



# Journal of Applied Sciences

ISSN 1812-5654

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## RFID based Intelligent Navigation Methodology of a Nonholonomic Indoor Autonomous Mobile Robot

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**Abstract:** This study described an Intelligent Navigation methodology of a nonholonomic mobile robot using Radio Frequency Identification Devices (RFID) which offers a promising alternative to various kinds of navigation strategy, such as the vision system, topological map and sensor fusion etc., that have been currently employed in this field. This study provides a novel solution that employs the use of received signal strength indication of an RFID tags in the 2D plane based on which the robot plan its path in its 2D workspace. The robots plans its path based on the range estimated by the use of RSSI between the tag and the receiver mounted on the robot. A probabilistic threshold model is used to estimate the proximity between the tag and the robot, by which the robot moves to the tag in-line and repeats itself until the last tag is reached, in the workspace. The average path errors were estimated to be  $\pm 2\%$  and the proximity error was estimated as  $\pm 3\%$  through experimental investigations. This proposed solution offers a cost effective, modular and computationally efficient navigation technique for large robotic applications which are employed for tightly couple tasks in an unknown workspace.

**Key words:** Nonholonomic systems, navigation, received signal strength, RFID system, wheeled mobile robot

### INTRODUCTION

Mobile robots have been around since the technology era began in the 1990s. Yet, motion planning and navigation still proves to be one of the most challenging problems in these systems. Until recent days, most of the navigation methods that have been addressed in the literatures are personalized toward structured environments with high complicity in computation and control. In most of the cases, practical realization of navigation algorithm is limited by means of the expensive hardware necessary to implement in the real-world robotic systems. In general, the real world robotic navigation problem can be divided into two categories such as (1) obtaining the position of the robot and (2) the practical realization of computationally effective robot's motion control strategy. Amongst the popular navigation techniques that are used till date are dead-reckoning (Borenstein *et al.*, 1997; Ojeda *et al.*, 2006), vision-based (De Souza and Kak, 2002), behavior-based (Khozaee and Ghaffari, 2009; Chetty *et al.*, 2011) and landmark based on sensory fusion (Batalin *et al.*, 2003) etc. However, most of these techniques depend on complex image processing algorithms, high computational loads, expensive hardware and/or prior knowledge of the environment. In addition,

these navigation strategies are also affected by sensor drifts, noise, small precision errors etc. which leads to cumulative errors. Further, relying on numerous sensors also makes the system vulnerable to their cumulative errors affecting the robots posture and orientation in the workspace inevitably.

Given these shortcomings, the recent attempts in the area of mobile robot navigation have witnessed an increasing interest in the emerging RFID technology as a promising alternative technique for mobile robot navigation (Kubitz *et al.*, 1997; Tsukiyama, 2002; Gharpure *et al.*, 2006; Gueaieb and Miah, 2008). According to literature, in most of the studies, RFID systems are used for localization of robots instead using it for navigation purposes. A navigation system based on RFID as artificial landmarks was presented by Kubitz *et al.* (1997). In this strategy, the global position of the tags, class of environment, tags unique identification data and other optional information are stored as the global date in the tag memory. A simple control architecture based on the motion states of the robots were employed to make the robot to reach the landmark within its topological workspace. Similarly, Tsukiyama (2002) proposed a navigation system in man-made environments, such as indoor environments, with RFID tags as artificial

landmarks. The mobile robot used in this system was equipped with a RFID tag sensor, a controller and a vision system. A simple control algorithm was also addressed which makes the necessary guidance for the robot to reach the desired position by reading the unique identification number of the tags pasted at the walls of the workspace. Further, RFID positioning principles and localization techniques were also elaborated in Bouet and Dos Santos (2008). Even though, in most of the cases the RFID tags are used to specify the trajectory of the robot and it is necessary to estimate the range between the tags and the reader accurately, in order to guide the robot in the desired direction. Therefore, it is necessary to have a fail proof range estimation technique and cost effective hardware for the system design.

The methods that are discussed and widely used for range measurement techniques in the RF communication includes Received Signal Strength Indicator (RSSI) (Saxena *et al.*, 2008), Time of Arrival (TOA), Time Difference of Arrival (TDOA) or Received Signal Phase (RSP) (Hekimian-Williams *et al.*, 2010). Range estimation based on received signal strength assumes, that the attenuation of emitted signal strength is a direct function of the distance between the emitter and the receiver. However, this cannot measure distance accurately as it typically suffers from signal path loss due to propagation, severe effects of multipath fading and shadowing in indoor environments. On the other hand, TOA estimates the distance by measuring the total propagation time of the signal from at least three different tags and then performs 'trilateration' for accurate positioning in 2D space. Nonetheless, the major drawback is that the transmitters and receivers are to be synchronized precisely with a timestamp in order to estimate the distance accurately.

Similarly, TDOA measures the relative location of a targeted transmitter by using the difference in time at which the signal emitted by a target arrives at multiple measuring units. The major drawback is that this method requires a precise time reference between the measurement units. Similarly TDOA also often suffers from multipath effects affecting the time of flight of the signals. The RSP, phase of received signal method, also called as the Phase Difference of Arrival (PDOA), uses the delay, expressed as a fraction of the signal's wavelength, to estimate distance between the tags and the receiver. However, it requires transmitters to be placed at particular locations and believe that they emit pure sinusoidal signals. The major drawback of the RSP method is that it strongly requires a line-of-sight signal path to limit localization errors, when applied in indoor environments.

Inspired from the literatures, the major scope of this study employs the use of active RFID technology to build an intelligent mobile robot navigation system for indoor

environments which is computationally effective and efficient in navigating the priori unknown environments. Received Signal Strength Indication is exploited as the range estimation technique between the active tag and the reader to achieve a cost effective localization method for mobile robots. Using the RSSI range measurements obtained from the tag, the position of the mobile robot is anticipated with respect to the inertial frame of reference. Thus, the mobile robot can be navigated through a partially unknown environment without any visual data or sensor inputs. A series of experimental investigations also been carried out, in order to evaluate the effectiveness of the proposed navigation method. First, the effectiveness of the RSSI is tested experimentally to obtain an empirical data towards range estimation. Based on the findings, further experiments were carried out to investigate the reliability and accuracy of this method. From the experimental data, a mathematical model was formulated to map the RSSI to distance. Experiments on the RSSI had proved that it was able to measure proximity using a probabilistic model. Therefore, the bearings of the tags were manually assigned as an alternative due to the lack of directional data. Based on the method proposed, a prototype robot was built to test its reliability and path errors.

## MATERIALS AND METHODS

The proposed navigation system consist of RFID communication modules with Tags and Receiver's, a simple prepositional control actions, differential drive mobile robot, in addition to the navigation algorithm. The proposed system relies on the RFID tags placed on the workspace of interest and the locations of the tags are priori unknown to the robot and it is made to travel based on the priority of the tags assigned by the identification number. The robot is made to exhibit a straight line trajectory to reach the closest point of the target tag from its initial posture and so on to navigate the environment. During navigation the receiver mounted on the robot is made to continuously read all the tags within its reach and process the RSSI of the target tag at that instant of time.

**RSSI model:** In order to estimate the distance as a function of the RSSI, a suitable mathematical model is required to map the RSSI readings to the line-of-sight distance between the transmitter and receiver. Therefore, a theoretical model which is used for this function is given by:

$$d_i = f(R_i), i \in N \quad (1)$$

where,  $d_i$  is the estimated line-of-sight distance between the receiver and transmitter,  $f$  being the mathematical

function that maps the RSSI measurements to  $d_i$ ,  $N$  is a set of RFID tag IDs with  $|N| = n$ ,  $R_i$  is the RSS value associated with tag  $i$  and  $n$  is the total number of RFID tags placed in the workspace of interest.

Even though, the RFID tags and receivers are used in the laboratory environment, several environmental such as reflection, refraction, radio noise and electromagnetic noise would affect the RSS measurements. However, these ambient noise signals are inevitable as it would also be expected from most environments. Therefore, in order to minimize the fluctuations in RSSI measurements due to noises, the mean value of 3 readings were taken for the same distance estimated by the receiver.

**Experimental setup:** Before conducting the experiments, the workspace was designed in such a way that there are no obstacles between the transmitter and receiver in the workspace, since the obstacle avoidance was not the major scope of this work. Figure 1 shows the physical setup of the RFID reader which is installed on the mobile robot as receiver. It also depicts the placement of tag at line of sight to the reader which simplifies the experimental workspace as a 2D workspace. In addition, this was also done to ensure that there is always a line-of-sight between the transmitter and receiver. As a direct result, the workspace parameters are reduced to a 2-D workspace which greatly simplifies the model and makes the process of estimating distance measurements easier.

Tag sense ZR-USB and ZT-50 is used as the RFID reader and tags for the experimental setup. The reader communicates via IEEE802.15.4 protocol with the operating frequency of 2.4 to 2.83 GHz, enabling for long range communication. Furthermore, the ZT-50 tag is built with a virtually omni-directional tag antenna which implies that the RSSI values will be consistent from any direction. Figure 2 depicts the communication model and RSSI data packet architecture, through which the RSSI data is transmitted. On the other hand, the Arduino Mega 1280 was used as the CPU of the robotic system which is used to run the navigation algorithm and guide the robot based on the received RSSI and tag priority.

A mobile robot is built based on the differential drive kinematic configuration which is nonholonomic in nature and driven by two independent wheels. Two standard continuous servo motors are used as the actuators which governs the motion of the robot in the workspace. In order to build a complete system, the individual modules are integrated together and implemented as a mobile robotic platform as shown in Fig. 1 and 3.

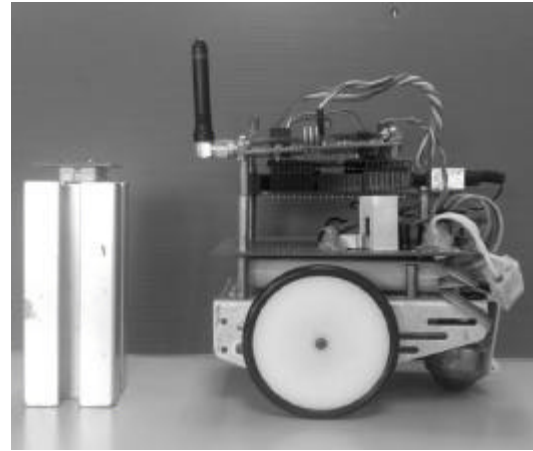


Fig. 1: Physical setup of experiments

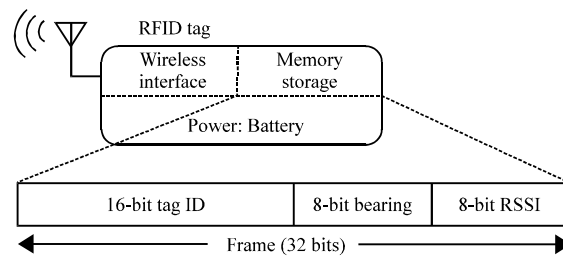


Fig. 2: Communication models of the Tag and reader as well as the RSSI data packet architecture

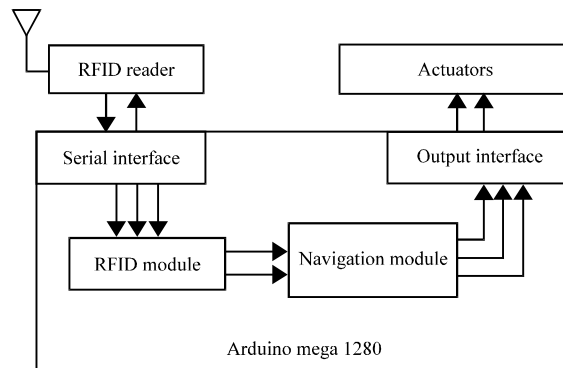


Fig. 3: Overall system of the mobile robot

**RSSI AND NAVIGATION ALGORITHM**

It is necessary to calibrate and have an empirical relationship to estimate the distance from the receiver to the RFID tag, before the implementation of RSSI for robot navigation problem. Therefore, the RSSI measurements

were taken by placing the tag directly in front of the reader in the line of sight to establish a reference point. The value of RSSI is measured by varying the distance between the reader and the tag from 0 to 10 m with the resolution of 0.1 m for three different power levels of the tag. The transmittance power of the tag was adjusted from low power, to medium and finally to high power. RFID tags yields a better transmittance power at High power level and the test was repeated for a distance of 0-1 m with a step size of 0.01 m in that power level. The sample size of the experiment is also increased to 10 samples per distance measurement. Subsequently, the average of 10 RSSI readings is used to develop the relationship.

Figure 4 illustrates the RSSI vs. distance up to 10 m for three different transmitting power levels. The RSSI vs. Distance graph for low transmitting power shows highly unstable nature and non-linear features. However, for high and medium transmitting power, the lines can be estimated to be linear up to 3 m but is unstable afterwards. Similarly, Fig. 5 shows the results of the test conducted up to a range of 1 m with 0.01 m resolution, in order to investigate the linearity of the RSSI, in high power transmitting mode. The RSSI readings were more stable and fluctuations decreased in magnitude. However, the fluctuations were still significant exact distance measurements.

**Probability model:** In order to minimize the fluctuations and develop an empirical relationship, a probability model is used since the estimated proximity of the tag to the reader is adequate to establish the distance relationship. Furthermore, the simplicity of this model also leads to the easy implementation on the mobile robot and at the same time, satisfies the criterion of being computationally efficient. The probability model is governed by the threshold of 90% of the RSSI readings with a straight line fit drawn as shown in Fig. 5, whereby the distance is estimated whenever the RSSI value exceeds the threshold, at that distance and given by:

$$y = -0.35*x+263 \quad (2)$$

For instance, for a distance of 5 cm, the equation gives the RSSI threshold to be 261. At a probability of 90%, the distance between the receiver and the transmitter was approximated to be 5 cm or less when the RSSI exceeds 263. Further tests were conducted by varying the probability from 85 to 95%. The algorithm was tested by programming the mobile robot to stop when the RSSI exceeds the threshold at a distance of 5 cm. After various tests, it was found that 90% gives the lowest proximity error of  $\pm 3$  cm.

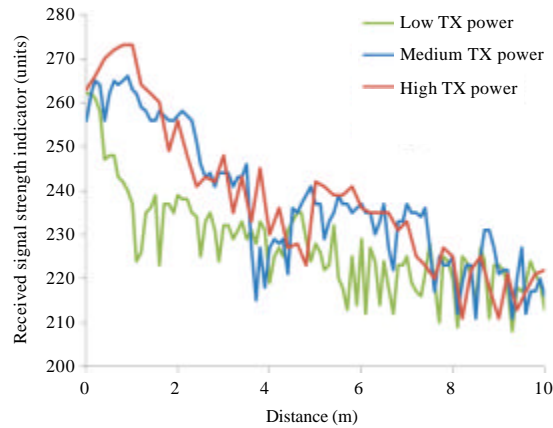


Fig. 4: Graph of RSSI vs. distance up to 10 m

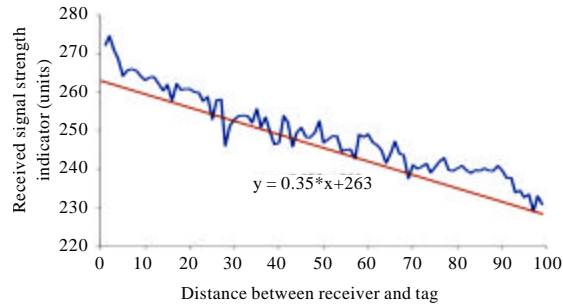


Fig. 5: Graph of RSSI vs. distance up to 1 m

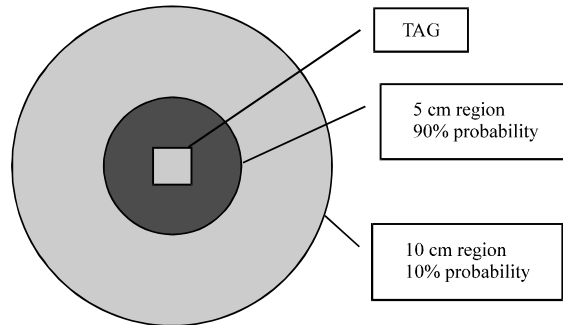


Fig. 6: Robots stop point at 90% probabilistic region

Figure 6 illustrates the distances whereby the robot stop and its statistical probabilities. The maximum distance at which the robot stops is estimated as 10 cm. However, the occurrence was rare and at the 5-10 cm region, the statistical probability was 10%. In addition, the 90% region was at exactly 5 cm which signifies the mobile robot to stop close to the desired distance consistently.

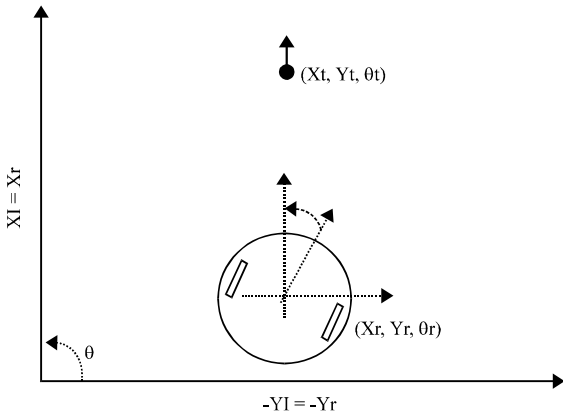


Fig. 7: Kinematic model of the robots in the workspace

**Navigation algorithm:** A decision making strategy is essential to coordinate the motion of the robot based on the RFID range estimation through RSSI. Hence, in this work, the navigation strategy based on the simple prepositional representation with the transformation function necessary to transform the RSSI data towards the control action is developed. The transformation function is determined by considering the kinematics of the robot model and the geometrical relationship between the initial and goal positions of the robot in the 2D polar coordinate representation as shown in Fig. 7 and given by:

$$\Delta R = \sqrt{(X_t - X_r)^2 + (Y_t - Y_r)^2} \tag{3}$$

$$\theta_t = \tan^{-1} \left( \frac{Y_t - Y_r}{X_t - X_r} \right) \tag{4}$$

$$\Delta \theta_t = \theta_r \pm \theta_t \tag{5}$$

The position of the robot in the workspace during its fly is obtained by the kinematic model as given by:

$$\begin{bmatrix} X_r \\ Y_r \\ \theta_r \end{bmatrix} = \begin{bmatrix} \cos \theta_r & 0 \\ \sin \theta_r & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{6}$$

where,  $v$  and  $\omega$  is the piecewise constant translational and rotational velocity of the robot around  $0.1 \text{ m sec}^{-1}$  and  $0.2 \text{ rad sec}^{-1}$  respectively.

By having Eq. 3 to 6 as the relationship, an intelligent navigation algorithm is developed by making the robot to receive the RSSI values from the tag that surrounds its environment.

Then the robot is made to perform its motion in a straight line towards selected tag of interest. The detailed

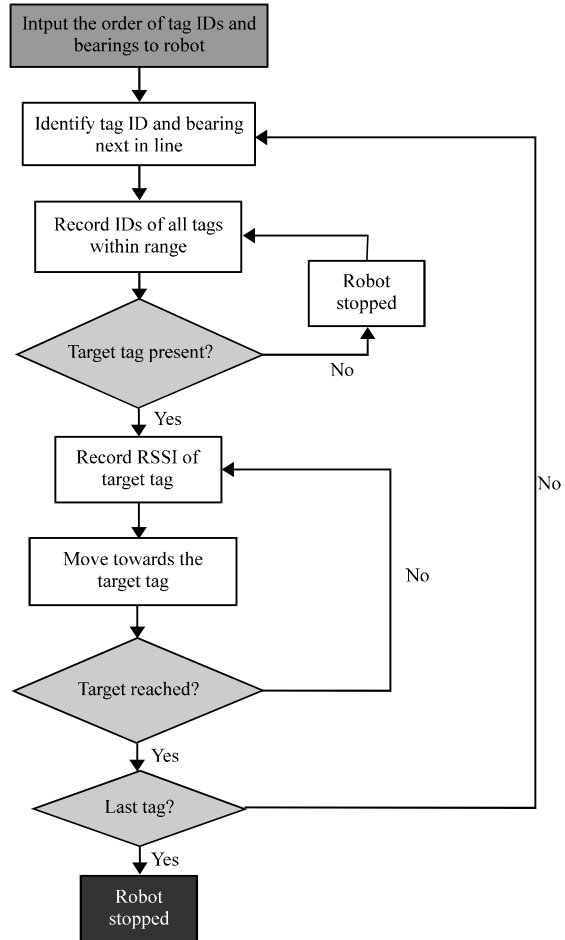


Fig. 8: Flowchart of the intelligent navigation algorithm

methodology of the navigation algorithm is represented as flowchart in Fig. 8. The order of tag IDs and its bearings are pre-loaded as the lookup table in the memory of the mobile robot. During the fly, robot determines the ID and its associated bearing of the next tag in-line and performs its motion until it does not find the target tag in the workspace. Once the target tag is identified, its RSSI is continuously recorded and the mobile robot moves towards it according to the bearing estimated by the robot. When the RSSI of the target tag exceeds the proximity threshold, the program repeats itself until the last tag has been reached. When the last tag is reached, the mobile robot stops. The performance evaluation of this algorithm is provided in the following section through experimental investigations

### EXPERIMENTAL INVESTIGATIONS

A set of experiments is conducted to test the performance of the proposed navigation algorithm. The



Fig. 9: Physical arrangements of tags and robot in the workspace

Table 1: Average experimental values of Tag to Tag navigation for 10 sets of experiments

Position	Actual value		Experimental value	
	X (m)	Y (m)	X (m)	Y (m)
Initial	0	-1	0	-1
Tag 1	1	-1	1.03	-0.97
Tag 2	-1	1	-0.98	0.95
Tag 3	1	1	1.04	0.97
Tag 4	-1	-1	-1.03	-0.96

main objective of the investigation is to test efficiency of the navigation algorithm to make the mobile robot to move towards the final tag based on their priority in a straight line motion. The mobile robot was programmed with the proposed navigation algorithm. The probability model of 90% is used as the RSSI threshold of 5 cm for distance estimation. In addition, the priority order of tags and their bearings were also loaded into the mobile robot. The tags act as beacons whereby the robot proceeds to the next tag in-line when the target tag has been reached.

Figure 9 shows the physical arrangement of the mobile robot experiment. The mobile robot was programmed to travel from tag 1 to tag 4 in numerical order which were positioned at (1,-1; -1,1; 1,1 and -1,-1) in accordance to the priority based on 1 to 4, respectively, in the coordinate frame as depicted in Fig. 10. The bearings of the tags are related w.r.t. the coordinate frame.

Figure 11 shows the performance of the navigation algorithm, where the robot moves from its initial position of (0,-1) in the coordinate frame to Tag 1 in a straight line motion and after successful completion it continues the motion in the similar fashion until it reaches the final tag. For the first phase i.e., from the starting point to the target point (tag 1) the robot took 12 sec to reach the target within the positional accuracy of 5 cm. Table 1 shows the average results of the end robot position during the fly, conducted for 10 times with the similar conditions to

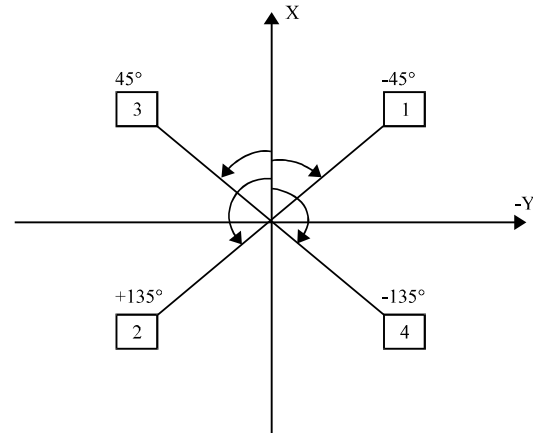


Fig. 10: Position of tag and bearing in the 2D coordinate frame

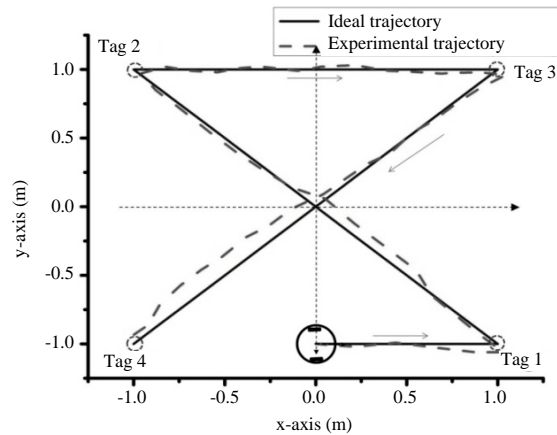


Fig. 11: Performance of the algorithm in guiding the robot in a straight line motion from tag 1 to 4

prove the effectiveness of the proposed algorithm. It can be observed that the average path errors were estimated as  $\pm 4$  cm whereas the proximity error was estimated to be  $\pm 3$  cm. The relatively small path and proximity errors prove that the probability model was highly repeatable and reliable for localisation purposes. It can also be observed from Fig. 9 and Table 1 that the positional error is limited within  $\pm 3\%$  in reaching the target tags. A slight drift in the robot trajectory could be observed throughout the workspace since the skid and steer and tire differences of the robot model are not considered in the model developed and it is assumed to be ideal while developing the navigation algorithm.

### CONCLUSION

An intelligent navigation methodology of a nonholonomic mobile robot using the received signal

strength indication of the RFID technology is developed and addressed in this study. A computationally simple algorithm which makes the robot to navigate in an in-line motion towards the goal is also developed and addressed in this paper. The effectiveness of the proposed algorithm is verified through experimental studies and the results have proven that RSSI can be used to estimate the proximity between the transmitter and the receiver for navigation purposes. It is also shown that the optimum probability threshold of 90% yields small errors in proximity of  $\pm 3$  cm and an average path error of  $\pm 2$  cm which are both relatively little for navigation purposes. In a nutshell, RFID technology was proven to provide a promising alternative for localization in mobile robots. However, several more experiments has to be conducted by having the robot to exhibit a complex path with the combination of straight and circular lines and also in the 3D workspace to prove the overall effectiveness of the proposed navigation methods which provides the future direction towards extending this study.

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