COOPERATIVE LOCALIZATION
Self-configuring Procedure of a Multi-robot Localization System with Passive RFID Technology

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Abstract: This preliminary simulation study introduces methods to configure a low cost localization system based on existing passive RFID technology. A group of small robots work together in order to configure the system autonomously. Probabilistic estimation methods are used for data fusion. The robots should be able to build and expand the localization system without human aid. When properly configured the system is able to offer positioning information with bounded error. The use of passive RFID tags as beacons makes the cost of expanding the robots' working area negligible.

1 INTRODUCTION

For a successful task execution a mobile robot has to know its position and heading. Different kinds of localization methods have already been developed. There are systems where all the needed equipment for the localization (wheel encoders, gyroscopes, laser scanner, etc.) is on board the robot. One problem with this kind of localization system is that over time the robot's estimate of its absolute location can get too erroneous for effectively continuing the mission. Also the cost of the high precision equipment can be considerable.

Another approach is to use external references such as beacons or landmarks for localization. The mobile robot can use absolute position data provided by measurements and calculations involving these external objects in order to obtain a better position estimate. The main problem with this kind of system is that the installation of the required external objects can be costly and time consuming.

The system introduced in this paper uses passive RFID tags as beacons. A passive RFID tag contains an antenna and an IC with small (0-1kbit) memory capacity. It operates on the power obtained from the reader antenna. A typical operating range for a 900MHz system is up to 2 meters. The cost of one tag is only a few cents and it does not need external connections or a power supply. Also the sticker-like tags are light to carry and a robot can place them on suitable spots when moving to new working areas.

A multi robot approach is used for the system configuration in order to replace the need of highly accurate sensors for robot's localization in the initial phase. Using a group of robots instead of one robot also gives better fault tolerance as a single fault will not endanger the whole mission.

2 RELATED WORK

Several studies have already been made on passive RFID localization in robotics using a mobile RFID reader (Hightower et al. 2000; Hähnel et al. 2004; Bohn 2006; Kulyukin et al. 2004 and Kleiner et al. 2006). All of these are very different from each other. Kulyukin et al. use a RFID system for recognition of specific places inside a building. The system is intended to help visually impaired people recognise specific office doors, elevators, etc. Kleiner et al. have been successfully using RFID tags for sharing mission related information in a

rescue scenario involving both robots and humans. Bohn introduces a super-distributed RFID tag infrastructure, where mobile objects may leave virtual traces in the physical space they traverse by writing an ID to the tags in the floor (up to 120 tags/m^2) while passing directly above them. Hightower et al. have designed a system to help people to localize objects equipped with passive RFID tags in their vicinity.

Hähnel et al. study the problem of localizing RFID tags with a mobile platform equipped with a laser scanner and a pair of fixed RFID antennas. A probabilistic sensor model of each antenna is used to estimate location of a detected tag. When a tag is detected for the first time a set of 1000 randomly chosen positions around the robot are chosen for initial estimates of the location of the tag. With each measurement the probability of these locations is calculated according to the sensor model. This is a single robot approach where the robot builds a database of tag positions. When localizing a robot with the RFID tags and odometry the position error was about 1 m.

The system proposed in this paper is based on similar technology as the aforementioned system by Hähnel et al. However, there are three major distinctions. Our approach uses several simple robots instead of one sophisticated robot. Instead of one database, the localization data is distributed to the tags. Also the relative displacement between the robot and a tag is based on measured bearing angles and not on a simple sensor model.

3 OPERATING PRINCIPLE

Our key interest is in developing a self configuring localization system using a group of simple, inexpensive robots. The idea is that even if the robots have only wheel encoders and an RFID reader for localization purposes they should be able to localize themselves within bounded error. An RFID reader is placed on each robot and stationary tags are placed around the working area of the robot group. The tags can be distributed by humans or by robots if they are equipped with an appropriate system (Kleiner et al. 2006)

The cooperative localization is based on a simple Kalman filter. When the robots are configuring the system and localizing the tags the main source of error is the accumulated odometry error which, on a group of robots, is assumed to follow roughly a Gaussian distribution. Thus when the location estimates of several independent robots on a

common object are combined, the location estimate of the object converges towards the correct position.

3.1 System Operation

In the beginning the passive RFID tags contain no data. The robots start at some chosen reference location. A robot uses wheel encoders in order to keep track of its current position. When a robot detects an RFID tag it calculates an estimate for the location of the tag. The estimate of the tag's location has an uncertainty, which is calculated each time the tag's location is estimated. The necessary algorithms are explained in chapter 3.2.

The location estimate and the uncertainty are stored in the memory of the tag. The next robot that detects the tag reads the information found on the tag and calculates a new estimate for the location of the tag by combining the information stored in the tag with the new measurements.

As soon as there is a position estimate stored in the tag's memory the robots can use the tag as a beacon in order to correct their own position. When exploring new areas the robots have to return often to areas with well localized beacons in order to maintain reasonable estimate of their own position.

3.2 RFID Localization

The RFID localization is based on the measured bearing angle to a beacon represented by a passive RFID tag. The antenna of the RFID reader is turned one full circle while trying to contact tags near the robot. For each detected tag a bearing angle is calculated based on the sector where the tag responded to the calls of the RFID reader.
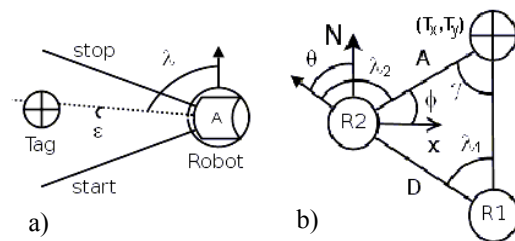

Figure 1a: Bearing angle estimation for a single RFID tag. 1b: Tag localization method.

The Figure 1a shows how the bearing angle of the tag is estimated. The start and stop angles define a sector where the tag responded to the readers calls. The bearing angle estimate λ is obtained by solving for the middle of the sector and subtracting the

systematic error ε. The systematic error depends on the geometry of the antenna and the immediate surroundings of the antenna's mounting place. It must be defined separately on each robot unless the robots and the antennas are exactly alike.

3.2.1 Tag Localization

The robot uses bearing angle measurements and odometry data in order to estimate the tag location (E_x, E_y). In Figure 1b places R1 and R2 represent two places where the robot has measured a relative bearing angle to the tag. The distance A to the tag is solved from the displacement D between the measurement places and the gamma angle. The absolute bearing angle φ is calculated as a function of the measured relative bearing angle λ_2 and the robot's estimated heading angle θ. A variance is calculated for each tag location estimate. The x- and y-coordinates have different variances which depend on the angle φ. The C and G are parameter constants

$$\gamma = |\lambda_2 - \lambda_1| \tag{1}$$

$$A = \frac{D \cdot \sin(\lambda_1)}{\sin \gamma} \tag{2}$$

$$\varphi = \frac{\pi}{2} - \theta + \lambda_2 \tag{3}$$

$$\begin{aligned} E_x &= r_x + a \cdot \cos(\varphi) \\ E_y &= r_y + a \cdot \sin(\varphi) \end{aligned} \tag{4}$$

$$\begin{aligned} var_x &= C + \frac{G \cdot \left| \cos\left(\varphi + \frac{\lambda_1 - \lambda_2}{2}\right) \right|}{\gamma^2} \\[2mm] var_y &= C + \frac{G \cdot \left| \sin\left(\varphi + \frac{\lambda_1 - \lambda_2}{2}\right) \right|}{\gamma^2} \end{aligned} \tag{5}$$

With each new angle measurement the robot calculates location estimates for the tag using all the previous angle measurement. Thus after two measurements the robot has one estimate for the tag location and n measurements give 1+2+3+...+(n-1) estimates.

Each estimate is fused with the previous estimate of the tag location using a simple Kalman filter. It is a recursive estimator, so all the prior information is contained in the previous estimate (Maybeck, 1979). The calculated variance P_k represents the uncertainty

in the location of the tag. The equations for the Kalman filter are shown below.

$$K(k) = \frac{P(k-1)}{P(k-1) + var} \tag{6}$$

$$x(k) = x(k-1) + K(k) \cdot [E - x(k-1)] \tag{7}$$

$$P(k) = P(k-1) - K(k) \cdot P(k-1) \tag{8}$$

Odometry error and angle measurement error may both cause significant deviation from the correct position. Thus several estimates from different robots are needed in order to properly localize the tag.

4 RESULTS

Simulation models for the multi-robot localization system were built in order to get an idea of the effects of different measurement errors. The simulations were run on Matlab. The system presented here simulates a scenario where a single tag is localized by a group of robots passing the tag one by one. Each robot has random error on its own position and heading angle estimate. Each bearing angle measurement also contains a random error. After each bearing angle measurement the robot calculates new estimate of the location of the tag. The result is then written on the tag's memory. A robot is able to detect the tag inside a circular area (r=50cm) in front of the tag. If the tag already contains an estimate of its position, the robot tries also to correct it's own position.

4.1 Effects of Inaccuracies

Several simulations were run with different parameters in order to discover the effects of inaccuracies in different estimates. First simulation contained 500 independent groups of ten robots passing the tag and localizing it cooperatively. The Figure 2 shows the average and maximum error in the estimated location of the tag as a function of the error in the bearing angle measurement for two different runs.

The curves A and C represent average and maximum error when the robots' position error was at most ±8 cm on each axis. The curves B and D represent a run where robot's position error was doubled to ±16 cm. The maximum heading angle

error was ±4° on both runs. The simulation results show that the bearing angle error is a lot smaller factor than the error in robot's position.
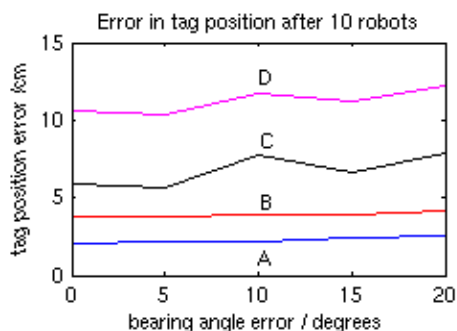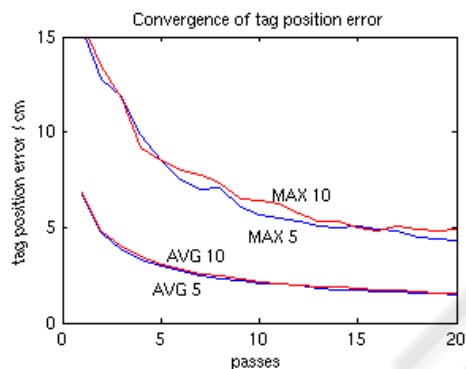

Figure 2: Effect of the bearing angle error.

Figure 3: Convergence of tag position estimate.

The Figure 3 shows the convergence of tag's position estimate when 1000 independent groups of 20 robots pass a tag. Two runs with different bearing angle error factors (5 and 10) were made. The curves show average and maximum error in tag position after each robot. The increase in bearing angle error does not have significant effect on the position error. Also a smaller group of robots can localize a tag when they pass the tag multiple times.

5 CONCLUSIONS

The simulations indicate that the tags can be localized with certain accuracy even if the angle measurement to the tag is not very accurate. The error in the tag's position depends on several different factors, such as errors in robot's position and heading angle estimate. When several robots participate in the localization the position error settles on an acceptable level.

This study suggests that it is possible to build a localization system that offers a bounded error after it has been autonomously configured by simple, inexpensive robots with readily available RFID technology.

6 FUTURE WORK

Initial tests for the bearing angle measurements in the office environment are under way. The first RFID localization modules for laboratory tests will be designed according to the information obtained from the angle measurement tests. The system will be tested with a group of small robots. In order to obtain accurate localization information further research is required in tag positioning and filtering of the bearing angle measurements in an office environment.

ACKNOWLEDGEMENTS

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