TOWARDS A COMPUTATIONALLY EFFICIENT RELATIVE POSITIONING SYSTEM FOR INDOOR ENVIRONMENTS
An RFID Approach

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Abstract: The recent advancements of Radio Frequency IDentification (RFID)-based localization approach has necessitates the development of effective solutions for mobile robot navigation systems in an indoor and/or outdoor environment. Among the most common problems pertaining to the modern RFID-based robot navigation systems are that multiple reference RF stations or excessive number of sensors are utilized for the location sensing with RFID, however, particularly in indoor environments, spatial layout or cost problems limit the applicability of those approaches. The contribution of the current manuscript is to devise a simple computationally efficient relative positioning system for indoor environments through a modified RFID tag architecture. The validity of the proposed RFID-based RPS is demonstrated using the real data collected in a typical indoor environment.

NOMENCLATURE

N	Total number of RFID tags
$\hat{p}$	Estimated robot position
p	True robot position
p_i	Position of tag i
$\hat{e}$	Robot position error
ΔRSS	Received signal strength difference
RSS_i	Average RSS value of tag i
RSS_{ji}	j^{th} RSS value of tag i

1 INTRODUCTION

Due to the advent of RFID and RFID systems (Nasri et al., 2008), and their applications in the field of robotics (Milella et al., 2007), positioning systems have been used to deliver location information in indoor and/or outdoor environments. The primary role of such localization systems is to estimate and report geographical information pertaining to the data processing unit associated with a mobile robot for the purpose of management, enhancement, and personalization services. The current manuscript contributes to the design and implementation of a modular, cost-effective, and an easy-to-implement mobile robot navigation algorithm in cooperation with an open RFID hardware architecture.

Most of the RFID-based navigation systems suggested in the literature are tailored along with the localization systems where the central task of an RFID system is to estimate the position of a mobile robot at a certain time instant. In the current work, an RFID reader is mounted on a mobile robot and some RFID tags are placed at 3-D locations (ceiling, for example) in an indoor environment. At every time instant, the reader broadcasts a time-varying Radio Frequency (RF) signal to all tags in its operating range and tags simply response back to the reader with their Received Signal Strength (RSS) measurements. These RSS values are then used by the mobile robot to approximate its relative position with respect to a desired path that the robot has to follow. Despite the significant contributions of RFID systems and RSS measurements in the literature to date, the localization problem of a mobile robot remains some significant technical challenges that must be overcome. Hence, our effort is devoted to the development of a positioning system for an indoor mobile robot where the previous methods might not work. The main contributions of the current work is to devise a computationally efficient relative positioning system for indoor environments using a modified RFID tag architecture. This approach is different from the existing RSS-based localization methods (Graefenstein and Bouzouraa, 2008) in that it uses the RSS measurements of the RF signal transmitted by the RFID

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reader. This is simply because the passive tag circuit is energized from the RF signal broadcasted by the reader. Hence, the RSS value in the tag circuitry is more significant than that in the RFID reader.

The rest of the paper is outlined as follows. Some of the most commonly used robot navigation and/or localization systems are given in section 2. Section 3 describes the proposed RFID-based relative positioning architecture followed by fundamentals of RFID system theory and its limitations. The RFID system implementation is discussed in section 4 followed by some real-time experimental results illustrated in section 5. Finally, conclusions with some future research avenue are drawn in section 6.

2 RELATED WORK

Mobile robot navigation and/or localization system has been the subject of several studies. Among the most common and popular navigation algorithms suggested in the state of the art are dead-reckoning-based, landmark-based, vision-based, behavior-based navigation techniques. Each of these navigation techniques has its own advantages and disadvantages, although it is difficult to rate them objectively. However, some aspects can be unequivocally compared, such as the computational complexity, the navigation accuracy, or the amount of information a priori required for the proper operation of the algorithm.

The fundamental idea behind the dead-reckoning navigation techniques is that they provide position, heading, translational, and rotational velocities of an autonomous mobile robot. These techniques are widely used due to their simplicity and easy maintenance (D'Orazio et al., 1993). The shortcomings of this technique is obviously that small precision errors and sensor drifts inevitably lead to increasing cumulative errors in the robot's position and orientation over time, unless an independent reference is used periodically to correct the errors. As an alternative to dead-reckoning-based methods, natural or artificial landmarks have been used at various locations in the environment in order to better estimate the position of the mobile robot (Lin and Lal Tummala, 1997; Yi and Choi, 2004). Nevertheless, a landmark-based navigation strategy relies on identification and subsequent recognition of distinct features or objects in the environment that may be a priori known or extracted dynamically. Due to sensors noise and possible dynamic changes of the operating environment, the recognition process of features or objects might become quite challenging. Given the shortcomings of the landmark-based techniques, some researchers shifted their interest to vision-based navigation systems. Vision sensors can have wide field-of-view, can have millisecond sampling rates, and can be easily used for trajectory planning (Desouza and Kak, 2002). Yet, some disadvantages of vision include lack of depth information, image occlusion, low resolution and the requirement for extensive data interpretation (recognition). As the development of different autonomous robot navigation techniques in real-world environments constitutes one of the major trends in current research on robotics, one important problem is to cope with the large amount of uncertainty inherited from natural environments. As such, soft computing techniques have received a considerable attention in recent years. Numerous navigation techniques have been suggested in the state of the art using some tools of computational intelligence such as fuzzy logic, neural network, neuro-fuzzy system, genetic algorithm, or several combinations of them.

With these concerns in mind, several works have considered localizing a mobile robot based on the application of emerging RFID technology owing to its wide availability, non-touch recognition system that transmits and processes the information on events and environments using a wireless frequency and small chips. Since an RFID system can recognize at high-speed and send data within various distances, the application of RFID technology has been increased and RFID systems have been applied for the robot technology recently (Kulyukin et al., 2004).

Hahnel et al. studied to improve the localization with a pair of RFID antennas (Hahnel et al., 2004). They presented a probabilistic measurement model for RFID readers that allow them to accurately localize the RFID tags in the environment.

In addition, robot's position estimation techniques can be classified as range-based and bearing-based. The main idea behind range-based techniques is to trilaterate the robot's position using some known reference points and the estimated distances at those points in the environment. Distances can be estimated from either RSS measurements or time-based methods. Although a small subset of such works have explored the use of Time of Flight (ToF) (Lanzisera et al., 2006) or Time Difference of Arrival (TDoA) measurements, RSS is generally the feature of choice for indoor positioning. This is due to the fact that RSS measurements can be obtained relatively effortlessly and inexpensively. In addition, no extra hardware (e.g., ultrasonic or infra-red) is needed for network-centric localization (Youssef, 2004). On the other hand, bearing-based schemes use the direction of arrival (DoA) of a target. However, these schemes require multiple range sensors in order to be better suited for mobile robot applications (Kim and Chong, 2009).

3 PROPOSED RFID-BASED RELATIVE POSITIONING (RPS)

The fundamental problem in most real-world localization systems is to produce position estimate from past observations on a discrete grid of points in an environment. Despite the significant limitations of RSS measurements stated in the literature, the proposed approach seeks a function modeled by

$$\hat{p} = f(p_1, \ldots, p_N),$$

where N is the total number of RFID tags placed in a 3D workspace, $p_i = (x_i, y_i, z_i)$ with $1 \leq i \leq N$ represents the coordinates of an RFID tag in the world coordinate system, and f is a function of RSS measurements associated with the RFID tags. $\hat{p} = (x_r, y_r, z_r)$ is the estimated relative position of the robot with respect to the desired path on the ground. In the current work, the position estimation is restricted to the 2D space due its simplicity, as such, z_r, which is the height information, is simply ignored. To quantify the navigation accuracy, the error model is defined by

$$\hat{e} = \|\hat{p} - p\|,$$

where p is the true position of the mobile robot.

In order to compute the estimated relative position of the mobile robot using an RFID system, RFID tags are arranged in a fixed pattern on the ceiling, for instance, as depicted in Figure 1. An RFID reader is mounted on the mobile robot and four tags are attached to the ceiling. The points P1, P2, P3, and P4 define the orthogonal projections of the four tags on the ground. The robot is supposed to navigate along the virtual desired path defined by the projection points.

3.1 Technical Background of an RFID System

We now review the fundamental properties of a commercially available RFID system in the market. RFID is a type of automatic object identification system. The principle of an RFID system consists of storing an individual static binary code to every object that need to be identified and the automatic seizing of information via radio waves. An RFID system is mainly composed of three main components: a tag, an RFID reader, and a host computer (Peris-Lopez et al., 2006).

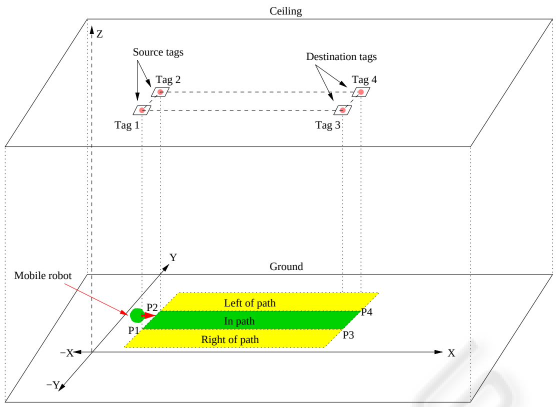


Figure 1: Relative position system setup.

The tag is composed of a microchip with some basic storage capabilities, and a coupling element such as antenna coil for communication. An RFID reader is generally composed of an RF module, a control unit, and a coupling element to interrogate electronic tags via RF communications. The purpose of the host computer is to execute a special purpose software in order to store, process, and analyze the data acquired by the reader. In the current work, an RFID reader is interfaced with the robot's central processing unit to perform further processing of tags' information.

3.2 Relative Positioning Technique

As mentioned above, most of the existing RFID systems available in the market provide only static information which limit its applicability in many real-world proximity-based RFID applications. In the current work, we propose a navigation strategy for guiding a mobile robot in an indoor environment using a customized RFID tag architecture that allows to encode some dynamic information along with its existing static ID. Figure 2 depicts a customized model of an RFID tag employed in the current research. The tag receives an RF signal transmitted by the reader which is then rectified to get its RSS value. In the present RFID system, the tag has some processing capability to convert the RSS value into an 8-bit binary code. As can be seen in figure 2, the RSS measurement of the RFID reader query is embedded with the tag's existing static binary ID (16-bit in this case) which is then backscattered to the RFID reader. It is important to articulate the fact that the reader architecture of the proposed RFID system requires no customization as it would read the 24-bit (16-bit tag-ID + 8-bit RSS) frame in exactly the same way it normally reads tag-IDs. The RFID reader extracts the frame backscattered by the tag which is then passed to the

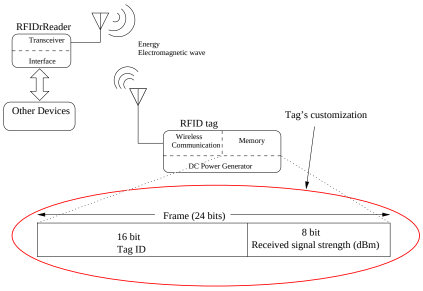


Figure 2: Proposed RFID architecture.

processing element on the robot's board to decode it into a tag-ID and an RSS value. The RSS values are used to approximate the relative position of the mobile robot with respect to its desired path.

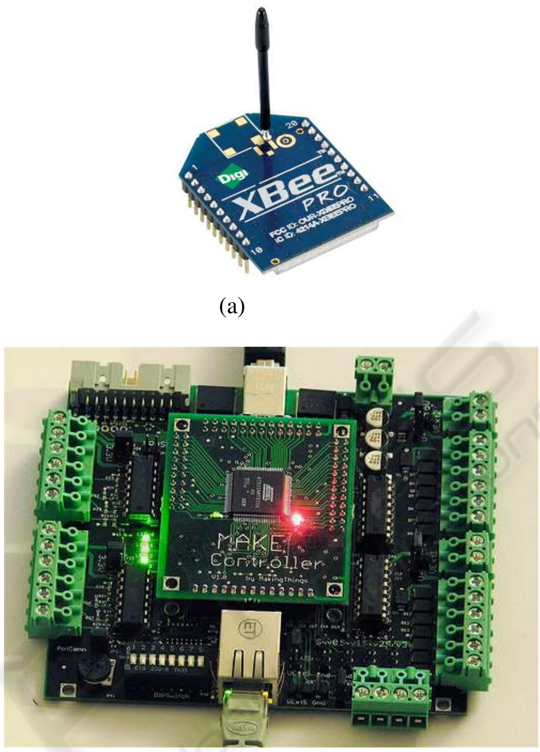
We now explain how the relative position of the robot can be approximated by incorporating tags' RSS values in an indoor environment. In this work, the robot is presented with a set of four tag-IDs, $S = \{1,2,3,4\}$, for instance, where tags with IDs 1 and 2 define the source (starting) point, and the tags with IDs 3 and 4 define the destination, respectively. Note that the tag coordinates in the world coordinate system are not necessarily known. The robot computes its position with respect to the desired path by extracting and decoding the frames backscattered by fours tags defining the path. The RSS values are then used to model the relative position which is defined by

$$\Delta RSS = (RSS_1 + RSS_3) - (RSS_2 + RSS_4) \ , \qquad (1)$$

where the RSS_i with $1 \leq i \leq 4$ represents the average RSS value associated with tag i. The RSS samples received from each tag are passed to an M-point moving average filter for better estimation. The filter is modeled as

$$RSS_i = \frac{1}{M} \sum_{j=1}^{M} RSS_{ji} \quad \forall i \in S \ , \qquad (2)$$

where RSS_{ji} is the j^{th} RSS value at tag i. The significance of ΔRSS is the amount of robot's divergence from its desired path. Ideally, ΔRSS is closest to nil when the robot is on the right track. It diverges from zero as the robot moves drifts away from its path. The sign of ΔRSS then depends on the side of the path the robot is located.



(a)

(b)

Figure 3: RFID system (a) RF module used to emulate an RFID tag[4] and (b) Make controller board used to emulate an RFID reader[2].

4 RFID SYSTEM IMPLEMENTATION

The proposed RFID system is emulated using the XBee Pro Modules[1] shown in Figure 3(a) as an integrated RF solution. The modules include MC13193 RF chip by freescale, which is compliant to the IEEE 802.15.4 norm (Graefenstein and Bouzouraa, 2008). One of the XBee Pro modules is attached to the Make Controller (MC) board[2] (figure 3(b)) to emulate a commercial RFID reader. The MC board secures the communication between the emulated RFID reader and the robot.

In order to obtain an RSS value from a tag i, $1 \leq i \leq 4$, the reader broadcasts a message with its own static address. The tags are simply configured to reply to the reader's query with their individual binary frames. As mentioned above, each tag's frame consists of its 16-bit static address and 8-bit RSS value.

[1] http://www.digi.com/products/wireless/point-multipoint/xbee-pro-series1-module.jsp, http://www.digi.com

[2] http://www.makingthings.com/, http://www.makingthings.com

The reader simply extracts and decodes the frames in order to get the tag's ID and the corresponding RSS value and then passes them along to the mobile robot for further processing.

5 EXPERIMENTAL RESULTS

The purpose of this section is to provide details on the experimental evaluation of the proposed relative positioning system using the emulated customized RFID tag architecture. The performance is evaluated using real data in a research laboratory that reflects a typical indoor operating environment.

The experiments of the proposed RFID-based RPS were carried out at discrete points distributed over approximately $3 \times 6 \times 2$ m test area of a research laboratory with four tags attached on four different posts (≈ 2 m high). The test area is divided into uniform square grids of 30×30 cm^2. The layout of the test environment is depicted in Figure 4. The orthogonal projection points of the four tags on the ground are what we call herein S1 and S2 for source, and D1 and D2 for destination. The desired trajectory is the line linking the midpoints of the lines connecting S1 and S2, and D1 and D2, respectively.

To test the proposed RPS concept, ΔRSS is computed at 30 different locations: 10 on the desired robot trajectory (shaded area in figure 4), 10 on its left, and 10 on its right. The results are revealed in Table 1. Each RSS value (in dB) is the output of an 8-point moving average filter as defined in (2). It can be seen from Table 1 that the data corresponding to the left of the path is globally larger than zero, which confirms that the robot is indeed out of its desired trajectory. However, the same conclusion cannot be generalized on the data collected on the right of the path since it is generally close to that collected on the path. This may be due to several reasons. The side test locations are only 0.6 m off the path, which is an insignificant distance compared to the height of the emulated RFID tags (2 m). In other words, the distance between S1 and robot location 5, for instance, is not significantly different from that between S1 and location 5R. This is a main source of ambiguity which contributes to this lack of precision. We believe that ΔRSS would be more distinguishable across the three regions if the side locations were at least 3 m off the path. This threshold highly depends on the RF signal attenuation with the distance traveled. It is also important to investigate better noise filtering techniques to filter the severe noise experienced at the testing scene. The lab at which the experiments were conducted contain an abundance of metal cabinets and obstacles of various materials. Such a choice was made on purpose to test worst condition scenarios.

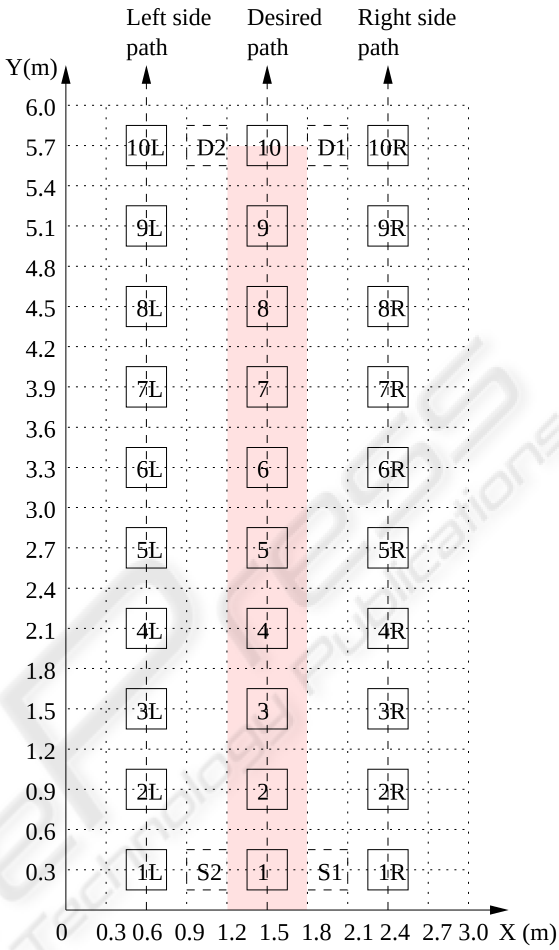


Figure 4: Experimental setup of the proposed navigation system.

6 CONCLUSIONS

The rising prominence of location estimation in many real-world applications necessitates the development of an appropriate positioning system in an indoor environment. Due to the ubiquity of such localization systems, the proposed RFID-based localization system provides a suitable and a cost-effective solution for devising such systems. In this paper, we have examined the problem of relative positioning system using RSS measurements of a modified RFID tag architecture and have proposed a novel guidance principle for a mobile robot to navigate in an indoor environment based on the strength of the RF signal transmitted by the RFID reader. As the first contribution of the

Table 1: Performance of the relative positioning system.

Position	S1	S2	D1	D2	ΔRSS
1L	41	41	58	53	5
2L	44	44	58	54	4
3L	47	46	59	54	6
4L	50	45	55	54	6
5L	50	48	50	50	2
6L	51	52	49	46	2
7L	53	57	53	40	9
8L	53	58	50	41	4
9L	54	55	48	42	5
10L	63	60	43	38	8
Average					**5.1**
Std. Dev.					**2.3**
1	28	36	53	56	-11
2	42	38	54	57	1
3	44	45	50	50	-1
4	47	46	54	56	-1
5	50	46	52	54	2
6	51	52	49	49	-1
7	52	54	49	42	5
8	55	53	41	49	-6
9	57	56	38	44	-5
10	57	61	39	36	-1
Average					**-1.8**
Std. Dev.					**4.5**
1R	37	42	62	57	0
2R	45	43	58	54	6
3R	43	47	56	51	1
4R	55	47	58	53	13
5R	54	51	49	49	3
6R	54	54	52	50	2
7R	56	57	49	48	0
8R	55	54	44	47	-2
9R	53	53	39	45	-6
10R	57	59	37	42	-7
Average					**1.0**
Std. Dev.					**5.8**

current work, spatial relative positioning is proposed to address the variability of tags' RSS patterns over the workspace. The proposed method was evaluated using real data from a typical office environment. Although the preliminary results reported in the present manuscript reveal what might be a promising indoor RPS method, more effort needs to be done to bring the proposed technique to a more mature stage.

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