An RFID-Based Robot Navigation System with a Customized RFID Tag Architecture

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***Abstract*—A major component of a mobile robot system is the ability to navigate accurately in unknown environments with little or no human intervention. In this paper, we present a modular and cost-effective navigation technique incorporating signals from RFID tags, an RFID reader, and a fuzzy logic controller (FLC). The RFID tags are placed at 3-dimensional positions in the robot's workspace in such a way that the lines linking their projection points on the ground define "free-ways" along which the robot is desired to navigate. The RFID reader is mounted on the mobile robot to communicate with the RFID tags to determine the robot's position. The FLC is then applied to guide the robot along a pre-defined trajectory in an unknown working environment. For this purpose, we introduce two minor changes to the RFID tag architecture while keeping that of the RFID reader unchanged. A simplistic circuit and a primitive microcontroller are added to the RFID tag to compute the signal's power received by the tag and encode it within the tag ID, respectively. This way, virtually any commercially available RFID reader can be used without the need for any special customization. The performance of the proposed navigation scheme is evaluated through several numerical simulations.**

I. INTRODUCTION

Navigation is a very important and challenging issue for mobile robots. It has received a considerable amount of attention to the numerous researchers in the past few years. In spite of large body of research works and significance advances in this field, researchers are yet to reach comfortable level of satisfaction. Most of the navigation algorithms proposed in the literature to date are either tailored towards particular structured environment or driven by overwhelming degree of computational complexity [1]. In some cases, hardware needed to implement the navigation algorithms is more costly than the robot itself. This makes the practical realization of such algorithms in most real-life robotic systems questionable.

The most common and popular navigation techniques suggested in the state of the art generally fall under one of the following categories: dead-reckoning-based, landmark-based, vision-based, and behavior-based techniques. Each navigation technique has its own advantages and disadvantages. Dead-reckoning navigation system provides position, heading, linear, and angular velocity of an autonomous mobile robot and it is widely used due to its simplicity and easy maintenance. The fundamental idea behind this navigation technique is the integration of the incremental motion over time [2]. The shortcomings of the dead-reckoning navigation system is that small precision errors and sensor drifts inevitably lead to increasing cumulative errors in the robot's position and orientation, unless an independent reference is used periodically to correct the error [3]. To overcome these shortcomings, researchers shifted their attention to landmark-based mobile robot navigation system. In recent years, a significant research body has been conducted on robotics that incorporate several sensors and landmarks as navigation media in the operating environment [4]. However, landmark-based navigation strategies rely on the identification and subsequent recognition of distinct features or objects in the environment that may be a priori known or extracted dynamically. However, due to the noise in sensors and possible change in the environment, the recognition process of features or objects might be difficult. To resolve these issues, some researchers investigated vision-based navigation systems [5] where a mobile robot uses visual features to guide itself in the environment. Such techniques also revealed some disadvantages, which include the lack of information depth, complex image processing algorithms with high computational burden, and the dependence on the working environment.

Another research avenue was to opt for behavior-based navigation systems. This type of paradigms were credited to be suitable for unstructured environments as they can incorporate a large number of sensors. They can also be accompanied with tools of computation intelligence, such as fuzzy logic, neural networks, genetic algorithms, and several combinations of them. Nevertheless, behavior-based navigation techniques also require a high computational power and in some cases they lead to significant cumulative errors due to the inevitable noise associated to the sensor measurements. To overcome some of the demerits of the aforementioned techniques, integrating RFID systems emerged lately as a promising alternative navigation method. In some studies, RFID tags are placed in predefined locations in the workspace and the robot is pre-equipped with an RFID reader to communicate with the tags during its navigation in the environment. However, all RFID-based mobile robot navigation methods suggested in the literature to date are based on binary proximity signals to decide on whether the robot is within a certain proximity from a pre-defined location on the floor. As such, these methods are tailored more towards coarse robot localization rather than navigation.

In the current manuscript we describe a novel navigation technique in which customized RFID tags are mounted in fixed locations in the 3-dimensional space. The tags are used to define the desired trajectory of the robot. The aim of the navigation algorithm is then to make the robot navigate along the virtual lines on the ground linking the orthogonal projection points of the tags on the ground. Unlike other studies of this kind reported in the literature, there is no restriction on where the tags should be mounted. For indoor applications, they can be mounted on the ceiling, whereas in outdoors they can be mounted on posts, for example. The reader mounted on the mobile robot transmits a radio frequency signal while moving in its workspace. The tag receives the signal and computes its received power. This power received by the tag is then encoded in its ID to generate a dynamic 40-bit frame, which is sent back to the reader. The robot maintains a predefined list of tag IDs and their corresponding coordinates in the world coordinate system. This list is used by the robot's processor along with the 40-bit frames received by at least three of the RFID tags within reach to estimate the robot's position. This enables the robot to calculate its orientation with respect to its destination. This angle is then fed to an FLC to decide on its direction tuneup to enhance its convergence towards the desired target. Once the robot reaches the first target, it follows the same procedure to reach the subsequent targets in the desired path. To the best of our knowledge, except the work of Gueaieb and Miah [6], all the RFID-based techniques proposed in the literature to date navigation are used in a localization context, and cannot be directly applied to navigation. It is worth mentioning that the work presented herein is the first attempt to use RFID technology as a means of navigation. Its is also the first milestone of a larger project to provide a fully-fledged practical non-vision-based robot navigation and unmanned-vehicle transportation solution.

The rest of the paper is organized as follows: a brief literature review of robot navigation systems is provided in section II. Section III offers an overview of the proposed RFID-based navigation system. In section IV, we describe how the navigation system is controlled through an FLC. A thorough evaluation of the proposed technique is provided in section V. Eventually, the paper is concluded in section VI with some concluding remarks and a few possible research avenues to extend the current work.

II. Related Works

RFID technology has become a promising alternative to several existing techniques of mobile robot navigation. Khubitz et al. presented a navigation system that uses RFID tags as artificial landmarks [7]. The tags' global position, environment class, environment position, and further optional data, are pre-stored in the tags' memory. The system also employs a behavior-based control architecture which enables the robot to reach any landmark within its working environment through a topological robot positioning approach. The behavior-based control architecture is specially designed to be able to integrate several positioning sensors with different accuracies and error categories while enabling the robot to navigate. A new navigation system in man-made environments, such as hallways, was developed in [8], where RFID tags are used as artificial landmarks and the mobile robot is equipped with an on-board laptop computer, an RFID tag sensor and a vision system. The RFID reader is mounted on the robot itself while the tags are pasted at particular locations on walls. At the junction of two passages, the RFID tag sensor reads the unique tag identification numbers and infers the necessary actions (turn left, right, or remain straight) to reach the desired positions. In [9], the authors developed an indoor location sensing prototype system which can be used for various mobile commerce applications. This suggested prototype system uses RFID technology for locating objects inside buildings. In 2005, another technique was proposed by Tsukiyama [10], where the robot tries to build a topological map of its surrounding environment to be used in path planning and navigation. Each node in the topological map is the intersection point of two passages. At these points, the robot has to decide on the next action according to a plan stored in the robot's memory to reach the target position. The robot then follows certain paths using an ultrasonic range finder until a tag is found. However, such a methodology is specific to a particular workspace and requires a substantial amount of customization for it to operate in a new environment. Chae et al. proposed a mobile robot localization method with the help of a combination of RFID and vision technologies [11]. The global localization of the robot is performed by incorporating signal detection from artificial landmarks represented by the RFID tags. The tags are assigned different weights which are determined by the RFID reader mounted on the robot. The algorithm takes advantage of a vision system incorporating a feature descriptor derived from a scene view of the robot environment, which provides the fine position and orientation of the robot. Although this algorithm offers an efficient localization method, it naturally inherits the typical shortcomings of vision-based techniques in general.

Some researchers proposed different mobile robot navigation techniques using the tools of computational intelligence like fuzzy logic, neural networks, genetic algorithms, or several combinations of them. For example, a genetic algorithm was used in [12] to design a mobile robot navigation framework. However, among the main drawbacks of this strategy, and of genetic-algorithm based approaches in general, is that it is non-deterministic and hence cannot operate in real-time. Fuzzy logic controllers were also tested in [13], [14] [15] for the navigation of single and multiple mobile robots, respectively, with the ability to avoid collision in a dynamic environment.

III. RFID-Based Navigation

Radio Frequency IDentification (RFID) is an automatic identification method that relies on storing and remotely retrieving data using data-carrying devices called RFID tags, or transponders. The radio frequency (RF) transceiver on the reader illuminates a short pulse of electromagnetic waves. The transponder receives the RF transmission, rectifies the received signal to obtain a DC power, known as the tag received power (TRP), to energize its IC memory.

A. RFID Tag Customization

To accommodate the requirements of the proposed navigation method, a few changes are introduced on the architecture of the conventional RFID tags. In here, we are equipping the transponder with a simple analog circuit and a primitive micro-controller to measure and convert the received power (in DB) into a 32 bit information as depicted in Fig. 1. The 40-bit frame is stored in the transponder's memory and is composed of two parts: (i) a static 8-bit field holding a unique tag ID identifying that particular tag, and (ii) a dynamic 32-bit field encoding the continuously measured TRP. The 8-bit tag ID enables the environment to have 256 distinct transponders in the robot's workspace. The 32-bit is organized into a 1-sign bit, 15-bit integer part, and 16-bit fraction part. The transponder modulates the 40-bit frame and backscatters it in response to the interrogation of the RFID reader. The signal generated by the transponder is then received by the reader to extract the frame. In the current research we are particularly interested in determining the robot's position and orientation based on the distance between the transponder and the reader mounted on the robot. This distance is inversely proportional to the TRP encoded in the 40-bit frame broadcasted by the transponder. Details of how to calculate the robot position and orientation are given in the next sections.

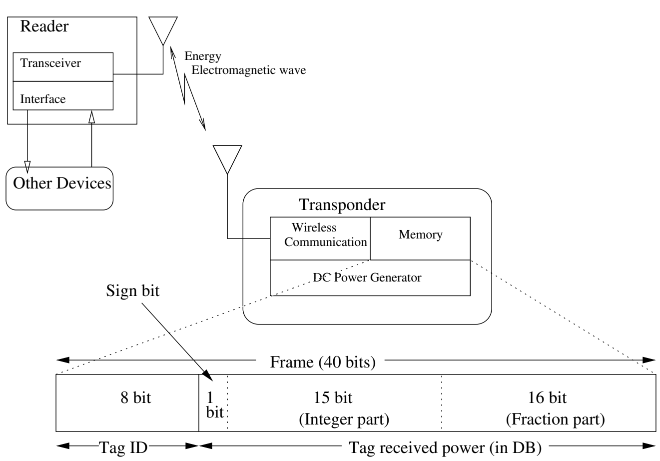


Fig. 1. Customized RFID system's architecture

B. Localization using RFID

In order to define its position, the robot maintains a list of tags and their predefined positions in space in its local memory (see Table I). The table consists of all the tag IDs along which the robot is desired to move. The robot continuously extracts and decodes the frames from at least three tags, say T_1, T_2, and T_3, to calculate its relative position with respect to the tags based on their a priori known locations in space and the TRP values embedded in their respective frames. This trilateration method is illustrated in Fig. 2.

TABLE I
TRANSPONDERS LIST STORED IN THE ROBOT'S MEMORY

Tag	Tag position
1	(x_1, y_1, z_1)
2	(x_2, y_2, z_2)
3	(x_3, y_3, z_3)
4	(x_4, y_4, z_4)
$\vdots$	$\vdots$

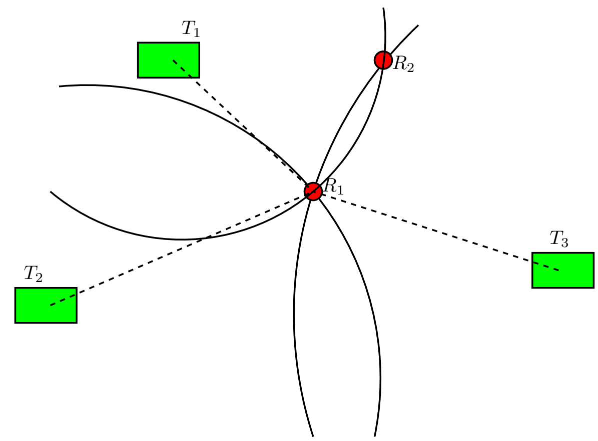


Fig. 2. Trilateration-based robot positioning system

The TRP is defined as follows [16]:

$$\text{TRP} = P_t G_{TX} G_{Tag} \left(\frac{\lambda}{4\pi r_0}\right)^2, \tag{1}$$

where P_t is the transmitted power by the RFID reader, G_{TX} and G_{Tag} are the antenna gains of the reader and the tag, respectively, λ is the wavelength, and r_0 is the Euclidean distance between the reader and the tag. In a real-world situation, however, the RF signal can be contaminated by noise due to the signal reverberations off various obstacles, such as walls, floor, and furniture, for instance. Therefore, a more realistic expression of (1) can be formulated as:

$$\text{TRP} = P_t \left(\frac{\lambda}{4\pi}\right)^2 \times$$
$$\left| G_0^{1/2} \frac{1}{r_0} exp(-jkr_0) + G_i \sum_{i=1}^{n} \Gamma(\alpha_i) \frac{1}{r_i} exp(-jkr_i) \right|^2, \tag{2}$$

where G_0 is the antenna gain in the direct path, G_i is the antenna gain along the direction of the ith ray, r_i is the distance between the reader and the tag along the ith ray, $\Gamma(\alpha_i)$ is the reflection coefficient associated to ray i, and n is the number of reverberated signals.

The robot's direction, ϕ_1, can be estimated using its two most recent position approximations. The robot's desired direction, ϕ_2, is calculated using the predetermined location of the target RFID tag. Hence, the angle ϕ by which the robot has to rotate to converge to its destination is determined by:

$$\phi = \phi_1 - \phi_2. \tag{3}$$

This is schematically depicted in Fig. 3. It would be easy to make the robot rotate by an angle ϕ if a compass, or at least a gyroscope, was used. However, in this manuscript, none of such sensors is assumed to be used. As such, and to make the robot converge to its target tag, an FLC is used with ϕ being its unique input. This controller is detailed in the following section.

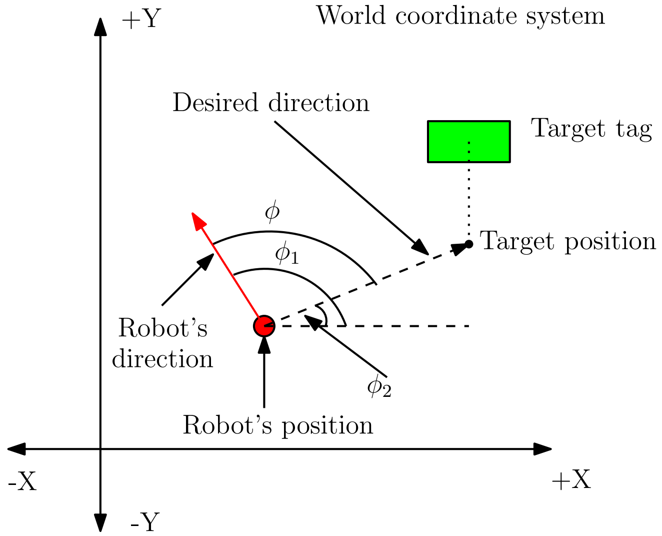


Fig. 3. Determining the robot's direction

IV. Fuzzy Logic Controller for Navigation

In here, a Mamdani-type FLC is used to calculate the tuneup angle $\Delta\theta$ (FLC's output) that the robot has to apply to its current direction ϕ_1 to converge to its target. The robot then uses the update rule (4) to update its direction.

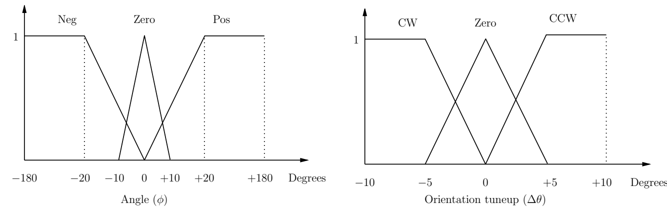
$$\phi_1^{(\text{new})} = \phi_1^{(\text{old})} + \Delta\theta. \tag{4}$$

The FLC takes the angle ϕ (defined in (3)) as its unique input.

The FLC's input and output membership functions are taken as linear triangular and trapezoidal membership functions for their higher computational efficiency [17], as shown in Fig. 4(a) and 4(b), respectively. The membership labels **Neg**, **Zero** and **Pos** are the linguistic terms used for the input variable ϕ. The terms **CW** (Clock Wise), **Zero** and **CCW** (Counter Clock Wise) are the fuzzy labels opted for the output variable $\Delta\theta$. Three fuzzy rules are set to reflect the fact that the angle ϕ is positive when the transmitting transponder in on the left side of the RFID reader and vice versa [6]. These rules are defined as follows:

If ϕ is *Neg* **Then** $\Delta\theta$ is *CCW*
If ϕ is *Zero* **Then** $\Delta\theta$ is *Zero*
If ϕ is *Pos* **Then** $\Delta\theta$ is *CW*

The rationale behind these rules is that the robot is supposed to turn left/right (CCW/CW) if the RFID tag is on the left/right of the reader, where ϕ is negative and positive, respectively.



(a) (b)

Fig. 4. (a) Input; and (b) Output membership functions.

V. Experimental Results

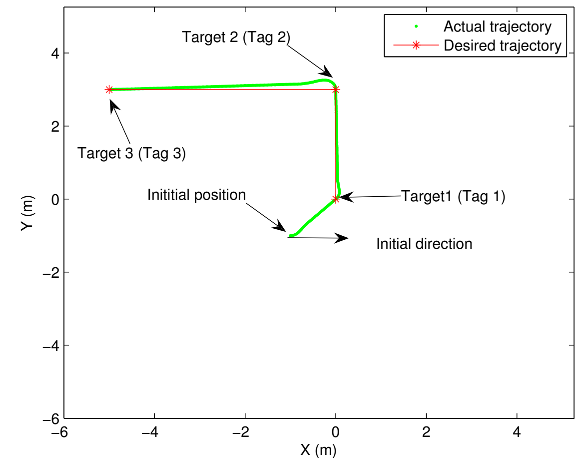
To evaluate the performance of the proposed navigation algorithm, two experiments are conducted under different tags and robot configurations. The simulations are carried out using the 3-D simulation platform Simbad [18]. The robot's workspace is taken as a research lab where RFID tags are attached on a 2 m height ceiling. It is worth pointing out that the height of the tags from the ground is not that relevant as long as they are within the RFID reader's communication range.

A. Experiment 1

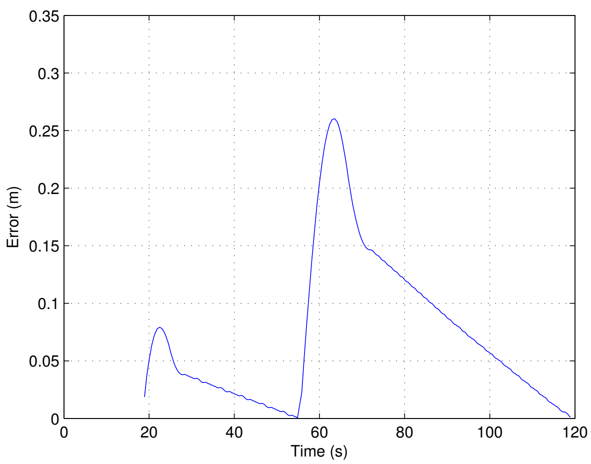
In the first experiment the mobile robot is placed at an initial 3-D position of $(x, y, z) = (-1, -1, 0)$ and an initial orientation of zero degree on the trigonometric circle, as illustrated in Fig. 5. The desired trajectory is defined as Tag1–Tag2–Tag3, where the tags are placed at $(0, 0, 2)$, $(0, 2, 2)$, and $(-4, 3, 2)$ m, respectively. No reverberations were taken into account in this experiment and the Euclidean distance r_0 between each tag and the RFID receiver mounted on the robot was directly derived from (1). The result of this experiment is presented in Fig. 5. At a first stage, the robot has to find its way to its first target, Tag1. It took it about 20 sec. to do that (that's where the plot in Fig. 5(b) starts). Once Tag1 is reached, it can be clearly seen that it had no trouble to navigate to Tag2 and from there to Tag3. Fig. 5(b) plots the robot's error in tracking its desired trajectory. This error is defined as the closest distance between the robot and its desired path, where the sign of the error indicates whether the robot is on the left or right hand side of that path. Fig. 5(b) reveals that the robot reached Tag2 at a time $t \approx 55$ sec. Then the tracking error drastically increased as it took the robot about 10 sec. to detect that it passed Tag2 and that it should pass to the next stage where it should be heading towards Tag3. However, right after that it quickly converged to its desired trajectory and finally stopped at the final destination Tag3.

B. Experiment 2

The purpose of this experiment is to study the ability of the proposed navigation scheme to sustain the noise in the RF communication channels, and to illustrate its fault tolerance characteristic. For this, four tags were located at $(0, 0, 2)$, $(0, 3, 2)$, $(-4, 3, 2)$, and $(4.5, 2, 2)$ m. The robot was set to have an initial position of $(-0.5, -0.5, 0)$ m and an initial orientation of 270 degrees, as illustrated in Fig. 8(a).



(a)



(b)

Fig. 5. Algorithm's performance in experiment 1: (a) desired vs. robot's trajectory; (b) tracking error.

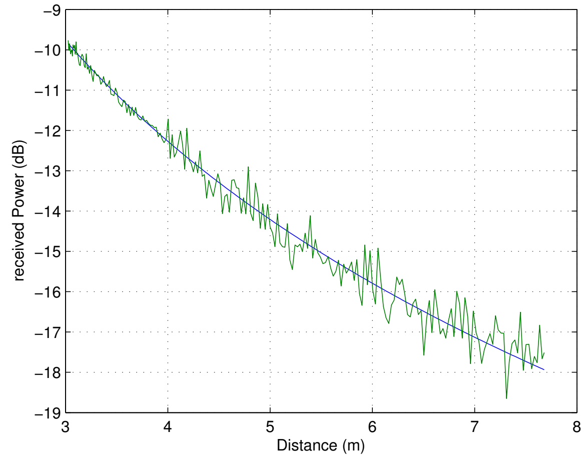


Fig. 6. Ideal vs. noisy RF signal

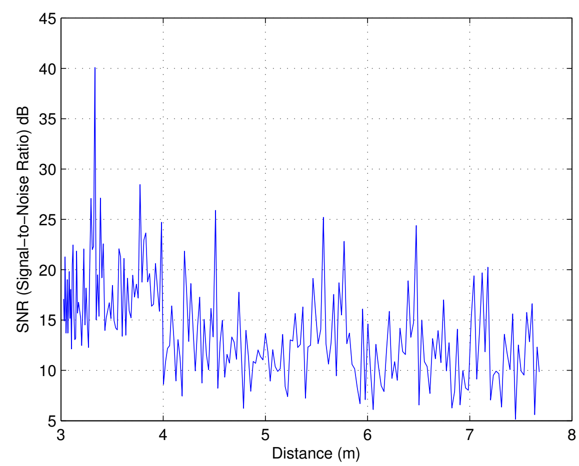
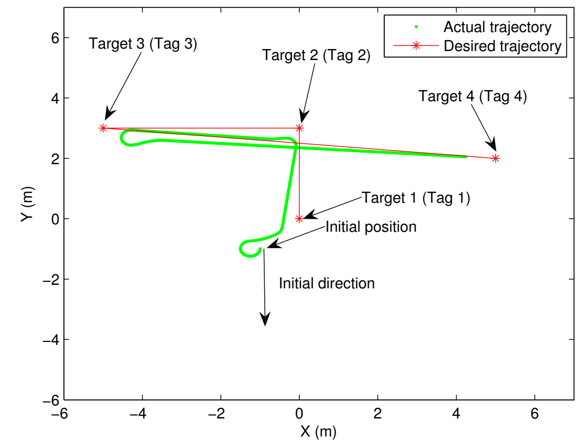


Fig. 7. Signal-to-noise ratio of the RF signal

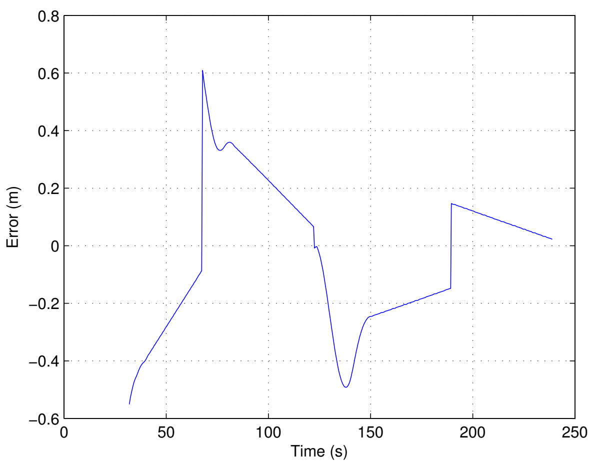
The desired trajectory was pre-programmed in the robot's memory as Tag1–Tag2–Tag3–Tag4. To make this experiment as realistic as possible in reflecting real-world systems, a noisy RF signal was considered to approximate the TRP as modeled in (2). An ideal vs. noisy RF signal plot is given in Fig. 6. The signal-to-noise ratio adopted in this experiment is shown in Fig. 7. A 1 sec. time averaging window was applied to filter the noisy TRPs read by the RFID reader. Like in experiment 1, the robot starts by searching its first destination, i.e., orthogonal projection point of Tag1 on the ground. It took the robot about 30 sec. to get within 0.55 m from this target. Then, the robot heads toward the next target marked by Tag2. As shown in Figs. 8(a) and 8(b), the robot's tracking error in this phase is deemed down from -55 cm to -10 cm in about 30 sec. Once the robot is approximately under Tag2, the next phase begins in which the Tag3 becomes the robot destination. Just like in the previous phases, the robot gets closer to its desired trajectory as it proceeds further towards its destination. To evaluate the method's fault-tolerance capability, Tag1 is turned off during this phase. In such a case, the trilateration is accomplished using the TRPs broadcasted by Tag2, Tag3, and Tag4. As can be seen from Fig. 8(b), this communication failure with Tag1 had little effect on the robot's tracking error for the rest of the experiment. Comparing experiment 1 and 2, we can observe that the RF noise did have an effect on the robot's tracking precision but this effect is insignificant as the tracking error is still within an acceptable region.

VI. Conclusion

In this paper, we have presented a novel mobile robot navigation technique using a customized RFID tag architecture. The transponder ID is integrated with the received power (TRP) of the signal sent by the RFID reader, which is then backscattered to the reader as a digital 40-bit frame, just like a regular conventional tag ID. The robot extracts the TRPs from the frames to compute the Euclidean distance between the robot and their respective transponders. At least three



(a)



(b)

Fig. 8. Algorithm's performance in experiment 2: (a) desired vs. robot's trajectory; (b) tracking error.

transponders are required to be within the robot's communication range to compute its position at any given time instant. The proposed navigation method is easy to implement, cost-effective, and modular as it is independent of the robot's working environment. It was also shown that it is fault tolerant and quite robust in the face of the RF noise due to signal reverberations. Having said that, it is important to articulate the fact that this technique is not meant to substitute vision-based navigation algorithms. Rather, it might be regarded as an alternative navigation solution for many robotic applications where vision might not be necessary. It is also worth mentioning here that although the method presented in this article was applied to mobile robot navigation, it can be easily extended to other applications as well, such as unmanned vehicle transportation for instance. A potential future research avenue to extend this work would be to append the algorithm with a real-time path planning module with dynamic obstacle avoidance mechanism.

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