Autonomous Mobile Robot Navigation via RFID Signal Strength Sensing

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***Abstract*—Autonomous mobile robots have been increasingly used in various applications within indoor environment notably for inventory and asset tracking in warehouses. Radio Frequency Identification (RFID) is one of the approaches considered for many related applications due to its automated recognition of objects and high penetrability through a wide range of materials. This paper proposes a technique for autonomous mobile robot navigation via RFID signal strength sensing where the robot is tasked to move towards a target object without knowing its current location. Both the robot and the target object are equipped with IEEE 802.15.4 based wireless sensor network modules which allow a point-to- point networking during the navigation. A set of experiments have been designed which include different initial heading angles of the robot with respect to the goal. The experimental results show good performance with an average steady-state error of no more than 28*cm* within a navigation area of approximately 7*m* × 7*m*, while for the time taken to reach the goal, the duration varies between 176s and 236s.**

***Index Terms*—direction sensing, indoor localization, RSSI**

I. Introduction

Autonomous mobile robots have been widely used for navigation purposes as well as industrial applications such as path tracking and object detections. When navigating indoors, they are typically faced with many difficulties particularly on searching and moving towards a specific object. Recent advances in wireless sensor network technologies have shown new approaches of indoor navigations via radio frequency identification (RFID) technique [1, 2]. Designed as a con- tactless and low energy consumption device, the RFID technique was initially used to replace conventional smart card systems which were prone to problems of wear and damage by frequent contacts [3]. As RFID technique relies on a radio frequency (RF) interface for the contactless functionality, it also provides the ability to identify and to locate targeted objects by analysing the strength of signals received. This method is well-known as Received Signal Strength Indication (RSSI) which calculates the existing amount of power in a radio signal as an index of estimated value for signal strength collected on an antenna.

Evaluating the signal strength at the receiver can diagnose the status of a communication connection. RSSI detects the difference between the strengths of the sent and accepted signal which will then be used to calculate the distance between two nodes. Whenever the transmitter shortens the distance to the receiver, the conveying signal at the secured antenna turns stronger marked by higher RSSI value [4].

Location estimation or localization, which is another common application of WSNs, is usually performed using radio frequency (RF) technique as the associated signal strength is easily obtained during the wireless transmission. This is particularly useful for indoor navigation and tracking in which the Global Positioning System (GPS) satellite navigation fails to operate. The RF technique, also termed as received signal strength indication (RSSI) method, is typically used to estimate the distance between two sensor nodes, or transmitter and receiver. There are few ways to find the position by using the RSSI such as trilateration algorithm, maximum likelihood algorithm, least square algorithm and location fingerprint positioning method [2]. The trilateration algorithm uses distances from nodes with known position and calculate the intersection of distance to find the unknown position. The maximum likelihood algorithm, on the other hand, approximates the location of a node by reducing the differences between the measured distances and estimated distances [3]. The least square algorithm uses distance from known position and roughly predict the position of unknown node, while the location fingerprint positioning method uses data from database and preliminary analytical model or specific orientation to calculate the position of the unknown point [4].

The RSSI method possesses a significant advantage due to its high penetrability through a wide range of materials and requires no line-of-sight to exchange data between the transmitter and receiver. Various location estimation or localization techniques have been introduced in the literature such as trilateration algorithm and via fingerprinting and landmark approached [1, 5, 6]. Nevertheless, without sufficient numbers of RFID transmitters, localization via the RFID approach can be very taxing as communication between tag and reader is sensitive to the environment. The most common technical challenge associated with the RFID based system is to stabilize identification performance associated with the

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working conditions of radio waves. Radio frequency signals are more likely to be distorted by obstacles that reflect and scatter the transmitting signals [7, 8].

For applications where the mobile robot needs to locate and approach a certain object in the indoor environments, it should learn how to classify these signals to provide relevant measurement throughout the navigation area. The task will be more challenging if the robot does not know its own current location and orientation, the antennas' sensing area is fixed, and the navigation area is not free of obstructions. Therefore, autonomous motion to localize the target object needs to be developed to achieve the requirement. In this work, a differential drive mobile robot attached with a forward-facing RFID reader is used to navigate in a specified area, and is assigned a task to find the targeted object or goal which contains an RFID transmitter. The scope is limited to indoor navigation with a dimension of 7m x 7m, and the performance is evaluated when the robot is initialized at different heading angles with respect to the goal. The next section presents the methodology employed in this work.

II. Methodology

A. Autonomous Navigation and Direction Sensing

Received Signal Strength (RSS) system develops an algorithm to discover the location of the target nodes by quantifying the RSS values from multiple unmoving sensor nodes with their coordinates known. The main concept that drives the RSS system is that the configured transmission power P_T at the transmit- ting device can directly affect the received power P_R at the receiving device. For transmission which takes place in free space, the value of the signal strength is reduced along with the distance between the sender and the receiver. The received power P_R can be represented as

$$P_R = P_T \times G_T \times G_R \left(\frac{\lambda}{4\pi d}\right)^2 \tag{1}$$

where G_T is the transmitter's gain, G_R is the receiver's gain, λ is wavelength and d is the distance between the sender and the receiver. The received signal strength can be transformed into RSSI, denoted as R_s, which is the ratio of P_R to P_{ref} , i.e.

$$R_s = 10 \log \frac{P_R}{P_{ref}} \tag{2}$$

RSSI measures the transmission quality between two nodes from the varying distance between them. It is measured in dBm and thus a greater negative value in dBm points to a weaker signal. Localization scheme basically builds upon this method by considering variations on signal strength and eventually comparing the received signal level. The RSSI technique provides the distance measurement between the transmitter and the receiver based on the properties of the transmission signal. The relationship between the distance, d_T and R_s is given as

$$d_T = 10^{\frac{R_0 + R_s}{10n}} \tag{3}$$

where R_0 is the RSSI value at 1m, and n is the path loss exponent.

This work employs an off-the-shelf RFID reader where the antenna's position with respect to the module is fixed, hence for each coordination, its sensing area is non-adjustable. With regard to direction sensing, the proposed method is leveled to three stages. The first stage requires the head of the robot to turn 45˚ clockwise and 45˚ counterclockwise at its current position. The second stage attains the corresponding R_s from the two bearings. The third stage compares the gathered values of R_s and proceeds with the momentary movement based on the direction with higher R_s value. The third stage is repeated until the mobile robot enters a specified radial distance from the transponder that corresponds to R_s = 18 dBm. The sketches in Fig. 1 provide an overview regarding the whole self-governing navigation and direction sensing procedure.

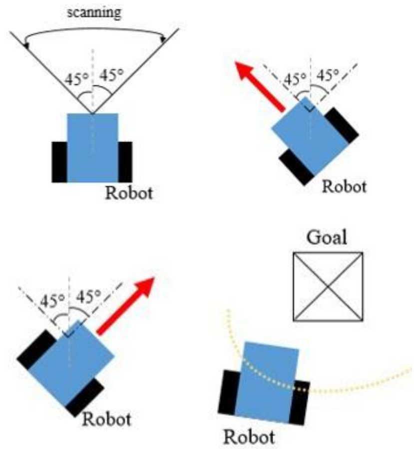

Figure 1. Illustrations on the autonomous direction sensing and navigation; from top left to bottom right: (i) The robot scans in the directions of 45˚ clockwise and 45˚ anticlockwise (ii) it moves 45˚ to the left when the detected left RSSI value is higher. (iii) it moves 45˚ to the right when the detected right RSSI value is higher. (iv) the robot arrives within the region of 0.20 m and stops moving.

B. Experimental Setup

The IEEE 802.15.4 radio modules are used for the RFID reader and transmitter throughout the experiments, and we employed a simple point-to-point networking between the target, robot and the PC as depicted in Fig. 2. The PC serves as the base station to log all the required data for performance evaluations.

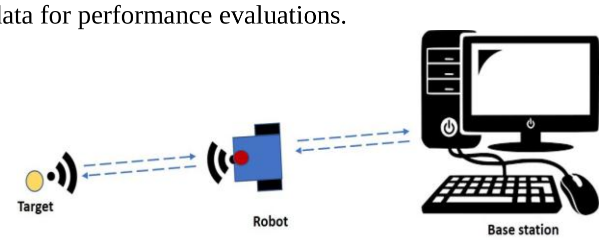

Figure 2. Point-to-point communications between the target, robot and the base station (PC).

The experimental area considered is a plane with approximately 700 cm x 700 cm dimension. The goal is placed at the coordinate of (100, 450) and the robot, which is located at a different coordinate needs to move towards the goal from different initial heading angle as illustrated as in Fig. 3. The initial heading angle is denoted as θ_0, and four values of θ_0 are considered for the experiments, which are 45∘, 135∘, 225∘, and 270∘. For each configuration, the experiment is conducted three times and the performance is evaluated based on the average steady-state error, which is the Euclidean distance between the final stop and goal coordinate; and settling time, defined as the time the robot stops moving once it settles down at its final position.

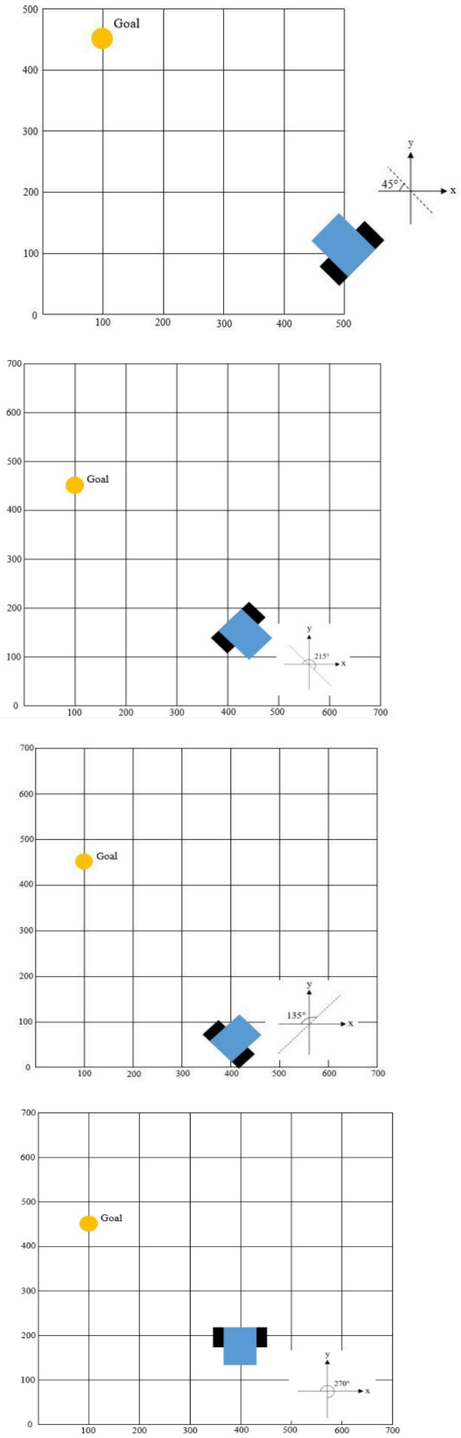

Figure 3. Initial positions and heading directions of the mobile robot with respect to the goal.

III. Experimental Results

The trajectories of the robot for all cases in the first experiment are recorded in Fig. 4 where the path is represented by the coloured lines. The figure shows that the robot has successfully moved from different heading angles towards the goal. The corresponding values of R_s and the estimated distance, i.e. d_T , during the navigation are shown in Figs. 5 and 6 respectively. The experiments were then repeated for another two times, the average steady-state error and settling time are recorded in Table I and Table II respectively. Fig. 7 shows one of the images taken when the robot approaches the goal.

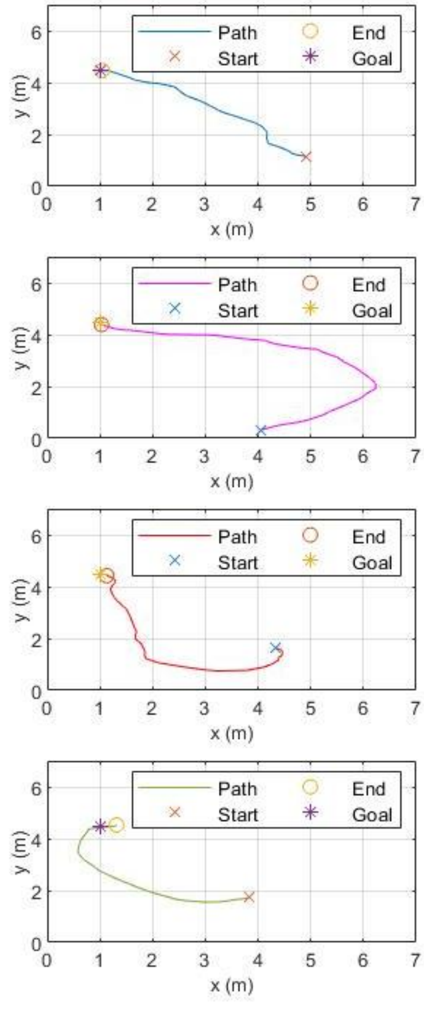

Figure 4. Trajectories of the robot when (from top) $\theta_0 = 45^{\circ}$, $\theta_0 = 135^{\circ}$ $\theta_0 = 225^{\circ}$ and $\theta_0 = 275^{\circ}$.

It can be observed that as time passes, all errors converge towards zero. The raw RSSI data, as expected, show the highest error with time with very high fluctuations, while the filtered ones show significant reductions in the error. The total error is calculated based on the area under the plots from starting to ending time, and the numerical results are recorded in Table I. Based on the calculated errors, it is clear that the proposed strategy can further reduce the error as compared to the results from the other methods.

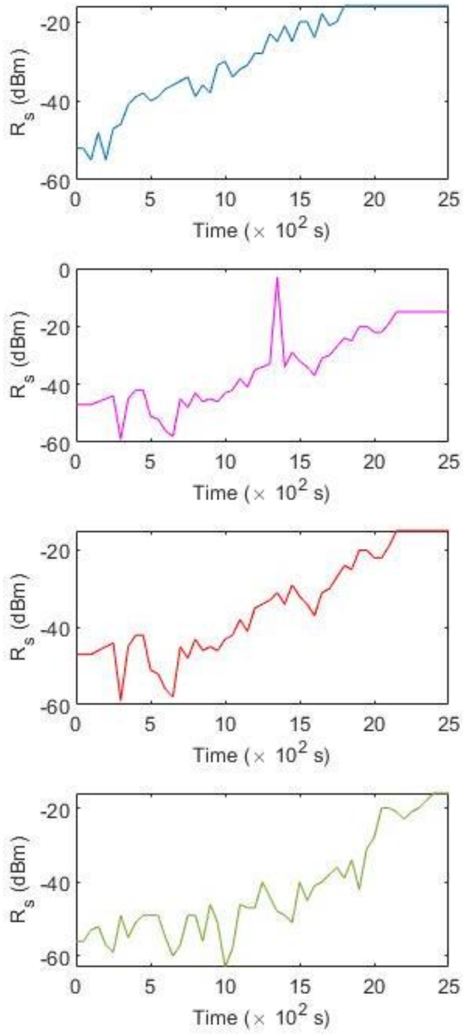

Figure 5. Values of R_s against time when (from top) $\theta_0 = 45^{\circ}$, $\theta_0 = 135^{\circ}$ $\theta_0 = 225^{\circ}$ and $\theta_0 = 275^{\circ}$.

TABLE I. PERFORMANCE EVALUATIONS IN TERMS OF STEADY STATE ERROR (IN CM) FOR ALL EXPERIMENTS.

Test	Initial Heading Angle, θ_0			
	45°	135°	225°	270°
1	28.19	17.7	22.8	45.89
2	9.52	4.75	9.5	20.83
3	7.71	11.86	17.2	16.58
Average	15.14	11.44	16.52	27.77

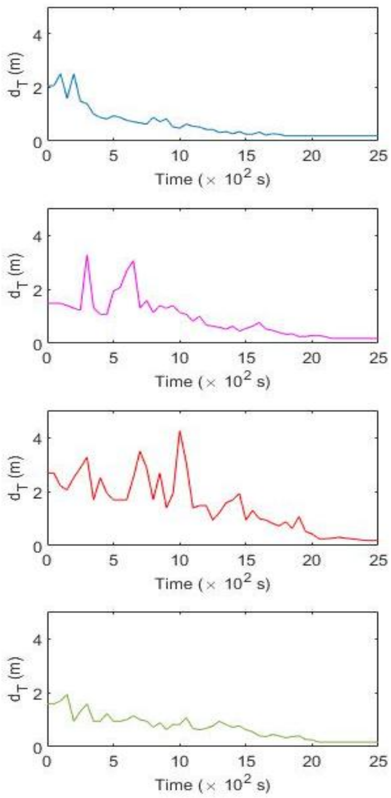

Figure 6. Values of d_T against time when (from top) $\theta_0 = 45^{\circ}$, $\theta_0 = 135^{\circ}$ $\theta_0 = 225^{\circ}$ and $\theta_0 = 275^{\circ}$.

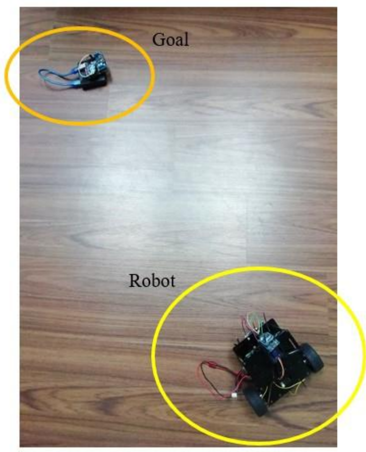

Figure 7. An image taken from one of the experiments when the robot approaches the goal.

TABLE II. PERFORMANCE EVALUATIONS IN TERMS OF SETTLING TIME (IN SECONDS) FOR ALL EXPERIMENTS.

Test	Initial Heading Angle, θ_0			
	45°	135°	225°	270°
1	166	220	231	202
2	186	205	247	190
3	177	215	229	221
Average	176.3	213.3	235.7	204.3

When θ_0 = 45°, the robot faces towards the transmitter module, hence allowing the wireless communication to be achieved in a direct manner as the range of the receiver module covers the transmitting signal perfectly. The robot moves towards the goal in a steady fashion without any hesitation. This explains the highest performance of this experiment with the shortest consuming time and the least steady state error. When θ_0 = 135°, it has been noticed that the robot moves to the right side at the beginning and eventually travels on the appropriate route after some period. Hence, the time taken for it to make its way towards the goal point is longer and yet it records a relatively small amount of error. When θ_0 = 225°, the robot is positioned with its back towards the goal. The signal transmission is interrupted by the blockage of the robot's body. Retrieving the accurate RSSI values will require relatively more effort. The navigation path predicted by the robot is more distant and thus consumes more time to approach the goal. A quite similar scenario can also be seen in the last robot's configuration, i.e. when θ_0 = 270°.

IV. Discussions and Conclusions

An autonomous navigation via RFID modules has been proposed with a suitable direction sensing algorithm. The mobile robot detects the target transponder to acquire its identity and RSSI measurement. A set of experiments have been designed by alternating the orientation of the robot with respect to the goal. The experimental results show good performance with an average steady-state error of no more than 28*cm* within a navigation area of approximately 7*m x* 7*m*. The average settling time achieved varies between 176s and 236s.

For future work, a dual-directional antenna can be considered to replace the regular antenna for a more efficient automated target acquisition and precise docking for the indoor mobile robot navigation. Besides, other methods such as Direction of Arrival and Time-of-Arrival may also be integrated together with the proposed direction sensing algorithm to achieve better performance.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

J. H. Teo and A. Loganathan conducted the research; J. H. Teo conducted the experiments; J. H. Teo analyzed the data; J. H. Teo wrote the paper; P. Goh and N. S. Ahmad validated the results; N. S. Ahmad supervised the project; all authors had approved the final version.

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