A Modular Cost-Effective Mobile Robot Navigation System Using RFID Technology

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***Abstract*— Skilled navigation in mobile robotics usually requires solving two problems pertaining to the knowledge of the position of the robot, and to a motion control strategy. When no prior knowledge of the environment is available, the problem becomes even more challenging, since the robot has to build a map of its surroundings as it moves. These three tasks ought to be solved in conjunction due to their interdependency. The present manuscript proposes a novel mobile robot navigation technique using a customized RFID reader with two receiving antennas mounted on the robot and a number of standard RFID tags attached in the robot's environment to define its path. In here, we show that using the RF signal from the RFID tags as an analog feedback signals can be a promising strategy to navigate a mobile robot within an unknown or uncertain indoor environment. This method is computationally simpler and more cost-effective than many of its counterparts in the state of the art. It is also modular and easy to implement since it is independent of the robot's architecture and its workspace. A set of numerical computer simulations are provided to illustrate the effectiveness of the proposed scheme.**

***Index Terms*— RFID, Phase Difference, Fuzzy Logic Controller, Robot Sensing and Perception.**

I. INTRODUCTION

Navigation is one of the main modules in a mobile robotic system. A large body of research works has been conducted in the field of mobile robot navigation. The most common and popular navigation methods proposed in the literature to date rely on dead-reckoning-based, landmark-based, vision-based, and behavior-based techniques. Among the common problems pertaining to these techniques is that they depend on complex image processing algorithms, expensive hardware, and/or a priori knowledge of the environment.

The fundamental idea behind dead-reckoning navigation systems is the integration of incremental motion over time [2]. In this navigation method a 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]. The studies in [4], [5] are developed based on the integration of dead-reckoning and visual landmark recognition methodologies for the navigation control of a vehicle along a predetermined path in a forest. The indoor mobile robot navigation presented in [6] uses global ultrasonic system for the robot's position estimation while navigating in an environment.

Hallmann et al. [7] developed a mobile robot B14 to navigate in a partially known environment. The vehicle is equipped with 16 sonar, 16 infrared sensors, an on-board Pentium computer, and a gray-scale camera in which a map of the robot's environment is built based on the information fed by the sonar and infrared sensors mounted on the robot. In addition to artificial landmarks, natural landmarks have also been exploited in a number of robot navigation algorithms. For instance, Betge-Brezetz et al. [8] focused on the high level representation of the natural scene to guide a mobile robot in a priori unknown environment. The landmarks in this case are defined as natural objects extracted from perceptual data. A similar algorithm for natural landmark extraction from sonar data streamed from a mobile platform is developed in [9]. In there, the robot has to have complex image processing and pattern recognition algorithms to locate itself in its workspace. Some researchers shifted their attention to other types of vision-based navigation methods to improve the robot position estimation by tracing the visual features in the environment and using them as landmarks [10]. This measurement usually returns bearing to the visual features only, with no a priori knowledge of the landmark positions. Nevertheless, such a technique also has its own disadvantages, which include the lack of information depth, complex image processing algorithms with high computational burden, and its dependence on the working environment. A number of the aforementioned paradigms were accompanied with tools of computational intelligence, such as fuzzy logic, artificial neural networks, genetic algorithms, and several combinations of them. For example, a genetic algorithm was used in [11] 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 [12], [13] for the navigation of single and multiple mobile robots, respectively, with the ability to avoid collision in a dynamic environment.

Recent attempts in the area of mobile robot navigation have witnessed an increasing interest in the emerging

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RFID technology as a promising alternative to the aforementioned strategies, thanks to its ease of use, flexibility, and low cost. RFID tags were used as artificial landmarks placed in particular locations in the workspace to communicate with robots equipped with RFID readers to estimate their positions in environment. Khubitz et al. [14] presented a navigation system that uses RFID tags as artificial landmarks. The tags' global positions, environment class, environment position, and further optional data, are pre-stored in the tags' memory. Some navigation systems in man-made environments, such as hallways, were developed in [15], [16], where RFID tags are used as artificial landmarks for a mobile robot that 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. 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. [17] proposed a mobile robot localization method with the help of a combination of RFID and vision technologies. The global localization of the robot is performed by incorporating signal detection from artificial landmarks represented by the RFID tags. Although this algorithm offers an efficient localization method, it naturally inherits the typical shortcomings of vision-based techniques in general. So, In most cases where RFID systems were applied to mobile robot systems, they were mainly used for robot localization and not for navigation [18].

The current manuscript describes a novel navigation technique that uses a customized two-antenna RFID reader mounted on the robot and a number of tags attached in the robot's workspace. 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 paths linking the orthogonal projection points of the tags on the ground. The reader continuously sends RF signals to the tags in its operating region and receives some analog information represented in the "phase difference" of the received signal. This analog signal is used to determine the relative position of the robot with respect to the tags. The phase difference is then passed to the fuzzy logic controller to provide necessary control actions to the actuators of the mobile robot. It is important to note, however, that due to the excessive noise characterizing RF signals in general, the computer simulations are based on a noisy model of the RF signal received by the reader. Unlike many previous 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 or walls, for example. It is worth pointing out that a mobile robotic system is typically composed of various modules, such as a localization module, navigation module, path planner, obstacle detection module, etc. (Fig. 1). Nevertheless, the present paper tackles the problems of robot localization and navigation only.

The rest of the manuscript is organized as follows: Section II illustrates the overall architecture of our proposed navigation system. The different steps of the navigation algorithm are described in section III. The performance of the proposed algorithm is demonstrated through a series of numerical simulations presented in section IV. Finally, conclusions are drawn in section V.

II. System Architecture

The proposed navigation system consists of two fundamental modules: an RFID communication module and a Fuzzy Logic Controller (FLC) navigation module. The RFID communication module is responsible for communicating with the tags (or transponders) through an RFID reader with two receiving antennas mounted on the robot. A high level system configuration setup of the current navigation technique is depicted in Fig. 2, where two RFID tags, T_1 and T_2, are attached on the ceiling. The robot's desired trajectory is the straight-line segment connecting the orthogonal projection points, A and B, of tags T_1 and T_2, respectively. The robot employs the FLC module in order to provide the necessary control action to its actuators, which is required to move the robot from one point to another in its workspace. Consider a scenario where the robot is presented with a desired trajectory defined by an ordered sequence of tag IDs, like $(00, 01)$, for instance, then it first navigates to the orthogonal projection point of the tag with ID 00, then it moves along the virtual straight line linking the orthogonal projection points of tag IDs 00 and 01, where it will stop. The novelty in this navigation scheme is that it is independent of the tag positions, odometry information, and structure of the working environment.

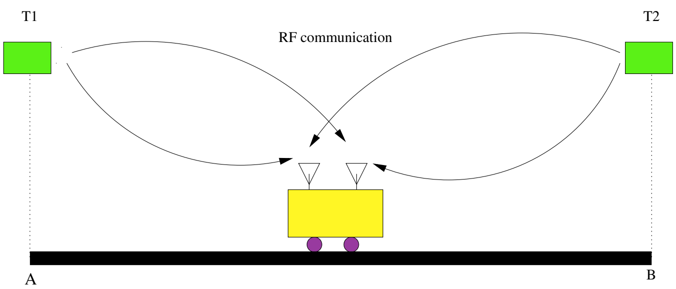

Figure 2. High-level system configuration with two RFID tags.

A. RFID Communication Module

Before starting the mission, the robot sends time-multiplexed single-tone sinusoidal signals with different frequencies, and then listens to the backscattered signals from the RFID tags. The high level architecture of the custom-designed RFID communication module is depicted in Fig. 3. Preliminary studies were conducted to confirm the fact that using a custom-built RFID reader with two receiving antennas can determine the relative position of the tag (left or right) with respect to the reader

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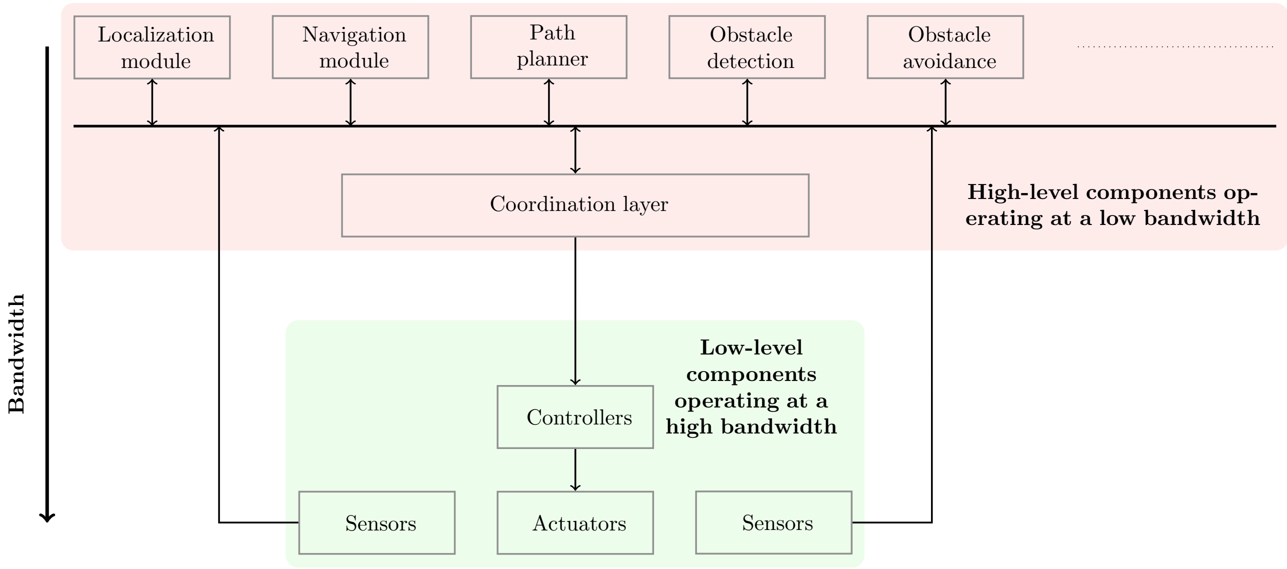

Figure 1. Different modules of mobile robotic systems.

mounted on the robot. Let ϕ_1 and ϕ_2 be the phase angles of the signal received by the reader's receiving antennas 1 and 2, respectively. The phase difference, $\Delta\phi$, is then defined by

$$\Delta\phi = \phi_1 - \phi_2. \tag{1}$$

This phase difference is then passed to the FLC in order to decide on the robot's direction.

B. Fuzzy Logic Controller

The purpose of the FLC in the current navigation algorithm is to provide intelligent actions to be taken by the robot. In the current work, we use a single-input single-output Mamdani-type FLC as shown in Fig. 4. The aim of the FLC is to decide on the amount of tuneup $\Delta\theta$ that the robot has to apply to its current direction θ to converge to its target position. The FLC's input is the phase difference $\Delta\phi$ provided by the two directional antennas mounted to the RFID reader on the robot. The robot then uses this information to update its direction following the update rule (2).

$$\theta^{(\text{new})} = \theta^{(\text{old})} + \Delta\theta \tag{2}$$

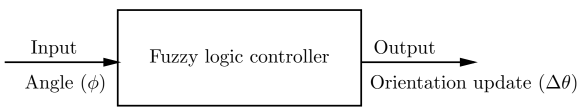

Figure 4. FLC model used by the mobile robot.

The fuzzification and defuzzification membership functions are taken as linear triangular and trapezoidal membership functions for their higher computational efficiency [19], as depicted in Fig. 5. An empirical analysis was performed to optimize these membership function parameters to improve the FLC's performance. The "min" and "max" operators are adopted as the t-norm and s-norm operators, while the defuzzification method is set to be the center of area.

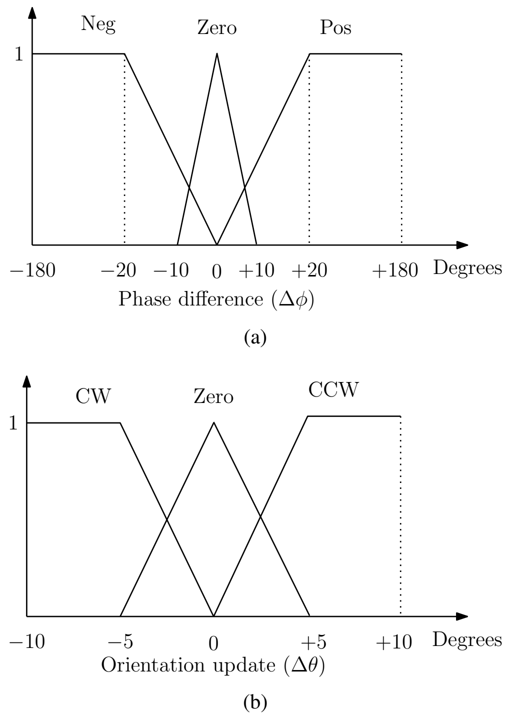

Figure 5. FLC's membership functions. (a) input; and (b) output membership functions.

Three fuzzy rules are defined to reflect the fact that the phase difference of the signal is positive when the transmitting transponder is on the left side of the receiving antenna and vice versa. These rules are:

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

The rationale behind these rules is that the robot is

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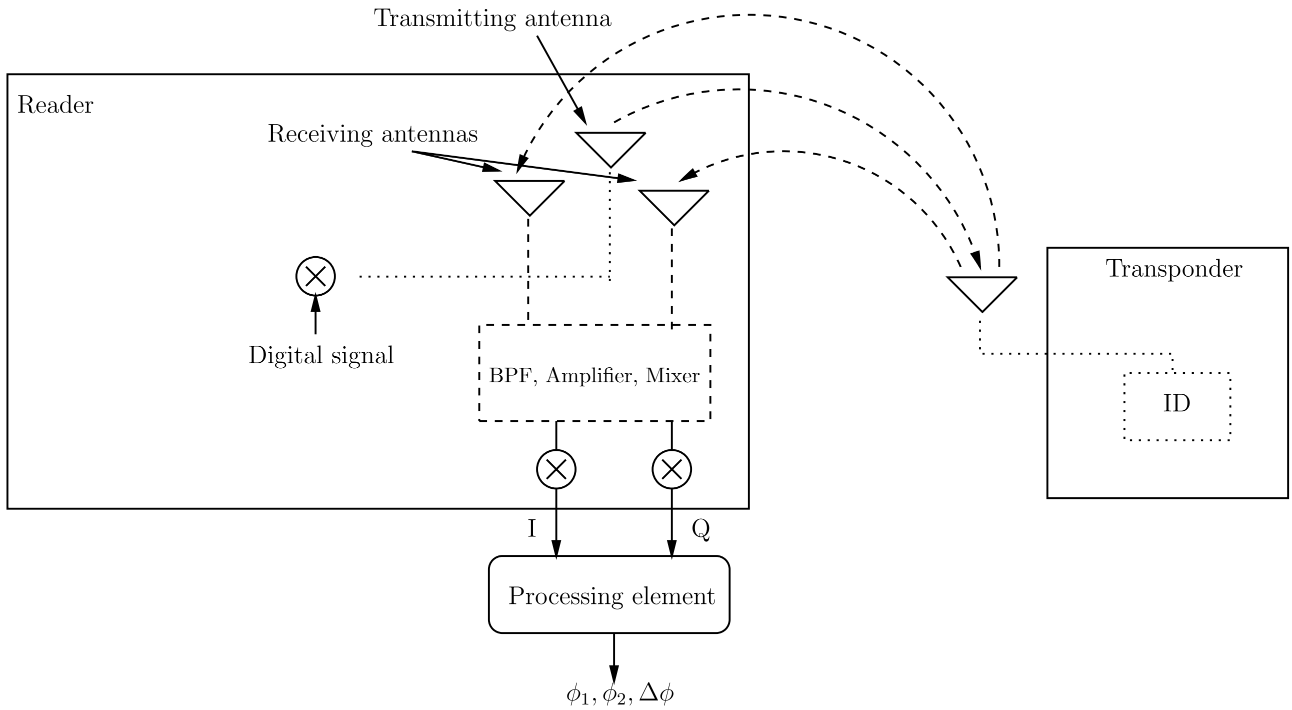

Figure 3. RFID system setup to compute the phase difference.

supposed to turn left/right (CCW/CW, for counter-clock wise and clock-wise, respectively) if the RFID tag is on the left/right of the receiving antenna, where $\Delta\phi$ is negative and positive, respectively.

III. Proposed Navigation Algorithm

This section explains how the modules described above fit into the overall navigation framework. The efficient coordination among the RFID communication module, FLC, and different actuators of the robot allows it to have less computational overhead while being executed on the robot's processor. The following is a description of the different steps of the algorithm.

Step 1: The robot is pre-programmed with an ordered list of tag ID numbers defining its desired path.

Step 2: The target tag of the current navigation phase is determined from the ordered list of tags defining the complete robot's desired path.

Step 3: Once the target tag is known, the robot scans through the signals backscattered from all the tags within its communication range and records the phase angles ϕ_1 and ϕ_2 of the signal coming from the tag representing the target tag at that time instant.

Step 4: The phase difference, $\Delta\phi$, of the destination tag's signal is calculated as defined in (1). $\Delta\phi$ is then passed to the FLC to quantize the tuneup the robot has to apply to its direction to better direct itself towards its destination. The robot updates its heading as in (2) and dispatches the required control action to its relevant actuators.

Step 6: Once the robot reaches the destination tag, it checks for more available destination tag IDs in the desired path. If the current destination tag is the last tag, then the robot simply stops. If not, the algorithm restarts from **Step 2**.

A thorough evaluation of this algorithm's performance is provided in the following section.

IV. Simulations and Results

Two different experiments are carried out to test the performance of the proposed navigation algorithm. The first experiment aims at evaluating the algorithm's ability to guide the mobile robot along a two-segment path regardless of its initial orientation. The second experiment demonstrates the algorithm's performance in tracking a complex path. The simulations are conducted using the 3-D simulation platform Simbad.[1] The robot's workspace considered in the simulation is an external obstacle-free environment with all the RFID tags attached to a 3 m height ceiling. It is important to point out that it is not the aim of this research to tackle the obstacle avoidance problem. This can be achieved by a separate module that can be added to the current architecture. The translational and rotational velocities of the robot are set to 0.2 m/s and 0.4 rad/s, respectively.

In the current work, a noisy RF signal is adopted to better demonstrate the effectiveness of the navigation algorithm. The phase difference of the received signal is considered to be highly contaminated by the ambient noise from the environment. The noise model used in the simulation is shown in Fig. 6. As can be seen, the noise of the phase difference tends to increase with respect to the distance between the reader and the tag.

[1] http://sourceforge.net/projects/simbad

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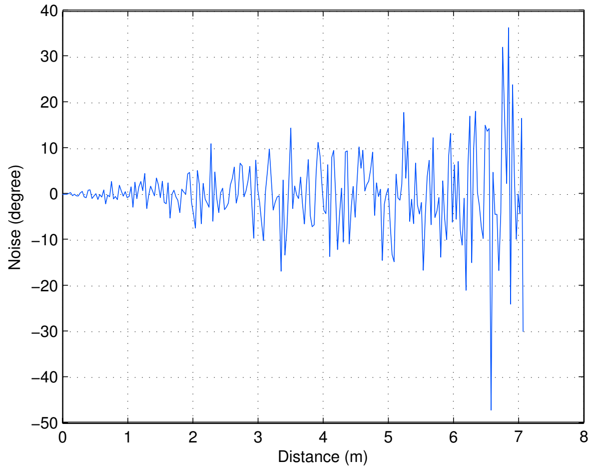


Figure 6. Noisy phase difference model.

The performance metrics adopted are the robot's actual trajectory, the trajectory tracking error, and the Root Mean Squired Error (RMSE) defined by

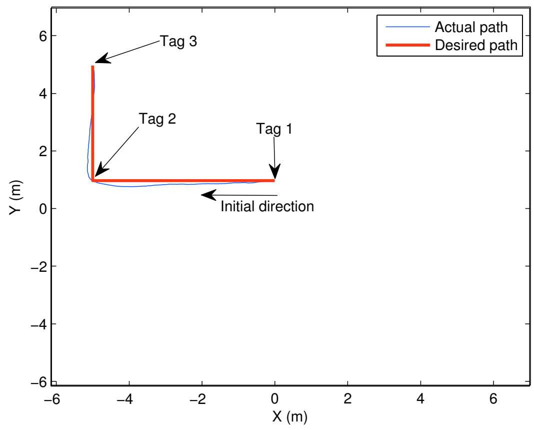
$$RMSE = \sqrt{\frac{\sum_{t=1}^{T}[e(t)]^2}{T}} \tag{3}$$

where t is the discrete time index, T is the total number of time indices, and $e(t)$ is the tracking error at time instant t.

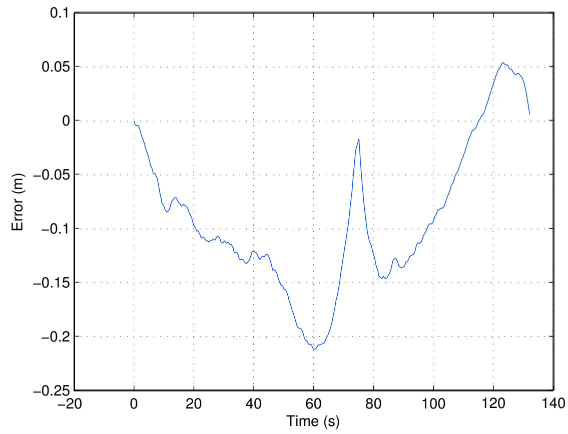
A. Following a Two-segment Path

This experiment is performed by placing three tags on the ceiling which defines a two-segment path on the ground. The robot is initially placed under the first tag , Tag 1, heading towards the projection of Tag 2 on the ground. The initial orientation of the robot in this case is 180 degrees. The actual and desired trajectories of the robot are depicted in Fig. 7(a). First, the robot's mission is to navigate along the line-segment connecting the orthogonal projection points of Tag 1 and Tag 2. Once the robot reaches Tag 2, it tuned its direction towards Tag 3 as its final destination point. The tracking error $e(t)$ along this pathway is shown in Fig. 7(b). The sign (positive/negative) of the error indicates the side on which the robot is located with respect to the desired line-segment. As can be seen, the error increases around the corners before the robot realizes that it is diverging from its path and tunes its heading to converge back to it.

In order to show the effectiveness of the proposed algorithm regardless of its initial orientation, this experiment is repeated by placing the robot right under Tag 1 with an initial orientation of 90 degrees. Figs. 8(a) and 8(b) show that the robot is capable of achieving its goal despite the noisy RF feedback signals from the tags. The RMSE recorded for both experiments are 0.12 m and 0.21 m, respectively. The robot's navigation time for each individual segment of the path is summarized in Table I.



(a)



(b)

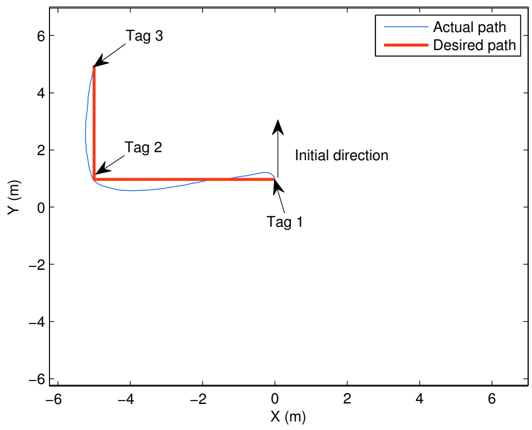
Figure 7. Algorithm's performance in a two-segment path with an initial orientation of 180 degrees. (a) Actual and desired trajectories; (b) Tracking errors.

B. Following a Complex Path

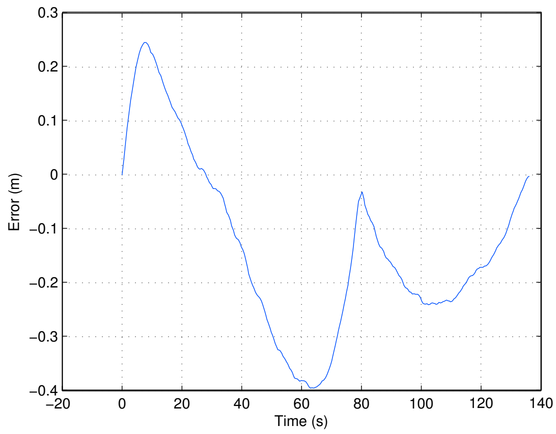
The purpose of this experiment is to study the algorithm's performance in guiding the mobile robot along a more complex path. In order to accomplish such a mission, four equidistant RFID tags are attached on the ceiling. The actual and desired trajectories for this test are shown in Fig. 9(a). The initial position of the robot is right under Tag 1 while heading towards Tag 2. The robot has to complete the path connecting the orthogonal projection points of Tag 1 – Tag 2 – Tag 3 – Tag 4 – Tag 1. The corresponding trajectory tracking error is shown in Fig. 9(b). This experiment demonstrates the fact that the proposed algorithm has the ability to guide a mobile robot along a desired trajectory regardless of the path's complexity. Although the RMSE over the full path was 0.18 m, most of the error was transient and due to corner turns. The navigation time to complete this path is given in Table I.

V. Conclusion

A novel RFID-based robot navigation system is proposed in this paper. The robot is first presented with a



(a)



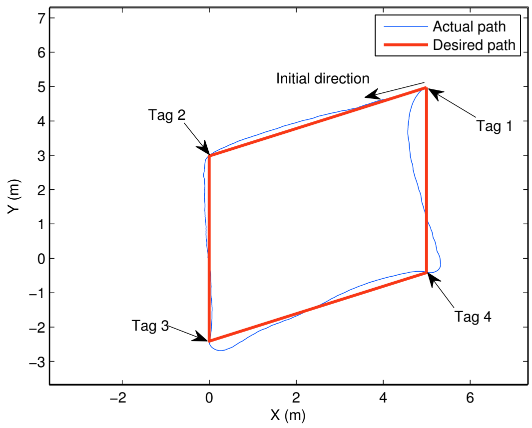
(b)

Figure 8. Algorithm's performance in a two-segment path with an initial orientation of 90 degrees. (a) Actual and desired trajectories; (b) Tracking errors.

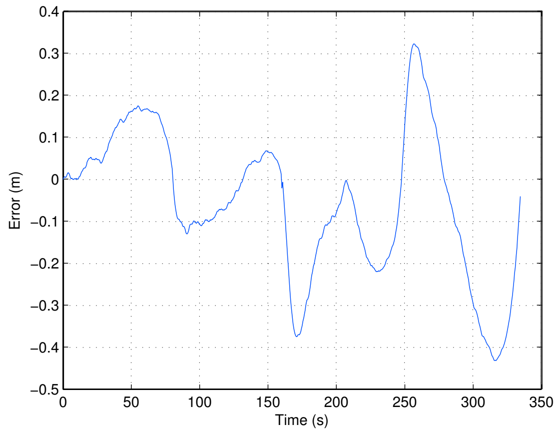
sequence of tag IDs defining its desired trajectory. This sequence is then broken into a sequence of ordered pairs of IDs each of which represents a line segment of the overall trajectory. The mobile robot tracks each segment by continuously assessing the phase difference of the RF signals at the reader's two receiving antennas coming from the current segment's target tag. An FLC is adopted to compute the control effort necessary for the robot actuators to tune its orientation appropriately. Computer simulations were run to demonstrate the algorithm's efficiency in tracking various paths of different complexities despite the noise in the RF feedback signal. The proposed algorithm is very modular as it can be easily implemented on virtually any type of robotic systems and working environments. It is computationally inexpensive as it is free of any visual data processing.

TABLE I.
NAVIGATION TIME OF THE MOBILE ROBOT FROM ITS INITIAL TO FINAL POSITION

	Time to reach (sec.)		
	Two-segment path		Complex path
	180 degrees	90 degrees	-
Tag 2	75.6	80.1	68.2
Tag 3	56.6	57.8	86.7
Tag 4	-	-	93.6
Tag 1	-	-	98.9
Total	132.2	137.9	347.4



(a)



(b)

Figure 9. Proposed algorithm's performance in following a complex desired path. (a) Robot's trajectory; and (b) Tracking error.

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