A RFID LANDMARK NAVIGATION AUXILIARY SYSTEM

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ABSTRACT
This paper proposes the development of an RFID system to aid in the navigation of autonomous mobile robots. The use of the system to enable a mobile robot to estimate its pose is described. The paper presents a method to obtain fine orientation readings, a task neglected by former works. We also analyze one uncertainty source of this approach. Experimental and simulation results are presented in the paper to demonstrate the effect of the method. Finally, we present a possible alternative method to adapt to non-constant speed movement.

KEYWORDS: mobile robot, RFID, tags, navigation, calibration, pose estimation.

1. INTRODUCTION
For mobile robots most methods for measuring position are relative measurements. Readings of shaft encoders on robot wheels are frequently used to collect displacement information, since this information is simple to get and inexpensive. By counting the number of rotations of a robot’s wheels and using knowledge of the wheel size, the change in the position of a robot be obtained. A robot can then calculate its current position by integrating all past differential motions. This method is known as dead-reckoning. However dead-reckoning cannot be used to determine a robot’s exact position over long distances because the technique suffers from both systematic and non-systematic errors. Even if the systematic errors are modeled and compensated for, there will still exist uncertainty in the sensor outputs [1], plus unpredictable non-systematic errors such as wheel slippage. Therefore, the estimated position of a robot is described by an area (for example, an error ellipse [2]) rather than a point.

One way to improve the position estimation is to fuse odometry information with additional sensor data from sources such as GPS [3], INS [4] or cameras [5]. However, the above solutions are not fit for all environments or all mobile agents. For example, some robots are not big enough to hold GPS or INS systems. In addition, GPS signals are not available in many places, such as in buildings, caves, areas that are adjacent to tall buildings, and the surfaces of other planets. A robot’s vision may lose the ability to aid in navigation in low visibility environments and in open areas that lack distinctive features. In this paper, we propose a RFID (Radio Frequency Identification) based pose (position and orientation) calibration system for robots as a supplement for other localization methods. A cheap, durable, and robust RFID system is deployed in the robot’s working environment, and is used as an artificial landmark to help mobile agents calibrate their pose.

RFID is an information exchange solution based on an electromagnetic transmission technique. A typical RFID system is composed of a reader/antenna and a transponder/tag. The antenna is used to read/write or charge up tags. Many types of antennas and tags can be used. A gate like antenna has a large reading range, while a stick like antenna has better orientation selectivity. The tag is embedded in the environment and used to store brief information. Currently, RFIDs are used in many fields: security and access control, animal identification,
package tracking, etc. Some features of the RFID system allow their application for use in localization of mobile agents: 1) Such a system can exchange data without visual contact or physical contact. This means it can be embedded in the environment and dust or low visibility will not affect its function. 2) Since the passive tag can hold information without using any power for a long time, it’s a durable source of information. 3) RFID tags can be distinctive from each other by assigning them different IDs. This makes RFID tags an ideal landmark for use in robot localization. This paper introduces the implementation of an artificial landmark/calibration system that uses RFIDs. The calibration system may be placed in an environment by a robot during exploration, and used by subsequent robots traversing the same area. In this scenario, the second robot will benefit from the experience of the first robot.

2. RELATED WORK

RF techniques have been used for robot localization and tracking for many years. Bahl and Venkata presented an RF based system, RADAR, for locating and tracking users inside a building [6]. Olaf Kubitz, et al., presented an RFID application for autonomous mobile robots’ navigation in [7]. In their approach, an RFID is used as artificial landmark to offer topological position information and to facilitate a map matching process. G. Kantor, et al., described a system where RF tags are placed in known locations and, in conjunction with encoder and gyro data, are used to localize a robot moving in an open area [8]. Even in the case that the tag locations are initially unknown, the tag locations can be approximately determined using a batch scheme. These were continuously updated using the position of the robot and a Kalman filter. They also attempt to use this technology to help firefighters navigate in a burning building. Kurabayashi and Asama developed an IDC (Intelligent Data Carrier) module to help mobile robots navigate [9]. IDCs are deployed near key positions (such as pits, road junctions) to transmit information about the local environment via an RF signal, so that mobile robots may avoid obstacles and dead ends. In Vladimir Kulyukin’s research work, RFID tags were deployed at critical positions to trigger different robots behaviors, such as wall-following, left/right turning, passing doorways, etc. [10]. Hae Don Chon, et al., proposed embedding RFID tags in roads to help vehicles’ navigate in tunnels and downtown areas [11]. D. Hähnel, et al., presented a probabilistic measurement model for RFID readers that allow for accurately localizing RFID tags in an environment using long reading range gate antenna [12]. They also presented an approach to generate maps of RFID tags with mobile robots. Weiguo Lin, et al., presented a tag-camera combination as an indoor environment localization solution [14]. In their approach, localization is implemented with two steps: detecting ID tag in one node with RF communication and measuring position and orientation of a robot relative to this node with a camera. They use additional hardware and cameras to achieve fine heading information.

All of the above methods are used for robot localization. They either do not give fine orientation information or need additional devices to calculate robot pose. The purpose of this investigation is to develop a more affordable and less complex system. We propose a method that uses RFIDs to determine both a robot’s position and its orientation.

3. WORKING THEORY OF RFID CALIBRATE ARRAY

3.1 Hardware Setting

RFID antennas can read tags that are located in a region around the antenna. The combination of the antenna and transponder (RFID tag) types determines the distance and the shape of this readable zone. Because a stick antenna has higher orientation selectivity, it can distinguish different tags in a narrower region than a gate antenna can. Also, different types of transponders will be detected differently by an antenna. Fig. 1(a) shows several Texas Instrument tags. After comparing their performance (size, readable distance, readable zone size, whether readable zone is isotropic, etc.) we chose a 30 mm disk transponder as the tag in this project. Fig. 1(b) shows
one 30 mm disk tag’s readable zone for a stick antenna. Fig. 1(c) shows the readable area that was measured for an antenna set with three stick antennas mounted on the front of a robot. The poses of the three antennas are adjusted so that each antenna’s reading area is approximately a round shape region with 110 mm radius, with a partial overlap in each antenna’s readable range. Fig. 1(d) shows the antenna group mounted on a Pioneer mobile robot from ActiveMedia Robotics (aka MobileRobots, Inc.). These three antennas work alternatively to scan the area in front of the mobile robot. A multiplexer, located on the rear deck of the robot, is used to switch readings between antennas.

3.2 Basic Idea of the Approach

Fig. 2 shows the antenna set’s reading zone in front of the robot for a 30 mm disk tag. A1, A2 and A3 represent the three antenna’s circular shape reading zones, respectively. One tag has 4 possible states when captured by a mobile robot: 1) detected by antenna A1 only; 2) detected by both A1 and A2; 3) detected by both A2 and A3; and 4) detected by A3 only. For example, in the case shown in Fig. 2 the tag falls in A1’s reading zone. As a robot moves forward, a fixed tag will enter the reading range of an antenna, and then leave it. The position of the tag relative to the antenna will cut a trajectory, \( b \), through the antenna’s reading range, which is indicated by circle A1. The length of segment \( b \) is obtained by multiplying the velocity of the robot by the half-length of time the tag is sensed. The radius of circle \( r \) is known and \( a \) can be calculated from \( r \) and \( b \). Thus the distance between tag and robot’s axis \( d \) is obtained:

\[
d = \sqrt{r^2 - \left( \frac{1}{2} vt^2 \right)^2 + r}
\]  

(1)

Knowing \( d \) and \( h \) (the distance between the robot’s center (O) and antenna set’s center (O’)), the distance between the robot’s center and the tag is determined.

With a single tag, a robot’s position can be calculated, but not its bearing. For this, more tags are required. In this project, a set of 7 RFID tags is used to determine the pose of a robot. Each tag is given a different ID number, and the tags are placed together in a hexagon shaped array (Fig. 3). This array can be used to determine both position and heading information, and its size means that it is more likely to be sensed by a robot than a single tag is. Any two tags can be treated as a tag pair. Each tag pair’s relative heading and length relationships are stored in lookup tables as follows: the row index is for the first detected tag’s ID number, the column index is for the IDs of subsequent detected tags.
Figure 2. Scan range of the antenna set. 
\( r \) is the radius of reading zone; \( O \) represents the position of robot’s center and \( O' \) represents antenna set’s center. \( h \), the distance between the robot’s center and the center of the antenna set.

Figure 3. A scheme of RFID array. Any two tags can be used to calculate a robot’s pose. An array is used to increase the chance that robot capture at least two tags.

Table 1. Angles Between Different Tag Pairs (Unit: °).

<table>
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<tr>
<th></th>
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<th>ID2</th>
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<th>ID4</th>
<th>ID5</th>
<th>ID6</th>
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<td>-60</td>
<td>-30</td>
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<td>-30</td>
<td>0</td>
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</table>

Table 2. Distance Between Different Tag Pairs in mm (The length of each side of the hexagon: 400 mm).

<table>
<thead>
<tr>
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A typical calibrating procedure can be demonstrated with the help of Fig. 4. As a robot moves with a constant speed \( v \) over the tag array, two tags are sensed, one after the other. Secondly, according to each tag’s contact time duration and which antenna captured the tag, two tags’ distance to the robot’s moving trajectory (\( d_1 \) and \( d_2 \) in Fig. 4) can be determined. The angle between the calibrating baseline, \( \text{tag}_2 - \text{tag}_1 \) (shown by the line indicated by L in Fig. 4), and robot’s heading can be calculated by:

\[
\theta = \sin^{-1}\left(\frac{d_1 + d_2}{L}\right)
\]  

Figure 4. Illustration of the calculation of robot heading.
The length of baseline $L$ can be found in Table 2, and the relative angle between the baseline tags can be found in Table 1. The robot only needs to record how long the antenna maintains contact with any two tags. Then a heading difference from the baseline (determined by those two tags) can be calculated. Suppose the distance from a tag to a moving robot’s trajectory is $D$, the heading of the robot is $\alpha$, and the angle between baseline tags is $\beta$. The pose of the robot can be calculated by the following formulae:

$$\alpha = \beta + \theta = \beta + \sin^{-1}\left(\frac{C\pm \sqrt{r^2-(vt_1)^2} \pm \sqrt{r^2-(vt_2)^2}}{L}\right)$$ \hspace{1cm} (3a)

$$D = C' \pm \sqrt{r^2-\left(\frac{1}{2} vt_2\right)^2}$$ \hspace{1cm} (3b)

The value of $C$ could be $2r$, $r$, $0$, $-r$, or $-2r$, and the value of $C'$ could be $r$, $0$, or $-r$, depending on which antenna’s reading zone the tags fall into. $t_1$ and $t_2$ are the length of time the tags are sensed by the antennas. Eqs. (3a) and (3b) resolve the relative position between robot and the array. A simple coordinate transform then leads to the robot’s current coordinates.

### 3.3 Uncertainty Analysis of the Calibrating System

The precision of the above method depends on an antenna’s scan speed and the speed of the robot since $d_1$ and $d_2$ in Fig. 4 are based on Eq. (1). The finite RFID antenna scan rate limits the certainty of $t$. Antennas first need to charge tags before they can read the information stored in the tag. In general, the higher the magnetic field strength the antenna has, the shorter charge time. For the antenna-tag combinations used, the nominal charge and read time is 100 ms [13].

If $l=1/2v_1t$, the uncertainty in the measurement of $l$ due to the time required to read a tag is $dl = 1/2v_1 dt$. Let $d_1 = d_2$ for purposes of simplicity. Differentiating (3a) and (3b) then gives the uncertainty of the calibration due to $dl$:

$$d\alpha = \frac{-2l}{\sqrt{L^2 - 4(r^2-l^2)\sqrt{r^2-l^2}}} dl$$ \hspace{1cm} (4a)

$$dD = \frac{-l}{\sqrt{r^2-l^2}} dl$$ \hspace{1cm} (4b)

Eqs. (4a) and (4b) indicate that the uncertainties depend on both $dl$ and $l$, thus the trajectory of a robot as it traverses the tag array also contributes to the uncertainty in the pose estimations. Suppose a robot’s speed is 100 mm/s, the antenna sample rate is 10 Hz (i.e., the uncertainty caused by the limited scan rate is $dl = 1/2\times100\text{mm/s}\times0.1\text{s}=5\text{mm}$), antenna’s reading zone is set as a circle with radius of 110 mm, and the distance between tag1 and tag2 is 400 mm. The uncertainties in pose calculations in this case are shown in Table 3.

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<th>90</th>
<th>80</th>
<th>70</th>
<th>60</th>
<th>50</th>
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<tr>
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<td>2</td>
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Table 3.

### 4. SIMULATION AND EXPERIMENT RESULT

A series of experiments was performed to test the effect of the RFID auxiliary navigation system. A Pioneer 2-DX robot was equipped with an RFID antenna set (see Fig. 3a), and the three antennas sequentially scanned the ground in front of the robot for magnetic tags at a scan rate 2.5
Hz. The robot was placed at different orientations to a tag array, and set in motion such that it traversed the array at a set speed of 100 mm/s. Results are shown in Tables 4 and 5. In Table 4, data from 30 experimental runs is shown. “Real” is the robot’s actual orientation passing the array as measured by protractor, “Calculated” is the result from RFID scan system. The statistical parameters of the RFID system’s error are shown in Table 5.

<table>
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Table 4. Experiment Result. (Unit: °)

<table>
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<th>Std. Dev.</th>
<th>Std. Err.</th>
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<td>-0.467</td>
<td>8.8</td>
<td>2.97</td>
<td>0.54</td>
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</table>

Table 5. Measurement Error Statistics.

Computer simulations were run to demonstrate the effect the RFID can have on a robot’s pose estimations. In Fig. 5 (a), a robot is required to follow a predetermined path, using only odometry. The uncertainty in the odometry readings is set such that the statistical variance in the position is 5.4 mm for every 100 mm of forward motion and the statistical variance in angle is 0.4° for every turn. These values come from tests on a Pioneer 2 robot traversing a smooth surface in a laboratory setting. Uncertainty estimations were updated in both the x and y directions ($\sigma_x^2, \sigma_y^2$) after each incremental time step in the simulation. For simplicity, we chose $\text{Max}(\sigma_x, \sigma_y)$ as the radius of a circle (rather than an ellipse) to indicate the uncertainty in the robot’s position. The circles show the 95% confidence region for robot position after every 5 meters of movement, assuming the errors are normally distributed during each time step. The solid line in Fig. 5 is the path the robot is instructed to follow, while the dashed lines indicate a 500 mm width “safe path” around the desired path. It is seen that these circles grow with increasing distance traveled, and eventually extend far beyond the safe region around the desired path. The simulations were run again with a tag array placed every five meters along the desired path. The accuracy of the calibration system was set to the worst case shown in Table 3. The results are shown in Fig. 5 (b), which indicates that with the tag calibration system, the robot can stay within the 500 mm wide safe zone along a 25m path.
Figure 5. Simulation of RFID array’s calibration effect.
(a) A robot traverses a path using odometry readings only. The circles show the uncertainty in possible positions of the robot. (b) The robot traverses a set path using both odometry and the RFID system.

4. DISCUSSION AND FURTHER WORK

There are several possible applications of the RFID system. The RFID tags can be deployed as “checkpoints” by a robot exploring an unknown environment, such as a planet’s surface. These checkpoints can be used as an aid in navigation and to designate landmarks. In such environments, there is no existing GPS analogue available for global positioning. In addition, devices such as compasses, which provide good absolute heading measurements on Earth with respect to true north of its magnetic field are not as effective on planet surfaces with negligible magnetic fields (such as Mars). The RFID system provides a solution for improving the accuracy of navigation in finite work areas that lack supporting infrastructure like GPS, or sufficient features and textures conducive to vision-based localization methods. In the future, robots will build infrastructure at outposts for humans on planetary surfaces. To succeed they will perform tasks such as construction and mobile docking with various structures in finite areas of the outposts. RFID systems would be useful in various ways. They could facilitate handling and mating of structural assemblies that use tags to communicate alignment or assembly instructions to robots that manipulate them. To facilitate operations at an outpost such as multi-robot excavation of terrain, prospecting for and mapping of raw materials, and navigation in hazardous terrain topographies, RFID tag arrays could be used to ensure the required levels of localization accuracy, demarcate locations of raw materials as resource landmarks, and designate hazardous keep-out zones as landmarks to avoid. In addition to embedding absolute position data in the tag, applications could embed information about robot instructions, raw materials, terrain properties, etc. Of course a means for initial strategic placement and installation of tags arrays would be needed.

We believe RFID checkpoints can be combined with other position estimation techniques to continually improve localization estimates. Each robot’s position estimation can be weighted by its uncertainty variance and fused into the original calibration system’s estimation by a data fusion algorithm such as Kalman filter [14][15][16]. And any visiting robot with an RFID reader and antenna can easily update the information stored in the tags.

All of the above work is based on perfect measurement assumption. However, in the real world, RF detection range and size can be affected by environmental factors, such as the presence of metal in the reading zone.

5. CONCLUSION

This paper proposes a new application of RFID technology. Several RFID tags form an array that can be used to calculate bearing and position information for mobile robots. The uncertainty caused by RFID’s limited scan speed is analyzed: when robots move with a 100mm/s speed, the worst orientation error is less than 5 degrees. Experiments and simulations indicated that the method has the potential for use in practical applications. Although some work needs to be done to improve the performance of this approach, the proposed method is a promising, inexpensive and robust way to improve robot navigation. Moreover, the method can be employed in several applications, such as autonomous planet surface exploration, robotic tour guiding, cave or mine rescue operations and helping the visually impaired.

6. REFERENCES


