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An Efficient Localization Algorithm for Mobile Robots based on RFID System

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Abstract: This paper presents an efficient localization scheme for an indoor mobile robot using an RFID system. The mobile robot carries an RFID reader at the bottom of the chassis, which reads the RFID tags on the floor to localize the mobile robot. Each RFID tag stores its own absolute position which is used to calculate the position, orientation and velocity of the mobile robot. However, a localization system based on RFID technology suffers from the estimation error inevitably. In this paper, a scheme to reduce the estimation error is newly introduced. Also for more efficient localizations, the orientation-estimation algorithm is introduced using only one RFID reader attached at the robot. In order to reduce the position error generating within RFID reader recognition area, an error-compensation algorithm based on the relations of the localization error to the gap between the tags and the velocity of the robot, is proposed. The main ideas proposed in this paper are successfully demonstrated to raise the accuracy of the robot localization through experiments.

Keywords: RFID, Localization, Mobile robot.

1. INTRODUCTION

An RFID (Radio Frequency IDentification) technology is a non-touch recognition system that transmits and processes the information on events and environments using a wireless frequency and small chips [1]. The RFID system can recognize at high-speed and send data within various distances. Therefore, the application of the RFID technology has been increased and an RFID has been applied for the robot technology (RT) recently [2-3]. With the development of the personal robot and advanced ubiquitous network robots, it is essential for the robots to recognize its own location and the environment and to keep high security in a common space with peoples. If an RFID technology is properly applied for the robot, the services for the users can be provided by the service robot at anytime at any places. The passive RFID technology has been utilized for the researches to recognize the position of the service robot [4]. There is a method that RFID passive tags are arranged on the floor to provide the absolute position data, which are free from the problems of conventional systems [5-6]. Note that dead reckoning sensors suffer from accumulating errors, laser and ultra-sonic sensor from line-of-sight, and CCD from the illumination. The absolute location of the robot can be obtained robustly, with the RFID tag and reader in sensor network space [7-8] where sensors are properly embedded several places to provide the absolute position information to the service robot. However some shortcomings are found in the localization systems using the RFID [9]. The antenna detects several tags within its detecting range and the numbers of detected tags are not constant all the times, which causes the position estimation error. On account of this problem, the precise localization system can not be achieved using the RFID tags unless locating many tags in very short interval ignoring the economical feasibility. Also, in the posture estimation of the mobile robot, two antennas are necessary to recognize the orientation of the robot since the orientation cannot be detected by using only one antenna.

In this paper, the problem to acquire position information including orientation of robot is introduced in the robot localization using RFID system. Also, the algorithms to reduce estimation error of robot and to achieve more efficient localization are newly proposed. In section 2, the state of the mobile robot in RFID sensor space is represented by position and orientation variables. The modeling of estimation error in RFID localization system is described in section 3. In section 4, an algorithm to compensate localization error has been described through the estimation error modeling, and the robot position has been estimated by experiments in section 5. Section 6 concludes and summarizes the main contributions of this paper.

2. POSITION ESTIMATION OF A MOBILE ROBOT

2.1 Position Recognition

In order to estimate the location of the robot using RFID system, RFID tags are arranged in a fixed pattern on the floor as shown in Fig. 1. Absolute coordinates of the location has been stored in each tag to provide the position data to the mobile robot. An RFID reader (antenna) has been installed to read the tag data on the bottom of the mobile robot. If the robot moves and stays on any tag, the RF field is formed by RFID reader antenna as shown in Fig. 2. All the tags within the circle of radius, r , which are under the effective area of RFID antenna, are activated. Fig. 3 shows the procedure to read all these tag data sequentially.

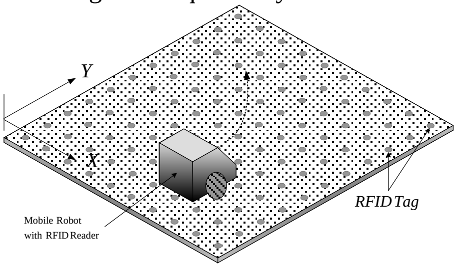


Fig. 1 Localization system using RFID.

When the localization process starts, the RFID reader gathers the position data of the tags under the effective area of antenna. The RFID reader repeatedly gathers the tag information sequentially when there are more than one tag in the RF field, since it can recognizes only one tags signal at a time. In order to receive other tag data within the recognizable area of the RF reader, the tag data previously read are stored to the PC. Then, the reader can receive the next tag information, and repeats this procedure until there is no unread tag left within the RF field. After all the information of tags is stored, and if a new tag is not detected any longer, the location of the mobile robot is calculated based on the tag data. At the moment, a new RF field is going to be selected with a new set of tags.

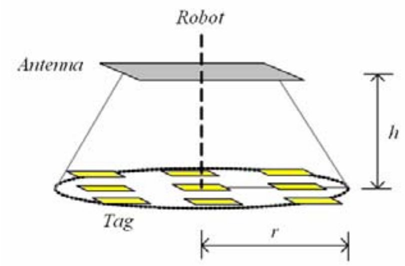


Fig. 2 Recognition area model of RFID antenna.

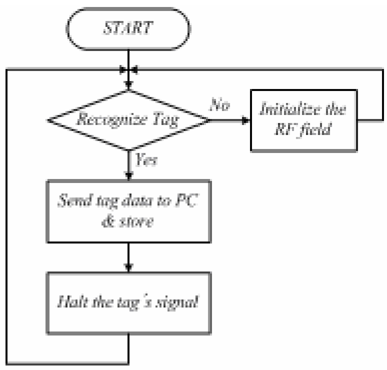


Fig. 3 Procedure to recognize the location of tags.

2.2 The orientation and position estimation

The orientation and position of the robot can be estimated using the multiple sets of the estimated position data. The orientation can be divided into initial-orientation and traveling-orientation, and the minimum two sets of position data are required for a robot to estimate the orientation. The initial orientation of the mobile robot can be estimated by the position data of A and B in Fig. 4.

2.2.1 Initial-orientation

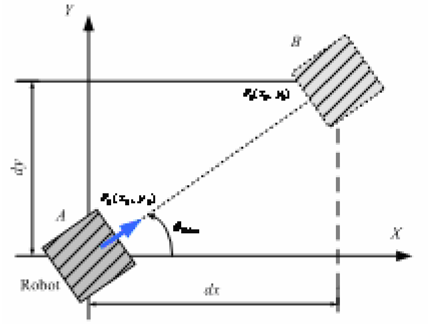


Fig. 4 Orientation estimation of the mobile robot.

When the location A is denoted as $P_0 = [x_0 \quad y_0]^T$, and the location B as $P_1 = [x_1 \quad y_1]^T$, the initial-orientation of the robot can be obtained as follows:

$$\tan\theta_{Robot} = \frac{y_1 - y_0}{x_1 - x_0} = \frac{dy}{dx} \tag{1}$$

$$\theta_{Robot} = \tan^{-1}\left(\frac{y_1 - y_0}{x_1 - x_0}\right) = \tan^{-1}\left(\frac{dy}{dx}\right). \tag{2}$$

Therefore, the initial state of the robot can be represented as a vector with position and orientation as follows:

$$P_0 = [x_0 \quad y_0 \quad \theta_{Robot}]^T = [x_0 \quad y_0 \quad \tan^{-1}(dy/dx)]^T. \tag{3}$$

2.2.2 Traveling orientation

From the initial position and orientation of the mobile robot, the consecutive orientation and position of the robot are estimated while it is moving. If the mobile robot moves from the location A to B as shown in Fig. 5, the state of the robot in initial position A and position B can be obtained. Using this information, rotation radius and angle can be calculated, and the state after the robot movement can be estimated.

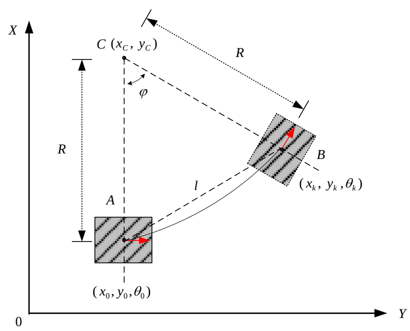


Fig. 5 Orientation estimation while the robot is moving.

The orientation of the mobile robot, θ_k , can be obtained by the summation of the initial orientation and the rotation angle as

$$\theta_k = \theta_0 + \varphi. \tag{4}$$

And the rotation radius of the robot, R, is represented as

$$R = \sqrt{(x_0 - x_C)^2 + (y_0 - y_C)^2} = \sqrt{(x_k - x_C)^2 + (y_k - y_C)^2} \quad (5)$$

The location C is the ICC (Instantaneous Center of Curvature) of the mobile robot, and the coordinates of the ICC can be determined as

$$\begin{bmatrix} x_C \\ y_C \end{bmatrix} = \begin{bmatrix} x_C \\ -\dfrac{1}{\tan(\theta_0)}(x_C - x_0) + y_0 \end{bmatrix}. \quad (6)$$

Also the rotation angle of the robot can be represented as follows:

$$\varphi = \cos^{-1}\left(1 - \frac{l^2}{2R^2}\right) \quad (7)$$

where $l = \sqrt{(x_0 - x_k)^2 + (y_0 - y_k)^2}$.

Using eqs. (3)~(7), the state of the robot with the traveling orientation can be represented as a vector,

$$P_k = \begin{bmatrix} x_k & y_k & \theta_k \end{bmatrix}^T = \begin{bmatrix} x_k & y_k & \theta_0 + \cos^{-1}\left(1 - \dfrac{l^2}{2R^2}\right) \end{bmatrix}^T . \quad (8)$$

3. UNCERTAINTY OF POSITION ESTIMATION

In the passive RFID localization system, the utilization of tag information is dependent on the system characteristics. In other words, even though the RFID reader detects an RFID tag within the recognition area, it cannot obtain a precise location value from the tag since the recognition area is not a point. The distance between RFID reader and tag is also a variable to be considered in the localization process. Therefore the classical localization system based on the triangulation technique with three distance data has too big error to be used for the mobile robot navigation.

The estimation error is unavoidable when the robot location is estimated by the coordinates of tags within the recognition area of the reader. The estimation error is modeled in this research to reduce or remove out this estimation error. If the tags are arranged in a regular pattern and the distance between them does not exceed the range of reader, the recognition area of the reader for the tags can be represented as a circle as shown in Fig. 6. Note that the antenna of the RFID has generally a circular shape.

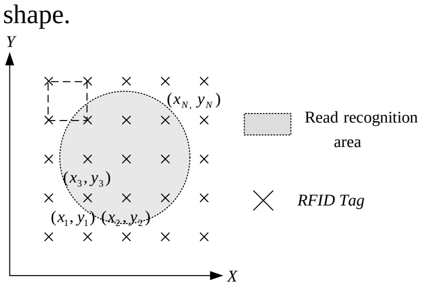


Fig. 6. Recognition area of RFID reader.

The position of the mobile robot (x_{est}, y_{est}) that carries a reader antenna on the bottom, can be obtained through the position data of the tags that are located within the recognition area of the reader as

$$x_{est} = \frac{\max\{x_1, \cdots, x_N\} + \min\{x_1, \cdots, x_N\}}{2} \quad (9)$$

$$y_{est} = \frac{\max\{y_1, \cdots, y_N\} + \min\{y_1, \cdots, y_N\}}{2} \quad (10)$$

where N represents the number of tags detected by the reader and $x_1, x_2, x_3, y_1, y_2, \cdots$ represents the coordinates information of the tags.

In the procedure of the mobile robot position estimation, there always exists the estimation error as shown in Fig. 7.

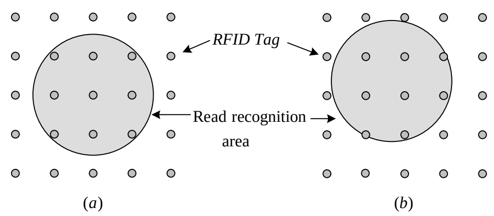


Fig. 7. Estimation error in RFID sensor space.

The position of antenna --coordinates of the mobile robot-- is estimated to be the same in Figs. 7(a) and 7(b) by eqs. (9) and (10), since the tags have the same coordinates. However, the real position of mobile robot is not same as shown in Fig. 7. The estimation error represents the gap between the real and estimated positions of the mobile robot. Therefore the size of estimation error is directly related to the gap between the RFID tags. Figure 8 illustrates the relationship between the estimation error and the gap between the RFID tags where only X-dimensional tags are considered, each tag from left to right has coordinates, $a_1, a_2, a_3, \cdots, a_{n-1}, a_n, a_{n+1}$, and the gap between the tags is d_{tag} .

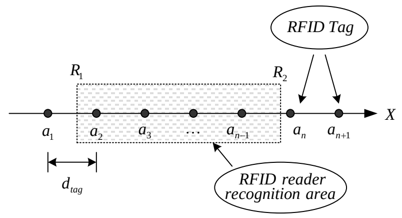


Fig. 8. Estimation error and the gap of tags.

The left boundary of the reader recognition area is denoted as R_1 and the right as R_2. That is, the RFID reader can detect tags located between R_1 and R_2. The estimation coordinates, R_{est_x}, and the real center position of the reader R_{real_x}, illustrated in Fig. 8, are represented as follows:

$$R_{est\_x} = \frac{a_2 + a_{n-1}}{2} \quad (11)$$

$$R_{real\_x} = \frac{R_1 + R_2}{2} . \quad (12)$$

The estimation error, e_{est}, is defined as

$$e_{est\_x} = \left| R_{est\_x} - R_{real\_x} \right| = \left| \frac{R_1 + R_2}{2} - \frac{a_2 + a_{n-1}}{2} \right| . \quad (13)$$

where the ranges of R_1 and R_2 can be described as

$$\begin{cases} a_1 < R_1 < a_2 \\ -d_{tag} < R_1 - a_2 < 0 \end{cases} \tag{14-a}$$

$$\begin{cases} a_{n-1} < R_2 < a_n \\ 0 < R_2 - a_{n-1} < d_{tag} \end{cases}. \tag{14-b}$$

From (11) and (12), now the range of estimation error can be represented as

$$e_{est\_x} = \left|\frac{(R_1 - a_2) + (R_2 - a_{n-1})}{2}\right| \le \frac{1}{2}\left|d_{tag}\right|. \tag{15}$$

Equation (15) shows that the estimation error is proportional to the gap between the tags and the maximum value is half of the gap. Therefore, the maximum estimation error in the X-Y Cartesian coordinates is represented as

$$e_{est\_\max} = \sqrt{(1/4)d_{tag}^{\ 2} + (1/4)d_{tag}^{\ 2}} \cong 0.707\, d_{tag}\ . \tag{16}$$

4. ALGORITHM FOR REDUCTION AND COMPENSATION OF THE ERROR

For the localization process of the mobile robot in the RFID sensor space, two schemes are introduced to reduce the error in this paper.

4.1 RFID tag allocation for reducing estimation error

When the gap between the tags is reduced, the accuracy of the estimation is improved as described in the previous section. But, this solution increases costs because it increases the number of tags. The optimal allocation of the RFID tags in the sensor space proposed in this paper aims to improve the accuracy of the position estimation without increasing the number of tags. Traditionally tags have been allocated in a square pattern (Fig. 7), but in this paper a triangular pattern (Fig. 9) is proposed to decrease the estimation error without increasing the number of tags.

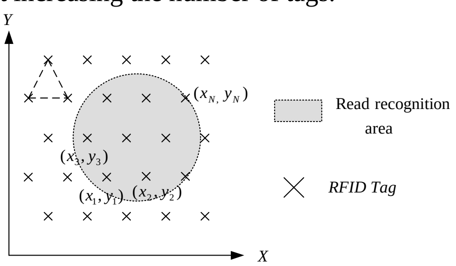


Fig. 9. RFID tag allocation and the recognition area of the reader in the triangular pattern.

Figure 10 illustrates the decrease of the estimation error in the triangular pattern space.

The coordinates of R_1 and R_2 are represented as follows:

$$\begin{cases} b_1 < R_1 < a_2 \\ -\dfrac{d_{tag}}{2} < R_1 - a_2 < 0 \end{cases} \tag{17-a}$$

$$\begin{cases} b_{n-1} < R_2 < a_n \\ 0 < R_2 - b_{n-1} < \dfrac{d_{tag}}{2} \end{cases}. \tag{17-b}$$

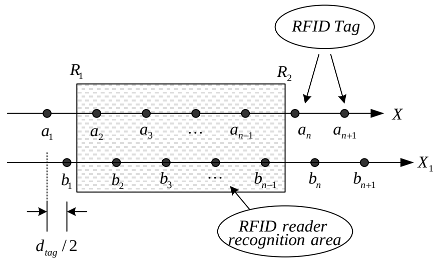


Fig. 10. Estimation error decrease in triangular pattern.

When the RFID tags are arranged in the triangular pattern as shown in fig. 10, the estimation error in x-direction can be decreased as follows:

$$e_{est\_x} = \left|R_{est\_x} - R_{real\_x}\right| = \left|\frac{R_1 + R_2}{2} - \frac{a_2 + b_{n-1}}{2}\right| \tag{18}$$

$$e_{est\_x} = \left|\frac{(R_1 - a_2) + (R_2 - b_{n-1})}{2}\right| \le \frac{1}{4}\left|d_{tag}\right|. \tag{19}$$

Therefore, the maximum estimation error in X-Y Cartesian coordinates can be represented as

$$e_{est\_\max} = \sqrt{(1/2)d_{tag}^{\ 2} + (1/4)d_{tag}^{\ 2}} \cong 0.58 d_{tag}\ . \tag{20}$$

4.2 Algorithm for error compensation

An error compensation algorithm is proposed in order to reduce the estimation error of the mobile robot in estimating its own position using the coordinates of RFID tags. Assuming that the initial-location of the robot is given correctly, the velocity and trajectory of the robot can be predicted from the initial location of the RFID system. The RFID estimation error is reduced by the proposed compensation algorithm which predicts the location of the robot based on the motion continuity. In Fig. 11, the error compensation procedure is illustrated.

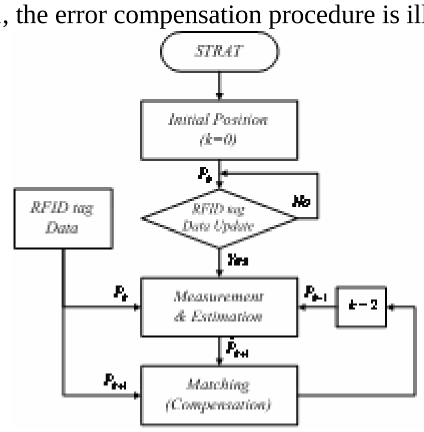


Fig. 11. Procedure of the error compensation.

4.2.1 Step 1:measurement

The states of the mobile robot are represented as the position and orientation in section 2. As shown in Fig. 12, the robot starts from a known state, $P_0 = [x_0 \quad y_0 \quad \theta_0]^T$, at time *t*=0. After *k* steps of time, a new state of the mobile robot, $P_k = [x_k \quad y_k \quad \theta_k]^T$ is estimated by the RFID tags. Utilizing the location information, the following observations are derived. The orientation variation of the mobile robot is same with rotation angle of the robot, and can be expressed by velocities of the right and left wheels as

$$\varphi = \theta_k - \theta_0 = \frac{\int_t^{t+\delta t} (u_L + u_R)\, dt}{r_w (u_L + u_R)} (u_R - u_L) \cdot \qquad (21)$$

Then the driving distance of the mobile robot, d, is represented as

$$d = R\varphi = \int_t^{t+\delta t} v_1\, dt = \int_t^{t+\delta t} \frac{u_L + u_R}{2} dt, \qquad (22)$$

where v_1 is the linear velocity of the mobile robot.

The rotation radius, R, is represented through the relation between the velocities of the right and left wheels and the width of robot as

$$R = \frac{r_w}{2}\left(\frac{u_R + u_L}{u_R - u_L}\right). \qquad (23)$$

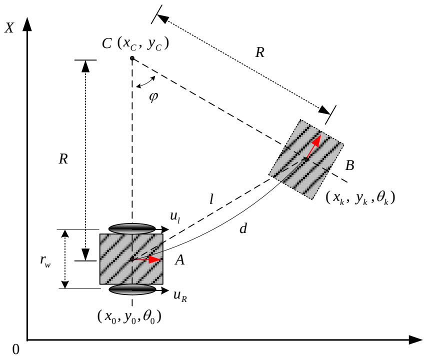


Fig. 12 Measurement and prediction model.

4.2.2 Step 2: estimation and compensation

The velocity, rotation angle and driving distance of the robot can be measured by the state obtained at k[th] time step, $P_k = [x_k \quad y_k \quad \theta_k]^T$ and the initial state, $P_0 = [x_0 \quad y_0 \quad \theta_0]^T$.

Using the motion continuity property, the state of the mobile robot at time $t=k+1$, $\hat{P}_{k+1} = [x_{k+1} \quad y_{k+1} \quad \theta_{k+1}]^T$, can be predicted as

$$\hat{x}_{k+1} = x_k + T\frac{u_L + u_R}{2}\cos(\theta_k) \qquad (24\text{-a})$$

$$\hat{y}_{k+1} = y_k + T\frac{u_L + u_R}{2}\sin(\theta_k), \qquad (24\text{-b})$$

where T is the sampling period.

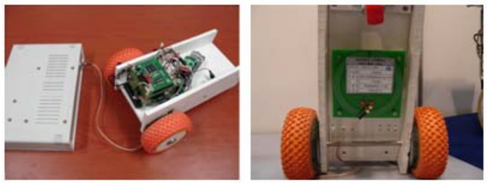
Using this predicted location, $\hat{P}_{k+1} = [x_{k+1} \quad y_{k+1} \quad \theta_{k+1}]^T$, of the robot in time $t=k+1$, the measuring location by the RFID tags is filtered and compensated. The process ends here, and the prediction of a new location is consecutively repeated at every step to reduce the measuring error by the estimation and compensation.

5. EXPERIMENTS AND RESULTS

For the localization of a mobile robot, it is assumed that the mobile robot moves along the designed path.

5.1 Experimental environment

The passive type RFID reader and tags are used for the real experiment. The main frequency of the RFID system is 13.56 Mhz, the position coordinates of the tags are pre-stored, and the tags are regularly allocated at the specific locations following a designed pattern. To show the superiority of the triangular pattern, the tags are allocated at every 0.1m in a row for both of the square and triangular patterns. The size of the RFID reader antenna is 0.1m*0.1m and that of epoxy tags is 3cm*3cm. Figure. 13 shows the mobile robot and RFID antenna for the experiment. The velocities of right and left wheels are sent from the main computer in radio frequency to the robot that has 2-differnetial driving mechanisms.



(a) Mobile robot (b) RFID antenna

Fig. 13 Mobile robot and RFID antenna.

5.2 Experimental results

The first experiment aims at the comparison of robot localization accuracies in triangular and rectangular patterns of tag allocation. The mobile robot follows the path-1 and path-2 while the RFID reader recognizes and reads the position data from the tags. The velocity of the robot is 0.25m/s along the path-1 and path-2, and sampling time is 0.04 sec.

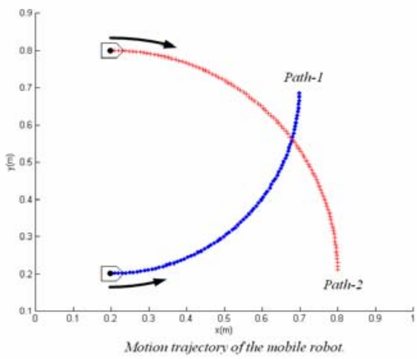
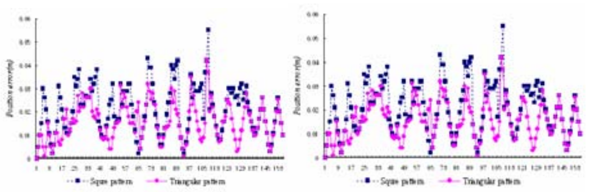


Fig. 14. Two different paths (Path-1 and Path-2) for the mobile robot navigation.

The estimation errors for Path-1 are represented in Figs. 15. The same results are shown by the path B. As it can be seen by comparing the errors, the estimation errors for the triangular pattern are a lot smaller than the square pattern for both of the Path-1 and Path-2. To express correct values, the average position error and orientation error is represented in Table 1. The fact that the triangular pattern of RFID tag allocation reduces the estimation error is described in section 4 by using the error model and it is demonstrated by the first experiment.

The object of the second experiment is to show reduction effect of the estimation error by the compensation algorithm proposed in this paper. The mobile robot moves along a circular trajectory, and estimates its own position using the RFID localization system.



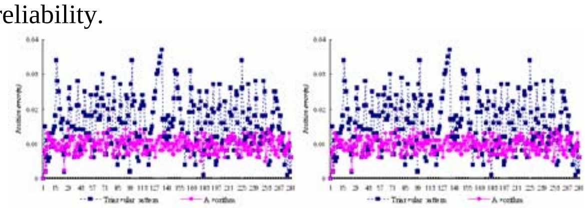
(a) The position error (b) The orientation error

Fig. 15. Estimation errors of Path-1 depending on the tag allocation patterns.

Table 1 Average of the position and orientation error by tag allocation patterns

	Path-1		Path-2	
	Position Error(m)	Orientation Error(deg)	Position Error(m)	Orientation Error(deg)
Square Pattern	0.02	1.72	0.02	1.42
Triangle Pattern	0.016	1.12	0.015	0.89

The experiments are conducted in the RFID sensor space with the triangular pattern of tag allocation. Through Fig. 17 and Table 2, it is clear that the estimation error of robot position decreases when the proposed error-compensation algorithm is applied. Moreover, the error-compensation algorithm reduces the variation of errors. There it is possible to estimate the correct location with high accuracy as well as high reliability.



(a) (b)

(a) Position error reduction. (b) Orientation error reduction.

Fig. 17. Error reduction by the compensation algorithm.

Table 2. Average errors of position and orientation estimations

	Position Error(m)		Orientation Error(deg)	
	W/O algorithm	With algorithm	W/O algorithm	With algorithm
Error	0.016	0.009	1.36	0.70

6. CONCLUSION

This paper proposes a new localization scheme in an RFID based sensor space, which is derived from the new ideas on the tag allocation and on the compensation of the mobile robot position for the efficient and accurate estimation. This scheme overcomes the shortcomings of the conventional absolute position estimations and improves the localization efficiency and accuracy. The main ideas are demonstrated by the experiments of a mobile robot navigating over the RFID-based sensor space. To illustrate the improved accuracy and efficiency of the position estimation scheme, the square and triangular tag patterns have been compared. The triangular pattern has shown better performance than the square pattern for position estimation of a mobile robot. When the robot moves in the RFID sensor space, the velocity and position of the robot are estimated and compensated to reduce the estimation error according to the localization scheme developed in this paper. Note that based on the approach described in the RFID sensor space, the absolute position of a mobile robot can be estimated precisely without any interferences from environments.

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