A Probabilistic Approach for Mobile Robot Localization under RFID Tag Infrastructures

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***Abstract* – SLAM(Simultaneous localization and mapping) and AI(Artificial intelligence) have been active research areas in robotics for two decades. In particular, localization is one of the most important issues in mobile robot research. Until now expensive sensors like a laser sensor have been used for the mobile robot's localization. Currently, as the RFID reader devices like antennas and RFID tags become increasingly smaller and cheaper, the proliferation of RFID technology is advancing rapidly. So, in this paper, the smart floor using passive RFID tags is proposed and, passive RFID tags are mainly used to identify the mobile robot's location on the smart floor. We discuss a number of challenges related to this approach, such as RFID tag distribution (density and structure), typing and clustering. In the smart floor using RFID tags, because the reader just can senses whether a RFID tag is in its sensing area, the localization error occurs as much as the sensing area of the RFID reader. And, until now, there is no study to estimate the pose of mobile robot using RFID tags. So, in this paper, two algorithms are suggested to. We use the Markov localization algorithm to reduce the location(X,Y) error and the Kalman Filter algorithm to estimate the pose(q) of a mobile robot. We applied these algorithms in our experiment with our personal robot CMR-P3. And we show the possibility of our probability approach using the cheap sensors like odometers and RFID tags for the mobile robot's localization on the smart floor.**

***Keywords* – Localization, Kalman filter, Markov localization, SLAM, RFID, smart floor**

I. INTRODUCTION

Until a recent date, Robots are used in few fields of industry and their uses have been limited in a little task. They are fixed at a certain point and just carry out same patterns of tasks repeatedly. But, nowadays, robots can carry out various tasks like guide and guard as the technologies of a robot are advancing rapidly. And a mobile robot can go around place to place. At present, the core technology needed for a mobile robot is localization. A robot should recognize their location in the environment to do various task elaborately. So, the study for localization of a mobile robot is made actively. Another important technology for a mobile robot is a map building because a robot must know the information of the environment for localization. SLAM(Simultaneous localization and mapping) is the method to carry out localization and map building simultaneously. In most of the study, dead reckoning , passive land marks recognition and map based methods have been used in mixed forms for SLAM. Odometry and inertia sensors, vision and range finders are used for these methods. These methods have some demerits. Natural landmarks recognition method using vision requires high computing power and the laser range finder is too expensive.

So, in this paper, we used the passive RFID(Radio frequency identification) tags for a smart floor environment and mobile robot's localization. A RFID tag is small and inexpensive and a robot can localize fast with this system. Firstly, we suggest the efficient arrangement and sensing methods of the RFID tags for a smart floor. There are some demerits in the RFID tag based localization method. A RFID reader just senses whether a RFID tag is in its sensing range or not. So localization error occurs as much as the sensing range of a reader and it is hard to get the robot's accurate pose information for this error. So, in this paper, we suggest the probability methods to improve this problem. We use the Markov localization method to reduce the position(X,Y) error and Kalman Filter method to estimate the robot's pose(q). We can raise the measurement accuracy of the robot's position and pose using the inexpensive sensors like odometry sensors and RFID tags.

As the RFID tag becomes small and inexpensive, the studies for using it in various fields have been carried out rapidly. They mostly have been used in the distribution industry. RFID tags can save the tracking and other information of mobile objects to manage them efficiently [1]. Recently, the RFID system is used as a sensor in the robot's field. In most of the previous methods, the RFID reader is fixed and the objects attaching the RFID tags move. But, in our RFID tag based localization system, many RFID tags are located at the place like a room and office, and the robot mounted a RFID reader goes around and recognizes them. For this reason, the most important issue in the smart floor is how to arrange the RFID tags in the environment.

II. RFID TAG SYSTEM

A. RFID Tag Distribution

There are two methods in the RFID tag arrangement like the random uniform distribution method and the regular distribution method. Many patterns of arrangement are introduced as a regular distribution method such as the grid pattern and the equilateral triangulation pattern.

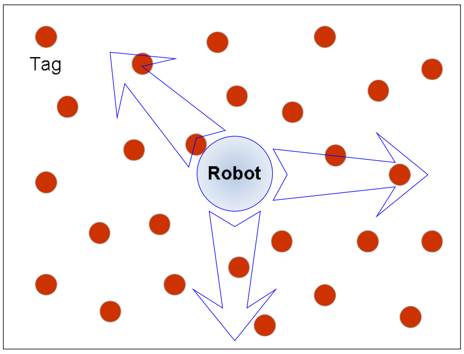


Figure 1. **Random uniform tags distribution method**

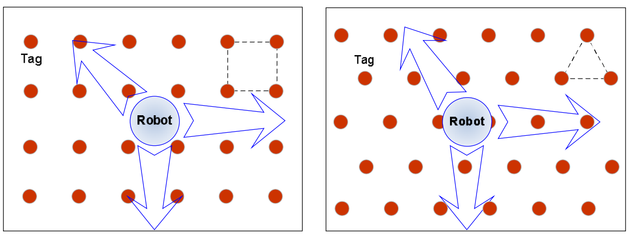
If we arrange the RFID tags arbitrarily but at the regular density by the random uniform distribution method like Figure 1, the probability that the robot senses a RFID tag "k" is not zero at any position.

$$p(tag_k \mid direction_i) \neq 0 \qquad (1)$$

But, if we arrange the RFID tags maintaining the same distance and pattern by the regular distribution method, the undesirable case that a robot doesn't sense any RFID tags can be occurred

$$p(tag_k \mid direction_i) = 0 \qquad (2)$$

We can prevent the occurrence of this case by raising the arrangement density of RFID tags. But if we raise the arrangement density of RFID tags, the cost raises too and the collision problem that a RFID reader senses too many RFID tags occurs.



a) Grid pattern b) Equilateral triangulation pattern

Figure 2. **Regular tags distribution methods**

In the case of applying the regular distribution, we must arrange RFID tags maintaining the regular distance and pattern, but getting the localization information is easy and we can apply it in a robot's localization without an additional special algorithm. In the case of using the random uniform distribution, we can arrange RFID tags easily, but the additional position setting algorithm for the RFID tags is required because of the irregular distances between tags. In this paper, we use the regular distribution method and arrange the RFID tags in the equilateral triangulation pattern which provides high probability in recognizing the tags.

B. Tag Recognition Errors

Localization error occurs as much as the sensing range of the RFID reader and it is hard to get the robot's pose information because a RFID reader just senses whether a RFID tag is its sensing range or not. In this paper, we suppose that the robot's moving direction is parallel to the virtual straight line where the RFID tags are laid and RFID tags come up to the sensing range of the RFID reader in the opposite direction. Figure 3 shows the localization error in the direction of Y axis. If the odometry information is not accurate when the sensor gages the RF signal power or the RFID reader passes the detection area, the errors specified like the equations (3),(4) occur when the RFID reader senses the RFID tag.

$$\text{Y axis : } 0 \leq p_{errorY} \leq R \qquad (3)$$

$$\text{X axis : } |p_{errorX}| \leq \sqrt{R^2 - p_{errorY}^2} \qquad (4)$$

As we can see in Figure 3, if the distance between the robot's (or reader's) center and the RFID tag's can be measured when the robot moving, the RFID tag system's error can be corrected. The center of RFID reader also can be estimated using the continuous repeat mode of the reading mode. In this case, the robot use the information of the odometry and the number of the answer from the RFID tags during the RFID reader is in the sensing range of one RFID tag.

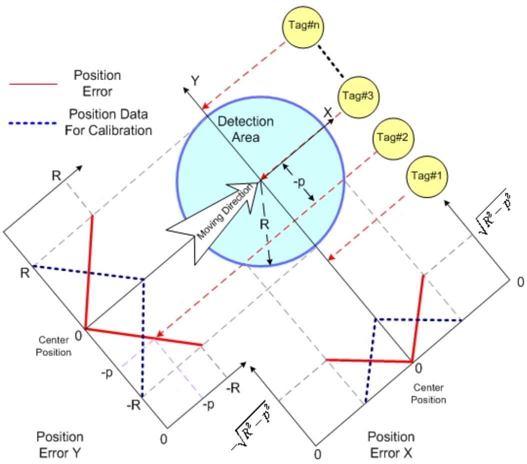


Figure 3. Position error

In this paper, we use the probability methods to reduce the localization error of the RFID system. As the result, we can reduce the sensing error that results from RFID reader's sensing range and raise the accuracy of localization even in the environment where the density of RFID tags is low.

III. LOCALIZATION WITH RFID TAGS

The direction (Θ) is estimated by the angle between the two RFID tags which a robot passed one after another. The robot's accurate position information is needed when sensing a RFID tag to estimate the robot's direction precisely. But, with the RFID tags based localization method, a robot cannot find its accurate position (*x, y*). A robot just can determine whether it is near the position (*x`*, *y`*) of the informed RFID tag in a certain distance. The distance error between the robot's real position and the estimated position is proportion to the standard deviation of the distance between the RFID tag and the RFID reader. So, we apply the Markov localization to find the robot's position more accurately and Kalman filter to estimate the robot's direction. The accuracy of the position and the direction is related each other. We can raise the accuracy of the direction by raising the accuracy of the position, and estimate the robot's position in the area where the robot cannot sense the any RFID tags by estimating the robot's direction precisely.

A. Position estimation

In this section, we show the process to estimate the robot's position (*x, y*) applying the Markov localization. We use the 2-dimentional array of 141 x 141 with the resolution of 1cm x 1cm to show the belief state of the robot's position. In general, 3-dimentional arrays are used to find the robot's position (*x, y, Θ*) in the Markov localization. But in this paper, we suppose that a robot is at the center of the array and limit the belief state to 70cm from the robot.

If l is the robot's position represented as (*x, y*), l_t is the robot's true location and L_t is the state variable of robot's location, the robot's position belief $Bel(L_t = l)$ at time t is defined like the equation (5) as a probability density.

$$Bel(L_t = l) = P(L_t = l \mid s_{1,\mathbf{K},t}, a_{1,\mathbf{K},t-1}) \tag{5}$$

In this equation, a_i and s_i are the input data of the motion model and the perception model at time i.

Firstly, the motion model is used to estimate the robot's present position. In this model, the probability at the present position $Bel(L_t = l)$ is dependent on the probability at the previous position $Bel(L_{t-1} = l')$. The motion model with the control input a_{t-1}, is specified as a conditional density like the equation (6).

$$P(L_t = l \mid L_{t-1} = l', a_{t-1}) Bel(L_{t-1} = l') \cdot \tag{6}$$

The probability that the robot's position is l at time t is specified like the equation (7) from the total probability and the Markov assumption[4].

$$Bel(L_t = l) = \sum_{l'} P(L_t = l \mid L_{t-1} = l', a_{t-1}) Bel(L_{t-1} = l') \tag{7}$$

The conditional density $P(L_t = l \mid L_{t-1} = l', a_{t-1}) Bel(L_{t-1} = l')$ is represented using the 2-dimentional array of 21 x 21 with the resolution of 1cm x 1cm. The probability at the position (l_x, l_y) is specified like the equation (8).

$$\begin{aligned} Bel(L_t = l) &= h \cdot \exp\left(-\frac{\sqrt{(\Delta x + l_x)^2 + (\Delta y + l_y)^2}}{2d \cdot s_d^2} \right) \\ &\cdot \exp\left(-\frac{q \cdot \left(\tan\left(\frac{\Delta x + l_x}{\Delta y + l_y} \right)^{-1} \right) - q}{2d \cdot s_q^2} \right) \end{aligned} \tag{8}$$

$$d = \sqrt{\Delta x^2 + \Delta y^2}$$

$$q = \tan\left(\frac{\Delta y}{\Delta x} \right)^{-1}$$

In this equation, *Δx and Δy* are the distance that the robot moves in straight along with a x-axis and a y-axis, l_x, l_y are the robot's position in the 2-dimentional array, h is normalizer and s_d^2, s_q^2 are the variances of the robot's moving distance and direction change.

The robot's position is renewed by the perceptual model when there is the input of useful sensor data. In this case, $Bel(L_t = l)$ is defined like the equation (9)

$$Bel(L_t = l) = h_t \cdot P(s_t \mid l) Bel(L_{t-1} = l) \tag{9}$$

In this equation, h_t represents the probability density normalizer $P(s_t \mid s_{1,\mathbf{K},t-1}, a_{1,\mathbf{K},t-1})^{-1}$ which is independent of L_t.

The Gaussian PDF(probability density function) was used for the sensor model of the RFID tag system like the equation (10).

$$P_m(d_i \mid l) = \frac{1}{s\sqrt{2p}} \exp^{-\frac{(d_i - tag_{cp})^2}{2s^2}} \tag{10}$$

In this equation, s is the standard deviation of the sensing values of the RFID system, tag_{cp} is the real center position of the RFID tags and d_i is the position of a point represented in the sensor model.

The accurate robot's position is not found by the RFID reader in sensor model because the RFID reader just can senses whether a RFID tag is in the sensing area or not. So we used the sensor model for the robot's position estimation to improve this problem.

B. Pose estimation

In the Previous section, we suggested the method to reduce the robot's position error results from the sensing distance of RFID tag system applying the Markov localization. In this section, we suggest the method to estimate the robot's pose q . For applying the standard Kalman filter model, we suppose that the robot's system model is a Linear Dynamic System and corrupted by the white noise represented as a Gaussian distribution.

We use the system model of the standard two-wheeled mobile robot to estimate the degree of the robot's location change (Δx, Δy, $\Delta\theta$). Δx, Δy is the same value used in the equation (8) of the section A. We omit prediction equation, orrection equation, error covariance propagation equation because they are general equations used in the Kalman filter model.

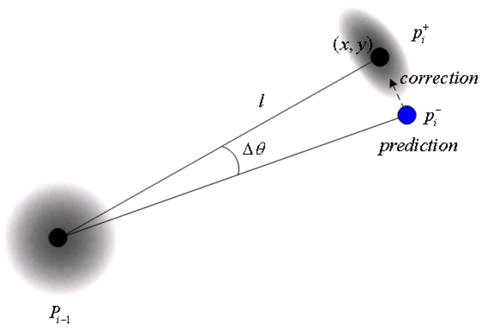


Figure 4. The Pose Estimation Method

The correction step is processed when a robot senses a RFID tag. In this step, the standard deviation σ is needed, but σ_x and σ_y of the RFID tag and sensor are too big to be used in the correction and σ_θ cannot be found directly.

In this paper, we suggest the method to find the standard deviation (σ_x, σ_y, σ_θ). Figure 4 shows the correction process in the case that the robot sensed the ith RFID tag and moved in a straight line and senses the (i+1)th RFID tag right away. If the robot senses a RFID tag, we can find the position showing the highest probability that the robot may be. We suppose it as the position where the robot is. Then the robot's pose q must be corrected as much as $\Delta\theta$.

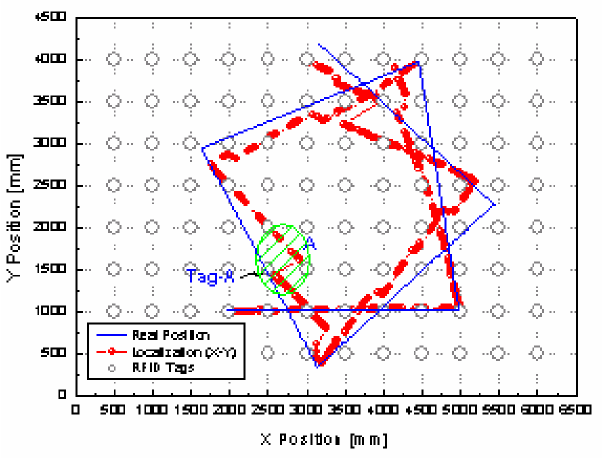
The method to approximate the standard deviations σ_x, σ_y from the belief state map of the Makov localization is like the equation (11). We can find the position of $2\sigma_x$ in the Gaussian function. We can find the position ($x_{p\text{-}max}$, $y_{p\text{-}max}$) showing the highest probability (p_{max}) and then, in the direction x+ and x-, search the position (x_{i-}, x_{i+}) where the probability is less than 1/8 of p_{max}. This is the position of $2\sigma_x$ in Gaussian function. σ_y is founded in the same way.

$$\begin{bmatrix} s_x \\ s_y \\ s_q \end{bmatrix} = \begin{bmatrix} \dfrac{\max\left(\left|x_{p-\max} - x_{i-}\right|, \left|x_{p-\max} - x_{i+}\right|\right)}{2} \\ \dfrac{\max\left(\left|y_{p-\max} - y_{i-}\right|, \left|y_{p-\max} - y_{i+}\right|\right)}{2} \\ \tan\left(\dfrac{\max(s_{x:i-1}, s_{y:i-1}) - \max(s_{x:i}, s_{y:i})}{l}\right)^{-1} \end{bmatrix} \quad (11)$$

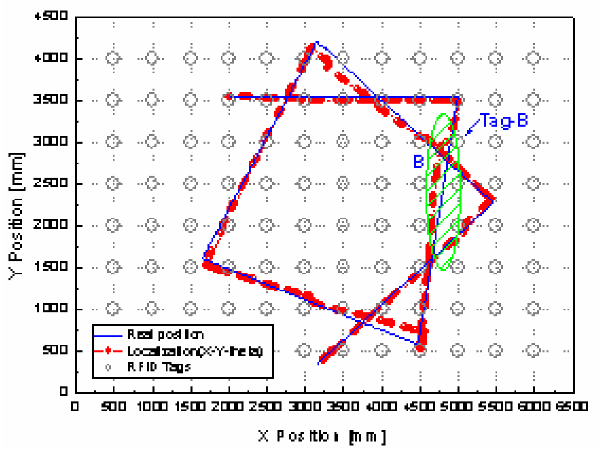
In this equation $s_{p:i}$ is the standard deviation of position derived form Gaussian PDF. This equation shows that the standard deviation of q is dependent on the standard deviation x,y. The robot's pose error is reduced by the process of prediction and correction.

IV. EXPERIMENTS

We simulate RFID based localization system applying the Kalman filter and Markov localization. In this simulation, we apply the standard model for Motion model. It has mostly been used in previous study. We arrange RFID tags at 500mm intervals by the grid pattern method and use the antenna of which radius is 100mm. Figure 5 shows the results of the simulation. This Figure shows the results of correction of X-Y and X-Y-q applying our localization algorithm. If a robot finds its position X-Y using only the position information getting from the RFID tags, the localization error increases continuously. In the Figure 5-a), before a robot come into the slanting lined area A and find a RFID tag, the robot cannot recognize its correct location. And find its correct location at the moment that the robot senses the Tag-A. So we estimate the robot's pose q applying the Markov localization and the Kalman filter localization algorithm. As the result, The localization error can be reduced remarkably as we can see in Figure 5-b). And the localization error is reduced in proportion to the number that the robot senses the RFID tags.



a) RFID based X-Y estimation



b) RFID based X-Y-q estimation

Figure 5. Results of the simulation

In this paper, we construct the smart floor using the RFID tags based on the results of our simulation. But we arrange the RFID tags by the equilateral triangulation pattern because the probability that the robot senses the RFID tags is higher than in the grid pattern method. Figure 6 shows the pattern of the arrangement of the RFID tags of smart floor.

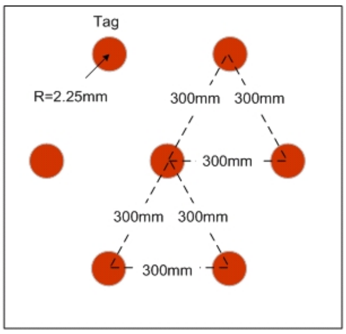
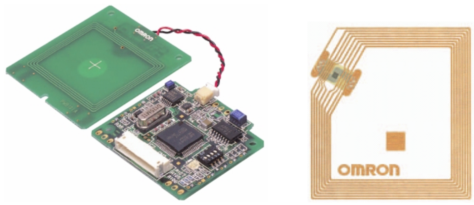


Figure 6. **RFID tag distribution**

The RFID system we construct is showed in Figure 6. This system consists of the V720D52P02 RFID tag and the V720-HMC73T RFID reader of OMRON. And the frequency of the RFID is13.56MHz. We mounted this RFID reader to the CMR-P3 which was developed as a differential type in KITECH.



a) V720-HMC73T RFID reader **b) V720D52P02 RFID tag**

Figure 7. Electromagnetic inductive RFID system [OMRON]

V. Conclusions

In this paper, we analysis the efficient arrangement method of the RFID tags for the smart floor. We suggest the sensor model of the RFID tag to reduce the robot's localization error applying the Markov localization and the Kalman filter localization algorithms. Especially, we can raise the accuracy of the robot's localization by correcting the robot's pose q and the X-Y position. In the previous study, some range finders have been used with RFID tag systems for the localization. They used the RFID tag system for position recognition and corrected the robot's pose q using range finders. But we carry out two process only using the RFID tags.

We reduce the error of the robot's pose q applying our localization algorithm. But it still has influence on the location error slightly. Furthermore, if the robot doesn't move in the straight line between two RFID tags, the error will get bigger. So, we will continue the study to reduce this error. And the studies about the most suitable RFID tag density and the path planning algorithm are needed for the most suitable localization.

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