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PLATFORM-ROBUST PASSIVE UHF RFID TAGS: A CASE-STUDY IN ROBOTICS

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Abstract—The use of Radio Frequency IDentification (RFID) technology in a large array of contexts is a matter of fact. In many cases, such as in robotic applications, the RFID tags should satisfy specific requisites so that read range, platform robustness, radiation properties, cost, and size must be properly taken into account during the design phase. In this work, the specific requirements of tags for RFID-assisted localization and navigation of mobile robots are highlighted and discussed. On such basis, an ad-hoc platform-robust RFID tag is designed, realized and exhaustively tested through both simulations and measurements. The achieved results are impressive and demonstrate the appropriateness of the proposed tag to operate in application scenarios where performance stability is mandatory.

1. INTRODUCTION

Radio Frequency IDentification (RFID) [1] is the most widely adopted technology for tracking objects and goods in supply chain and logistics applications. RFID systems consists of two devices: a reader (or interrogator) with energization and interrogation functions and a tag (or transponder) which is usually attached to objects and transmits back to the reader identification data. A typical RFID tag comprises two parts: an RFID chip and an antenna. This study focuses on passive UHF RFID systems — operating frequency 866–868 MHz in Europe, 902–928 MHz in US, and 952–954 MHz in Japan — and specifically on the EPC Class-1 Generation-2 standard (Gen2) [2]. Passive UHF RFID tags do not have an on-board power source, instead they use their

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antenna to harvest energy from the reader RF field and activate their circuitry. Moreover, passive tags do not transmit new power, rather they reflect back to the reader the received Continuous Wave (CW) by changing their antenna impedance (backscattering modulation) [3]. The tag antenna should be efficient and properly matched to the chip in order to maximize the harvested power and achieve the typical read range up to 10 meters.

Conventional planar tags suffer performance degradation when attached or in close proximity to reflecting, lossy, and capacitive bodies, with negative impact in several application scenarios [4, 5]. Among them, a robotic scenario is considered in this work: passive RFID tags attached to strategic positions in an indoor environment serve as anchors to support localization and navigation of mobile robots [6, 7]. In such a context, one of the main issue is the effect of multipath reflections which affect long range tags and cause localization errors due to false positive/negative readings. Another big challenge is to design tags which can operate well on any surface, including metallic ones, where general-purpose commercial tags do not work. Moreover, cost-effectiveness and ease of fabrication are other desired properties. Developing a low-cost passive tag whose behaviour is independent of the mounting surface is therefore an attractive issue in this application domain.

In this paper, a platform-robust passive RFID tag suitable for robotic applications is proposed. Since the size is not a stringent constraint — for instance, the tag could be integrated into walls, doors, etc. — the designed antenna takes advantage of a relatively large ground plane along with parasitic elements strategically positioned.

The paper is organized as follows. Relevant related works are discussed in Section 2 while the proposed tag antenna design and fundamental aspects such as return loss, current distribution, and radiation patterns are analyzed in Section 3. In Section 4.1, the platform-robustness of the proposed tag antenna is evaluated via simulation and the influence of parameters affecting resonance frequency and radiation patterns is investigated. In Section 4.2, the performance of the proposed platform-robust tag are compared with those of a conventional label-type tag. Read range and tag sensitivity, both measured experimentally by means of a commercial RFID reader and a flexible Software-Defined Radio (SDR) platform [8–10] are impressive and confirm the capability of the proposed tag to tackle the main challenges encountered in RFID-based robotic applications and not only. The relevant conclusions are finally drawn in Section 5.

2. RELATED WORKS

Indoor RFID-based localization and navigation of mobile robots is a widely discussed topic in the literature. It mainly relies on the "sensor model" concept [6, 7] which associates the probability of detecting an RFID tag and its position with respect to the antenna. Regardless of the adopted approach, i.e., based on tag detection events and/or RSS information, the sensor model is usually integrated into Monte Carlo Localization (MCL) algorithms to determine the tag pose (location and orientation).

In such a context, several aspects can dramatically influence the overall system performance. First of all, the material to which the tag is attached and the objects in its close proximity can negatively affect the backscattered signal. Location-dependent sensor models, i.e., one sensor model for each tag location, could be adopted to overcome such a problem. However, high computational resources are required in this case and the system cost, flexibility and ease of use are strongly affected.

Moreover, although long-range tags are mandatory in many application scenarios, their adoption in robotics is not suitable since multipath reflections and fading effects reduce the robot/tag localization accuracy. Tags with a suitable read range should be hence considered (for instance, 3 meters for a canonical corridor, slightly higher ranges in medium-size rooms, and so on).

Different approaches to design tag antennas with platform-independent performance have been investigated in the literature. Among them, the adoption of an Artificial Magnetic Conductor (AMC) or High-Impedance Surface (HIS) [11–13] are largely adopted solutions. The AMC exhibits high impedance in a specific frequency range and, because of its zero-reflection phase behaviour, can be put very close to a dipole-like antenna, thus keeping quite compact the overall tag structure. An AMC used as a ground plane brings two main benefits. First, the severe degradation of tag performance caused by different mounting surfaces can be prevented. Second, the antenna gain is increased. However, AMC-based antennas have relatively high cost compared to the dipole-like ones, are usually large and complex to fabricate, and have a narrow impedance bandwidth which limits their applications.

One of the mainly adopted strategies to stabilize the platform-dependent radiation pattern, bandwidth, and input impedance relies on Planar Inverted-F Antennas (PIFA) [14]. Broad bandwidth — usually achieved by means of very-low permittivity substrates — is another well-known technique to realize platform-independent antennas [15]. Regardless of the antenna bandwidth, a platform-tolerant impedance behaviour may be also achieved with a particular current distribution. In [16], antennas with surface currents induced by horizontal point sources above the ground plane are shown to be more platform tolerant compared to those with currents induced by vertical sources. Obviously, the proximity of the ground plane for dominating horizontal current leads to a very narrow bandwidth behaviour, not always suitable for RFID applications.

The effects of the mounting surface on the tag antenna impedance could be also minimized by using a quite large ground plane. For instance, authors in [17] show that a circular microstrip patch antenna having a ground plane beyond 1.3 times the patch size exhibits an input impedance which does not vary with the mounting surface.

3. ANTENNA DESIGN

Along with the already mentioned platform-robustness and suitable read ranges, also linear polarization, low-cost, ease of fabrication and, in particular, absence of side and back lobes, are strongly desired properties in the addressed robotic application [18]. More specifically, this last requirement is crucial to decrease the power wasting in non-desired space zones and, consequently, to reduce false positive/negative readings.

The geometry of the proposed RFID tag is shown in Fig. 1. The main radiating element is substantially based on the Multiple-Arm Folded Dipole proposed in [19], with four extra dipoles whose optimized dimensional parameters contribute to modify the impedance matching between chip and antenna and, consequently, to tune and set the desired read range. Moreover, since the minimization of the overall tag size is not crucial for the addressed application, a quite large

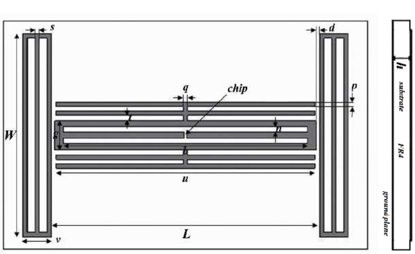


Figure 1. Geometry of the proposed RFID tag.

Figure 2. Prototype of the proposed tag.

substrate, optimized to increase the platform-robustness property, is used. Finally, taking advantage from the unutilized area, slotted parasitic elements are introduced to further reduce the interaction with the mounting surface.

For the practical optimization and final prototyping, an FR4 substrate with relative permittivity of 3.7 and thickness of 1.6 mm has been selected. Moreover, the Impinj Monza3 [20] RFID Gen2 chip with a measured impedance of $Z_c = 31 - j157\,\Omega$ at 866 MHz has been considered. The realized tag (see Fig. 2 for a prototype photo) occupies an area of $160 \times 100\,\text{mm}^2$. In Table 1, details about the optimized dimensions, according to the layout of Fig. 1, are reported.

The simulations performed by CST Microwave Studio [21] show a good impedance matching in a bandwidth of 19.9 MHz (equal to 2.29%) between 857.7–877.4 MHz, a directivity of 5.87 dBi, a Front-to-Back Ratio (FBR) equal to 15.3 dB, and a complete absence of side lobes. The designed tag achieves a read range of approximately

Table 1. Tag dimensions.

Parameter	Value [mm]	Parameter	Value [mm]
W	88.85	n	2.28
L	117.8	b	107.47
s	1.9	u	113.8
g	12.8	v	12.55
t	2.29	p	1.9
q	1.9	d	1.5
h	1.6	/	/

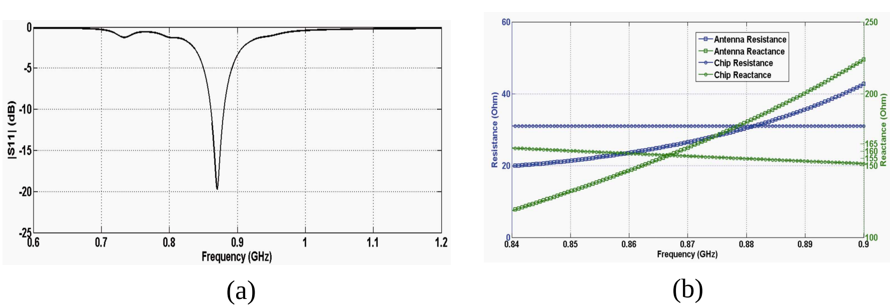


Figure 3. (a) Simulated return loss and (b) antenna impedance of the designed tag.

2.5 meters when the power emitted by the interrogating reader is 30 dBm, i.e., the maximum allowed output power Simulated Return Loss and comparison between antenna and chip impedances are shown in Fig. 3. It is worth noting that the reactance of the developed antenna is highly inductive and the impedance increases with frequency in the considered band. Although the resonance mode of the tag antenna is not clearly visible from the impedance curve, the tag is actually operating close to its resonance frequency. Indeed, antenna and chip reactance curves are in quite good agreement around the considered European UHF RFID band. The simulated 2D radiation patterns of the designed tag antenna are shown in Fig. 4.

As for the simulated current distribution, Fig. 5 shows that current is concentrated along the dipole in the middle of the main structure, on the area between the end of the central structure and the first added dipole and, even if slightly, on the parasitic patches.

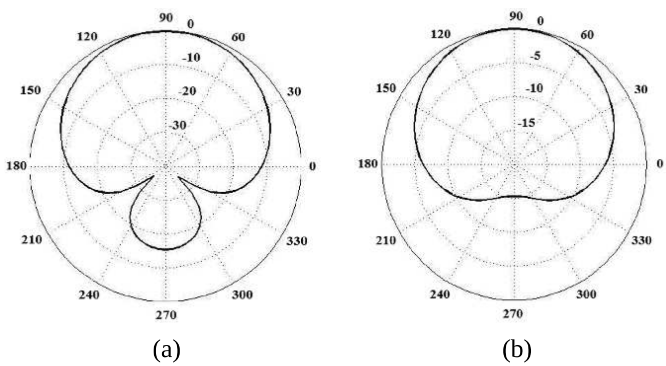


Figure 4. Simulated 2D radiation patterns: (a) H-plane and (b) E-plane.

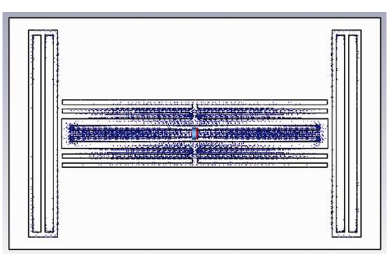


Figure 5. 2D current distribution.

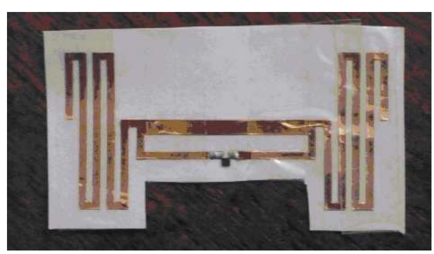


Figure 6. Conventional label-type tag used for comparison.

4. VALIDATION RESULTS

In this section, the platform-robustness of the proposed tag is demonstrated by simulations and measurements.

4.1. Simulations

In order to numerically assess the robustness of the designed tag, performance simulations have been carried out by varying the material of the surface where the tag is mounted on. More specifically, a scenario consisting of a $300 \times 300 \times 15\,\mathrm{mm}^3$ panel behind the tag has been simulated by means of CST-MW Studio and both Return Loss and radiation patterns have been determined for different permittivity values of the panel material, including the critical case of metal. The permittivity has been varied from 2.5 to 8.5 in order to evaluate both low-medium (e.g., cardboard, wood, plastic, glass, etc.) and medium-high (e.g., concrete) permittivity materials. Indeed, since the permittivity of concrete depends on the Moisture Component (MC) parameter [22], permittivity values from 4.5 (when MC = 0.2%) to 7.8 (when MC = 12%) can be exhibited at 866 MHz. For comparison purposes, simulations have been performed also for a canonical label-type built-in-lab tag (see Fig. 6) consisting of a meander antenna, a T-matching network, and the Impinj Monza3 chip.

Simulated Return Loss and radiation patterns for both the proposed and the label-type tags are reported in Fig. 7 and Fig. 8 respectively. It is worth clarifying that showed radiation patterns are normalized with respect to the maximum value achieved among all obtained patterns.

Simulation results indicate that performance of the proposed tag does not substantially depend on the mounting surface. In all

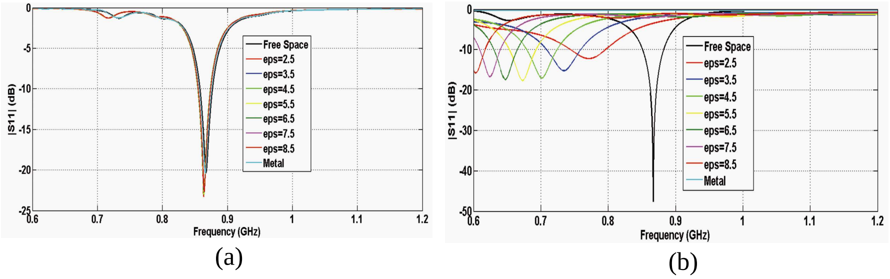


Figure 7. Simulated return loss of (a) the proposed and (b) label-type tags for different permittivity values.

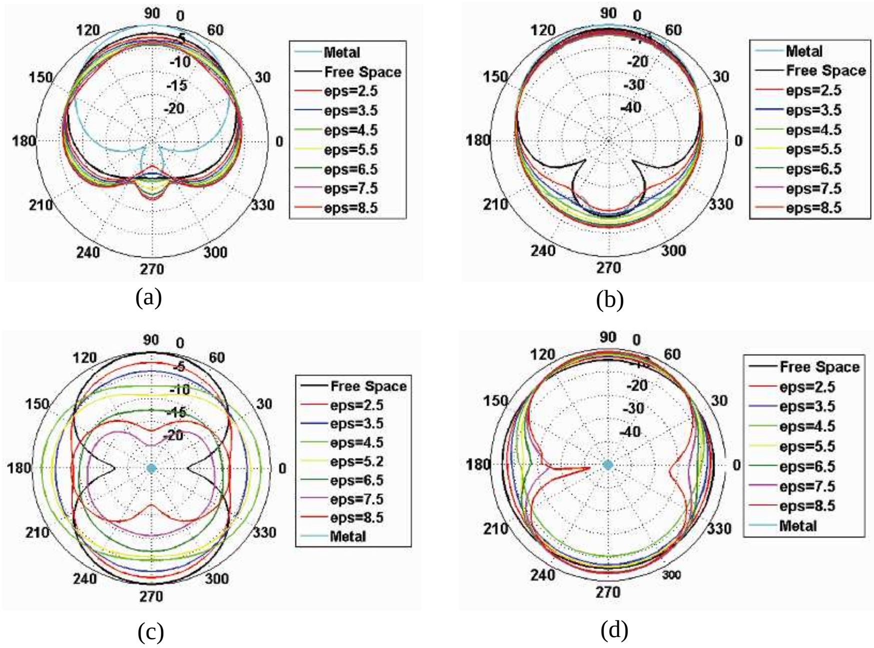
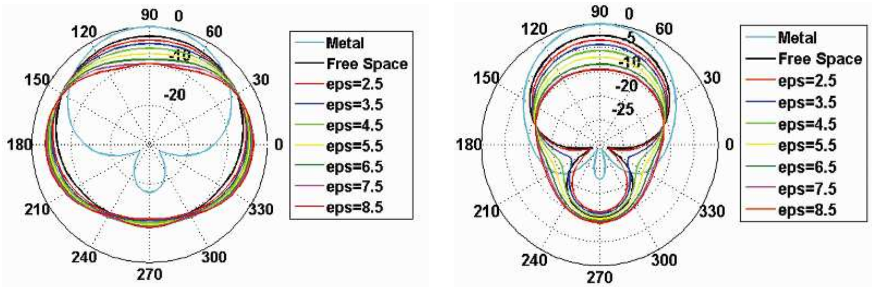


Figure 8. 2D radiation patterns of (a), (b) the proposed and (c), (d) label-type tags: (a), (c) *H*-plane and (b), (d) *E*-plane for different permittivity values.

scenarios, including the most critical with metal, tag performance is almost the same, thus demonstrating the expected platform-robust behaviour. On the other hand, performance of the label-type tag strongly depends on the mounting surface, with a complete absence of radiation on the metal case.

As previously mentioned, one of the most important parameter to achieve the desired platform robustness for the tag is the ground plane size. In order to quantify the impact of such a parameter, radiation pattern simulations of the proposed tag with a ground plane area of $133 \times 50\,\mathrm{mm}^2$ (instead of $160 \times 100\,\mathrm{mm}^2$) have been performed. Patch dimensions are kept constant. The direct comparison between Fig. 9 and the top side of Fig. 8(a) and Fig. 8(b) indicates that a smaller ground plane makes the tag less platform-robust, thus confirming the impact of the ratio between ground plane and patch dimensions on the desired platform-robustness property.



(a) (b)

Figure 9. 2D radiation patterns of the designed tag with reduced ground-plane dimensions: (a) H-plane and (b) E-plane for different permittivity values.

Table 2. Measured read range in meters.

Material	Proposed tag	Label-type tag
Wood	2.40	3.65
Metal	2.47	*Not detected*
Concrete (AAC)	2.48	2.88
Free Space	2.50	8.20

4.2. Measurements

The platform-robustness of the proposed passive UHF RFID tag has been also experimentally demonstrated.

In a first set of measurements, a large outdoor scenario has been considered and the maximum distance at which the tag can be read by a commercial RFID reader — operating in the 864–868 MHz European UHF RFID band with 30 dBm output power and a circularly polarized antenna — has been measured. Table 2 shows the read range of the proposed platform-robust tag compared to the previously considered label-type tag for different mounting surfaces. As for the proposed tag, the read range varies from 2.4 meters to 2.5 meters, regardless the supporting material (metal, concrete, wood and free space). As for the label-type tag, instead, the measured read range varies widely from 0 meters, i.e., the tag goes completely undetected when mounted on metal, to 8.2 meters in free space. This is a clear indication of the inappropriateness of conventional tags to operate regardless the mounting surface. Conversely, this strong radiative degradation is not exhibited by the proposed platform-robust tag, thus confirming the simulation results.

In a second set of experiments, the platform-robustness of the proposed tag has been further investigated. The anechoic environment depicted in Fig. 10 has been reproduced and a sensitivity analysis has been performed by means of the flexible Software-Defined Radio (SDR) tool appeared in our recent publications [8–10].

The minimum power required to communicate with the tag has been recorded at different frequencies in the 850–880 MHz band with 1 MHz step. Then, the tag sensitivity $P_{TH,tag}$ has been calculated according to the following equation:

$$P_{TH,tag} = EIRP_{ON} \left(\frac{\lambda}{4\pi d}\right)^2 \eta_{plf} \tag{1}$$

where $EIRP_{ON}$ is the minimum Equivalent Isotropically Radiated

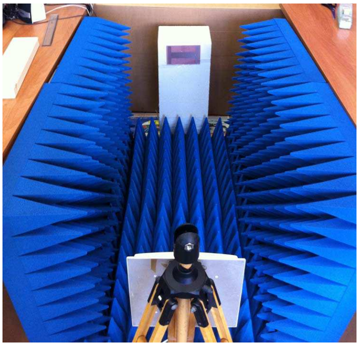


Figure 10. The controlled environment used for tag sensitivity experiments.

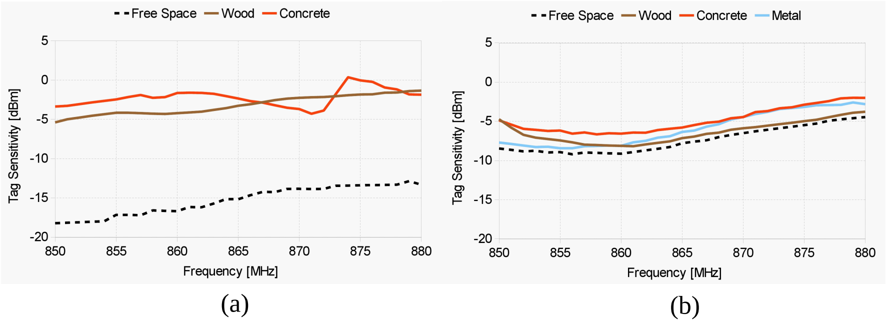


Figure 11. Measured sensitivity of (a) the label-type and (b) designed tag.

Table 3. Theoretical read range in meters.

Material	Proposed tag	Label-type tag
Wood	2.76	1.95
Metal	2.45	*Not detected*
Concrete (AAC)	2.32	1.74
Free Space	2.92	6.93

Power needed to obtain a tag response, λ is the wavelength, $\eta_{plf} = 0.5$ is the polarization loss factor due to the circularly polarized antenna used to interrogate the tag, and d is the tag-interrogator distance considered in experiments. As shown in the left side of Fig. 11, the sensitivity of the conventional label-type tag widely varies depending on the mounting surface: in the European RFID band (864–868 MHz), it is approximately −15 dBm for free-space and −3 dBm for wood and concrete. The tag goes always undetected when mounted on metal. As for the proposed platform-robust tag, the measured sensitivity (right side of Fig. 11) is quite invariant with the mounting surface: −7.5 dBm for free space, −7 dBm for wood, −5.5 dBm for concrete, and −6 dBm for metal in the European UHF RFID band. Moreover, the theoretical maximum read range is calculated by the following equation:

$$d_{MAX} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP \cdot \eta_{plf}}{P_{TH,tag}}} \tag{2}$$

and reported in Table 3. Results are in very good agreement with the measured read range in Table 2.

The achieved sensitivity results are in good agreement with those provided by simulations and read-range experiments, thus further confirming the desired platform-robust behaviour of the proposed tag. Moreover, for what concerns the application considered in this paper (i.e., RFID-based localization and navigation of mobile robots), it is worth emphasizing that the performance of the proposed tag in terms of read range fits well with suitable dimensions of canonical corridors.

5. CONCLUSION

In this work, a new microstrip RFID tag specifically tailored to improve RFID-based mobile robot navigation and localization is proposed. The tag, simple and cost-effective, guarantees the desired working range — set to 3 meters in this specific case — regardless the mounting surface. Platform robustness is achieved by means of the joint use of optimized substrates and parasitic elements, whilst the desired working range is set by accurately tuning the matching between RFID chip and antenna. The properties of such a new device have been exhaustively validated by means of Return Loss and Radiation Pattern simulations as well as tag sensitivity and read range measurements, and compared with a canonical label-type tag. The achieved results are impressive: they collectively demonstrate the appropriateness of the proposed approach to design high-performance RFID tags suited for applications requiring platform-robustness.

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