RFID positioning robot: An indoor navigation system

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RFID Positioning Robot: An Indoor Navigation System

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Abstract – **This paper describes a system to improve indoor navigation through use of radio frequency identification (RFID) technology. The terminal unit is an embedded system equipped with an RFID reader for localization, a mobile robot for navigation, and a combination of ultrasonic and IR sensors for obstacle detection and avoidance during navigation. To increase accuracy of an indoor guidance system, a triangulation method is proposed to accurately detect the location. While the proposed method can be verified by many methods, the accuracy is demonstrated through use of a mobile robot. It navigates to a designated location through continuously monitoring all RFID tags in the vicinity, localizing itself, and calculating the path to the destination.**

I. INTRODUCTION

One of the fundamental challenges in mobile robotics and warehouse management is object localization and navigation. While Global Positioning System (GPS) is a widely accepted solution for outdoor operation, its accuracy is very limited when operating indoors due to limited satellite reception. Answering this challenge of indoor object localization and navigation would be of immense help for several applications such as navigational assistance for the blind, tour guide robots, inventory and asset tracking, healthcare, and defense [1-11]. With the primary application of radio frequency identification (RFID) being object identification, RFID technology has seen a significant growth. While it can be used to efficiently identify an object, its scope is limited in localization. According to Chunag [12], concrete implementation of these techniques for a mobile robot was a challenging task, especially when using passive RFID tags as communication between tag and reader was sensitive to the environment. Answering this challenge, our system presents the research, design, and implementation of an autonomous RFID positioning robot as shown in Fig. 1. The RFID positioning robot will provide an accurate indoor navigation algorithm to be implemented for a versatile of applications. This system can assist with navigation through buildings, showcase student work, and also serve as a platform for undergraduate student research and design projects.

II. PREVIOUS WORK

Many different methods have been proposed for localization of RFID system including Angle of Arrival (AOA), Received Signal Strength Indicator (RSSI), and Time of Arrival (TOA). AOA measurement determines the angle between the transmitter receiver line and the reference direction [13], and the accuracy is dependent on number of receivers or the rotating device, and is more suitable for operating outdoors. RSSI on the other hand uses signal strength to determine the distance between the sender and receiver [13]. The advantage of this method is its cost efficiency and ease of implementation.

However, this requires heavy computation and extensive prior knowledge of the environment. The TOA method measures the time it takes for a signal to travel between source and receiver [14]. As the signal might travel on the direct or shortest path, TOA has less impact from multi-path environments. However, accurate time synchronization between the source and receiver needed for accurate time measurement by the micro/nano second, thus increasing the hardware cost for accurate localization.

In addition, several researchers have proposed algorithms to increase the accuracy of RFID positioning. Chunag [12] utilized RFID technology along with object localization in order to locate tag locations. He used Angle of Arrival (AOA) as well as Time of Arrival (TOA) and signal strength to determine the location of the RFID tags with increased accuracy and a better response time. Schneegans [15] focused on using RFID snapshots for mobile robot self-localization. He used RFID vision-based approaches for self-localization of a mobile robot. Park and Hashimoto [16] used trigonometric functions and RFID tag's Cartesian coordinates in a regular grid-like pattern and stated that RFID tag placement pattern should be adapted through experiments to suit different applications. Kim and Chong [17] validated mobile robot docking to a RFID transponder in the area occupied by obstacles. Their algorithm quantifies the potential error in the Direction of Arrival (DOA) estimate through dual-directional RFID antenna. While each of these methods serves the basic purpose, all have limitations including accuracy, obstacle detection, and cost. Improvement of these projects presents a feasible RFID system to accurately detect a position while indoors.

II. DESIGN IMPLEMENTATION

A. Chassis Design

The RFID Positioning Robot's chassis presented in Fig. 1 was based around an iRobot Create base produced by iRobot [18]. It is designed to mount three RFID antennas in an equilateral triangle position. The base is a 0.35mx0.35m square directly centered over the robot at an elevation of 0.05m to allow easy access to the robot's modular ports.
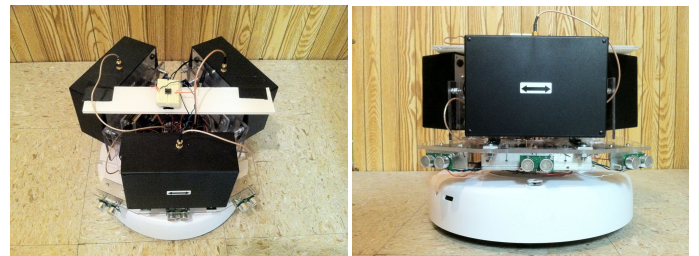

Fig 1: Model of an RFID Positioning Robot

B. Embedded System

The embedded system of the RFID Positioning Robot has been classified into input module and output module as in Fig. 2. The input module consists of the localization device, the obstacle detection sensors, and the user input device. The output module consists of the position display and the robot platform. Both these modules are interfaced using an embedded microcontroller that serves as the central command module, and provides information regarding the current location. Localization is performed using a SkyeTek DKM10 RFID system [19], and obstacle avoidance navigation is performed using ultrasonic range finders and infrared (IR) sensors [20, 21]. An LCD screen is used as an output to present current location. The RFID antennas will be mounted outside the chassis with one antenna on each side of the equilateral triangle. All other hardware is enclosed inside the triangle affixed on top of the iRobot Create platform.

Once the destination coordinates are input to the system through the keypad, the microcontroller [22] will initiate its routine. At the same time, the RFID reader communicates with the microcontroller to read RFID tags in its read range. When it determines that the robot is present at a point of interest, it will send an appropriate signal to the microcontroller. Accordingly, the microcontroller will communicate with the LCD screen and output the current location. The ultrasonic and IR sensors are integrated to the input ports of the Arduino Mega2560 microcontroller, which constantly monitors and sends appropriate signals when an obstacle is detected. These signals are then analyzed to determine the location of an obstacle, and initiate the obstacle avoidance routine accordingly.

III. SUB-SYSTEM OPERATION

A. Localization

The initial method of interest is a combination of TOA and a variation RSSI. Using TOA, the present location will be able to be determined through data collected from three antennas. Also, by varying transmission power levels of the antennas, a distance can be obtained from the correlation of readings found in each power level. As shown in Fig. 3, each antenna will vary its transmission power level to determine an estimated distance from the tag in its read range. With data obtained from the three antennas, coarse localization can be performed to triangulate the location using the distance formula in eq (1). When new tags are detected in the RFID read range, the current location
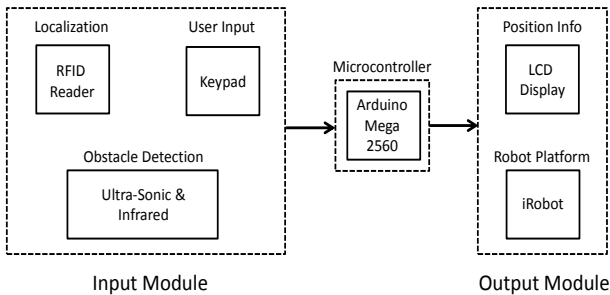
will then be recalculated. The process of recalculating the current position will reduce error for finer accuracy.

A SkyeTek DKM10 RFID development kit operating at 915 MHz has been used for this system. Through preliminary testing it was found that this development kit in combination with a patch antenna has a read range of approximately 1m. According to Han [23], the estimation errors in a triangular pattern are a lot smaller than in a square pattern. Accordingly, RFID tags will be placed in a triangular pattern shown in Fig. 3, where *td* is the distance between each tag. In Fig. 3, the robot is shown in between three RFID tags, with the read area surrounding the tags.

During localization, the RFID system must initially determine its position in reference to the tags read, which in some cases might be located to the left, right, or bottom of the three antennas shown. After estimating its location, the system will reference an internal memory map to discover the location of the destination tag. Through trigonometric analysis, it will determine the angle (θ) and distance *(d)* it must travel to reach the destination as in eq (1) and (2).

In order to differentiate between points of interest, each tag is encoded with 24 bytes of information. The first 22 bytes are common among all tags to ensure that correct tags are read, and prevent unwanted tags disrupting the operation of the robot. The last two bytes allows to code unique tags, sufficient to provide a coordinate system with each tag representing a specific point.

B. Obstacle Avoidance

The RFID Positioning Robot comprises of three ultrasonic sensors and two IR sensors integrated into the system as in Fig. 4. The three ultrasonic sensors will be configured on the front of the robot and two IR sensors will be centered on each side of
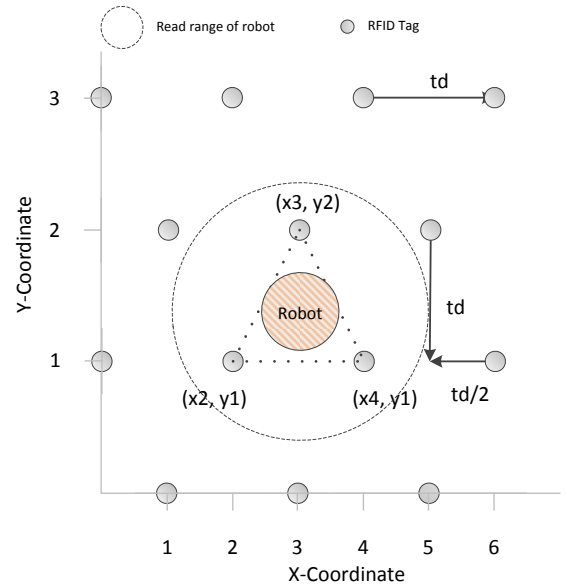

Fig 2: Embedded System with Input and Output Modules

Fig 3: Triangular Placement of RFID Tags and RFID Positioning Robot Read Range

the robot. When activated, the microcontroller continuously reads information from the five sensors, detects any obstacle present, and determines where the obstacle(s) is located.

The ultrasonic sensors on the front of the robot are used to scan for potential objects within range of the robot. There are five regions (marked 1-5) in which the object could be located, and the integrated ultrasonic system can identify in which of these regions is the obstacle present. Once this information is obtained, it considers the angle and distance of the obstacle with respect to the robot, and maneuvers the robot to go around the obstacle. The IR sensors are utilized for a few important reasons. The side IR's can be used for detection of an object directly to the side of the robot.

As the ultrasonic sensors determine the potential location of an obstacle with respect to the current location of the robot, it will determine the direction to turn in avoiding the obstacle. As presented in Fig. 5, if the obstacle was determined to be on the front right/left side, the robot will turn 90° to the left/right, and move forward until the right/left IR sensor no longer senses the obstacle, and track the distance travelled *'x'*. At this point, the robot will turn right/left by 90° and moves forward until the right/left IR sensor no longer detects presence of the obstacle, tracking the distance moved by *'y2+y3+y4.'* Later, the robot turns right/left by 90° and moves forward by distance *'x,'* and turns left/right by 90°. Overall, these side IR sensors will act as a cross-check to ensure that the robot moves past the obstacle. Once the robot returns to its original path, it will recalculate its position and correct for any error encountered to continue moving towards its final destination

C. Robot Navigation

The localization, robot navigation, and obstacle avoidance algorithms for the RFID system will send information to the microcontroller simultaneously. The RFID system begins by prompting the user for a coordinate location they would like to find. Fig. 6 shows a proposed method of localization proposed by Park [16]. The start position is represented as *S(xₛ,yₛ)* and the goal destination is represented by *G(xₘ,yₘ)*. When the robot detects a new RFID tag as shown in the figure, its route can be calculated using basic trigonometric eqs. (1) and (2).

$$d = \sqrt{\left(y_g - y_s\right)^2 + \left(x_g - x_s\right)^2} \tag{1}$$

$$\theta = Tan^{-1}\left(y_g - y_s / x_g - x_s\right) \tag{2}$$

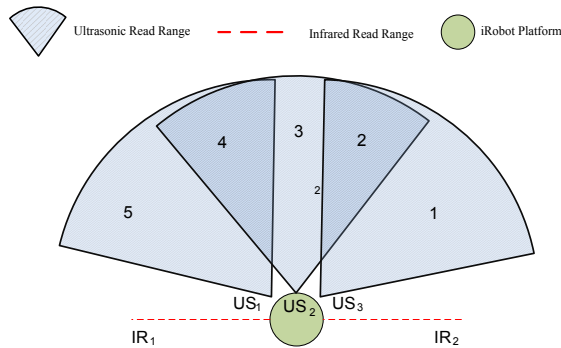where, *d* is the distance from the current location to the final location and *θ* is the correction angle.

Per the triangulation method described earlier, the current location of the iRobot is represented by $P(x_c, y_c)$. The read area, which is the shaded area around the robot, is used to search for tags in order to recognize its position and then progress towards its goal destination. Through this process, it will calculate the necessary distance *d* to the destination and *θ* is the angle of rotation. Once the system detects new tags, it will again calculate the distance and angle to correct the robot's path.

After entering the location, the algorithm will initiate the *RFID Subroutine,* in which all three antennas will initialize searching for surrounding tags. Once an inventory of tags has been obtained, the RFID reader will determine its current location. Based on its current location, the destination will be computed through distance and angle algorithms, and a travel path will be formed. If not enough tags have been found to determine the current location at the start, the system will invoke the *robot tag search subroutine,* and moves around the area in the predefined movement pattern. The process will be bypassed if a test pattern is already in motion. This process will allow the robot to maneuver the defined map in order to locate more tags upon the next scan. If the robot moves towards an out-of-bounds region, it will correct its movement based on a flag warning and rotate 180° towards the defined area. As the robot is moving forward, the front ultrasonic sensors and the IR sensor will constantly scan for potential objects. Only if both sensors detect an obstacle will the system initiate the "*Obstacle Avoidance Subroutine,*" in which the robot will navigate around the obstacle. At this point, the system will check if the robot has moved within the vicinity of the destination. If this is the case, a message will be displayed on the LCD screen indicating the robot has arrived at the desired location. The user will be able to choose at this point if another location will be selected, or if to stop the search.

IV. PRELIMINARY TESTING

The RFID Positioning Robot is a work-in-progress and preliminary testing has been completed. To test the ability in addressing the project requirements, the design team has created appropriate experiments to quantitatively and qualitatively assess the performance under a controlled environment. Data was collected and analyzed to validate the reliability of our system. Different experiments focused on testing each sub-system including: 1) iRobot's movement accuracy; 2) obstacle detection range; and 3) RFID localization.
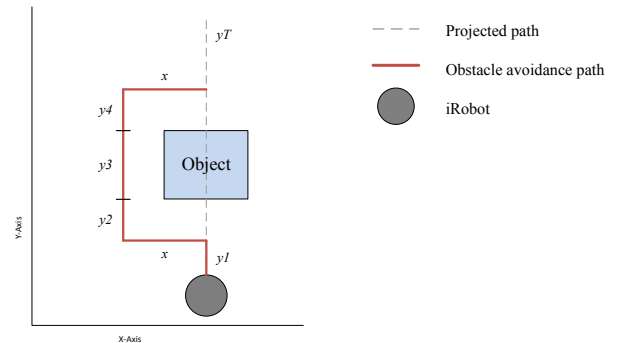

Fig. 4: Obstacle Detection Sensor Configuration

Fig. 5: Obstacle Avoidance Subroutine

The robot accuracy was tested to determine the error while traveling in a straight path. This data included change in the 'x' and 'y' coordinates as well as the orientation of the robot. Comparing the projected distance and the measured distance in multiple trials; driving the robot in 1.0 meter intervals. At each interval the robot location was measured and the error could be calculated when the robot travels a specified distance. The x and y errors were calculated to be 1.25% 1.5% respectively from the interval testing. Accordingly, it was found that the localization algorithm must account for any error encountered by the robot.

To accurately detect the location of an impending object, IR and ultrasonic sensor testing was completed. The testing of the ultrasonic sensor provided the beam pattern for our SRF04 to utilize the scanning area. Fig. 7 represents the beam pattern measured for the ultrasonic sensor. The two different beam patterns represent obstacle detection when the object is angled toward the sensor and when the object is parallel to the sensor. The sensing area was tested up to 5 ft. due to the scope of our project. While the ultrasonic can read up to 10ft, obstacles within the range of 3ft will be of a higher importance. Further testing was also performed to determine the distance at which the ultrasonic sensor would be most accurate. Fig. 8 shows the distribution of the accuracy after 500 readings. From the data it was found that distances less than 2.5 ft had an error under 6%. In the scope of our obstacle avoidance system, we will exclude objects outside of 3ft from the robot.
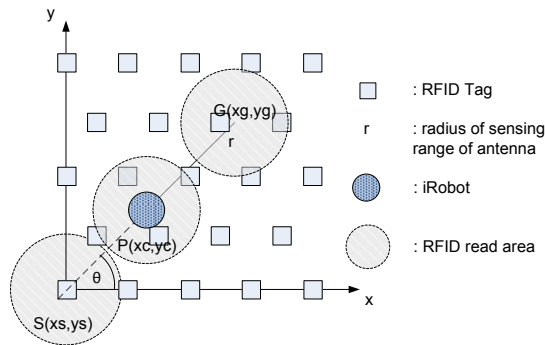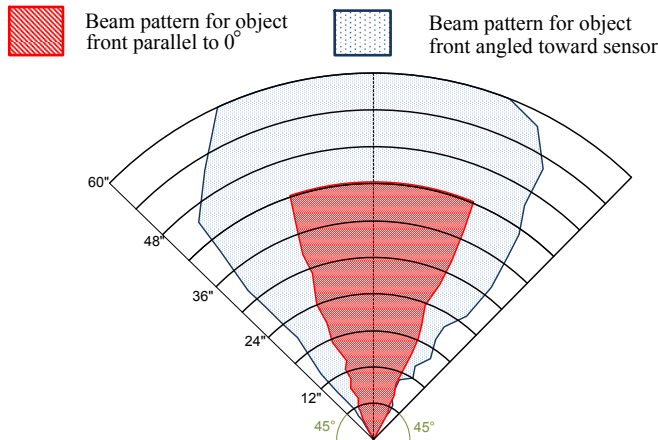
Along with testing of the ultrasonic sensor, testing of the IR sensor was done to determine an exponential relationship between the voltage output and the object distance. Fig. 9 shows this relation with the distance values. To accurately determine the distance of an object using the IR sensors, a relationship between the output voltage and the distance was determined as in eq (3),

$$y = 58.135x^{-1.129} \tag{3}$$

where, x represents the IR output voltage and y represents the object distance.

The RFID localization system was tested for optimal orientation, angle and placement of tags. During preliminary research, it was determined that each RFID antenna had a 180^0 read range. From this data, a theoretical read pattern was developed as in Fig. 10. The system is made up of three RFID antennas positioned in an equilateral orientation. This antenna placement was chosen to minimize overlapping of the antenna read patterns, maximize scan area, and avoid dead zones. The theoretical read pattern is broken down into six zones, in which only one antenna can read the larger zone, and two antennas can read the small overlapping zones. This method can be effectively used to localize the system through triangulation.

During testing, it was determined that the RFID system could read tags efficiently within 0.6m when RFID tags are placed in parallel to the antennas shown in Fig. 11. Similarly, it was also determined that the RFID system could read tags efficiently within 0.3m and 0.02m when RFID tags are placed
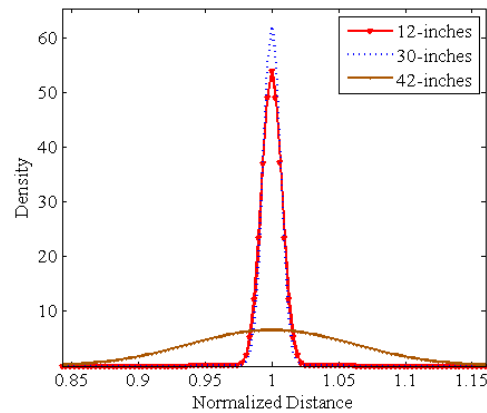

Fig. 6: Path Planning during Navigation

Fig. 7: Ultrasonic Sensor Beam Pattern

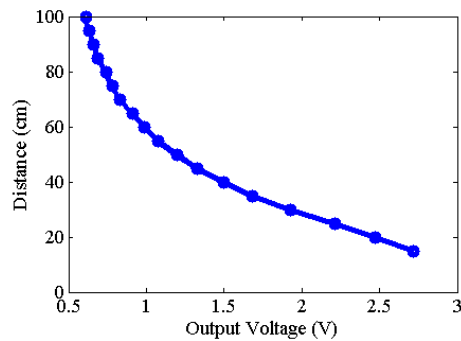**Fig. 8: Accuracy of Ultrasonic Sensor from multiple reads at different distances**

Fig. 9: Relationship between infrared sensor output voltage and obstacle distance

in at 45° and 90° with respect to the antennas shown in Fig. 12 and Fig. 13. Additional testing of read ranges with multiple tags, and combination of orientations is in progress, to determine the ideal placement strategy.
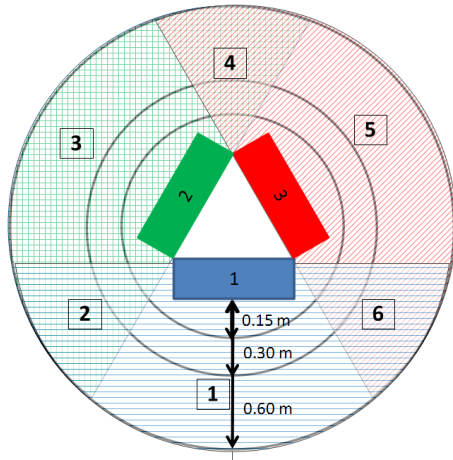

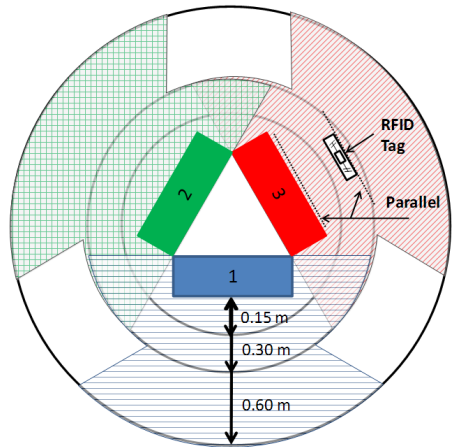**Fig. 10: Theoretical read range of RFID reader antennas**

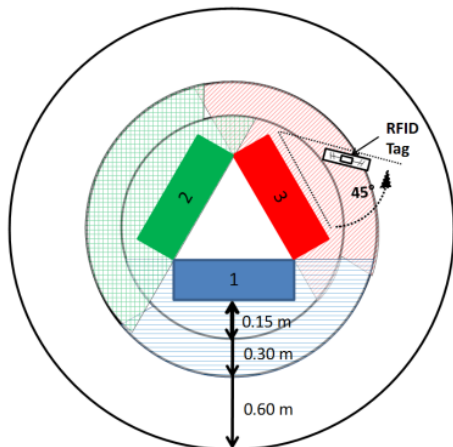**Fig. 11: Antenna read range with parallel tag orientation**

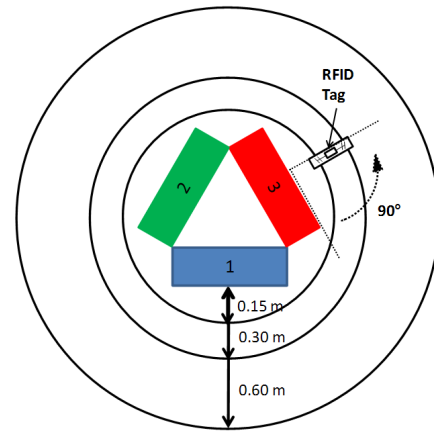**Fig. 12: Antenna read range with 45° tag orientation**

Fig. 13: Antenna read range with 90° tag orientation

V. CONCLUSION

The concept of utilizing RFID for indoor localization has been shown to be both technically and economically feasible. The RFID positioning robot was successfully designed to provide autonomous navigation for indoor applications. In the near future, we plan to improve the localization and navigation algorithm to improve accuracy. Further analysis will be performed to accurately identify a specified location by placing RFID tags at different distances and orientations. While we are currently able to determine our location within 30cm, further analysis will provide improvement on the accuracy.

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