109/TASE.2021.3057433.

[6] E. Tavanti, P. Nepa, R. Gabbrielli, and M. Pirozzi, "Review on Systems Combining Computer Vision and Radio Frequency Identification," *IEEE Internet Things J.*, vol. 12, no. 2, pp. 1291–1319, Jan. 2025, doi: 10.1109/JIOT.2024.3484755.

[7] "Impinj xArray." [Online]. Available: https://support.impinj.com/hc/article_attachments/360001941860.