An Efficient Localization Scheme for a Differential-Driving Mobile Robot Based on RFID System

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***Abstract*—This paper presents an efficient localization scheme for an indoors mobile robot using Radio-Frequency IDentification (RFID) systems. 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 of the RFID tags 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 inevitably suffers from an estimation error. In this paper, a new triangular pattern of arranging the RFID tags on the floor has been proposed to reduce the estimation error of the conventional square pattern. In addition, the motion-continuity property of the differential-driving mobile robot has been utilized to improve the localization accuracy of the mobile robot. According to the conventional approach, two readers are necessary to identify the orientation of the mobile robot. Therefore, this new approach, based on the motion-continuity property of the differential-driving mobile robot, provides a cheap and fast estimation of the orientation. The proposed algorithms used to raise the accuracy of the robot localization are successfully verified through experiments.**

***Index Terms*—Localization, mobile robot, motion continuity, Radio-Frequency IDentification (RFID).**

I. Introduction

Radio-Frequency-Identification (RFID) technology is essential for a nontouching recognition system that transmits and processes the information on events and environments using a wireless frequency and small chips [1], [2]. The RFID system can recognize tags at high speed and send the tag data within various distances. Therefore, the application of the RFID technology has recently been increased and it has been applied for robot technology [3], [4]. With the development of the personal robot and advanced ubiquitous network robots, it is essential for the robots to recognize their own location and environment and to maintain high security in a common space with people. If RFID technology is properly applied to the robot, the services for the users can be provided by the robot at anytime and at any place.

The passive RFID technology has been utilized for the researchers to recognize the position of the service robot [5]. An absolute localization scheme is proposed using RFID passive tags arranged on the floor, which are free from the problems of conventional sensor systems [6]–[8]. For example, dead-reckoning sensors suffer from accumulation errors, the laser and ultrasonic sensor from line-of-sight errors, the charged-coupled device from the illumination, etc. The absolute location of the robot can be obtained robustly with the RFID tags and a reader in the sensor-network space. There are two typical uses of the tags: The active tags on the ceiling and the passive tags on the floor [9], [10]. However, some shortcomings are found in the RFID-based localization systems [11]. Since the reader antenna detects several tags within its detecting range and the mobile robot is moving while the reader is gathering the data from the tags, the position-estimation error is inherent for this method. Therefore, the precise localization is not easy for the RFID-based system. Putting more tags, while ignoring the economics, may increase the localization accuracy. However, this also increases the time in reading the tags, which limits the accuracy. In addition, an additional expensive reader is necessary to recognize the orientation of the mobile robot since the orientation cannot be detected by using only one reader.

In this paper, a precise localization scheme using the RFID system has been proposed for the mobile-robot navigation. The proposed system aims at reducing the localization error of the mobile robot, both by the triangular pattern [13] of the tags and by the orientation-estimation algorithm, without extra expenses. In Section II, the localization of the mobile robot [14] in the RFID space with a triangular allocation of the tags is analyzed to show the accuracy improvement. In Section III, a new orientation estimation of the mobile robot has been described based on the motion dynamics of the mobile robot. In Section IV, the real experiments are carried out to verify the effectiveness of the triangular pattern and the orientation-estimation algorithm. Section V concludes and summarizes the main contributions of this paper, which improve the localization efficiency of a mobile robot with RFID technology [15] by proposing a new triangular tag-arrangement pattern.

II. Position Estimation of a Mobile Robot

In order to estimate the robot position using the RFID system, RFID tags are arranged in a fixed pattern on the floor, as shown in Fig. 1. Since the tag arrangement on the floor is preplanned, each tag stores its absolute position data and sends them out when they are requested. The RFID reader (antenna) installed on the bottom of the mobile robot gathers the tag data.

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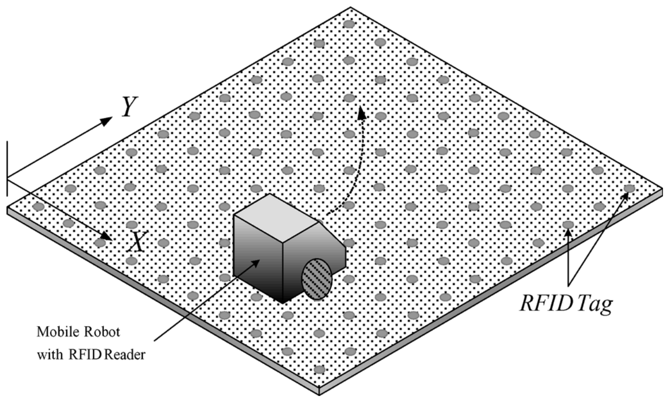


Fig. 1. Localization system using RFID.

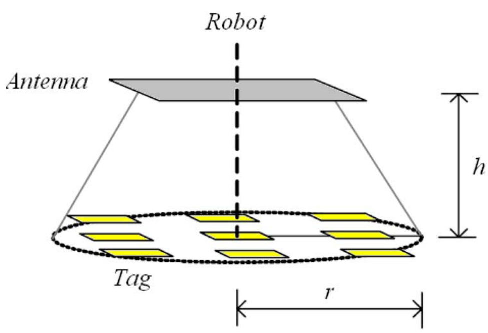


Fig. 2. Effective area of the RFID antenna model.

When the robot moves and stays on any tags, the RFID reader antenna forms an effective area, as shown in Fig. 2. All the tags within the circle of radius r, which are under the effective area of the RFID antenna, are activated. Notice that it is not desirable to increase h, since this may also increase the noise level when reading the tags.

When the localization process starts, the RFID reader gathers the position data from the tags under the effective area of the antenna. The RFID reader sequentially gathers the tag information, since it can recognize only one tag signal at a time. In order to receive other tag data within the effective area of the RFID reader, the tag data previously read are stored in the memory. Then, the reader receives the next tag information and repeats this procedure until there is no unread tag left within the effective area. After all the information of the tags is stored, the location of the mobile robot is calculated based on the collected tag data. At that moment, a new set of tags is selected for the next step of localization.

In this process, there are two critical factors which deteriorate the localization accuracy: the distance between the tags and the scanning and processing time. In this section, the localization error, based on the distance between the tags, is analyzed and a new tag-arrangement pattern is proposed.

A. Position Recognition

In the passive RFID localization system, the utilization of the tag information is dependent on the system characteristics. In other words, even though the RFID system reads the tags within the recognition area, it cannot obtain a precise-location value since there are several tags in the area. In addition, the distance between the tags is a crucial factor, which determines the localization accuracy. Therefore, the estimation error is unavoidable when the robot location is estimated by the coordinates of the tags within the recognition area of the reader.

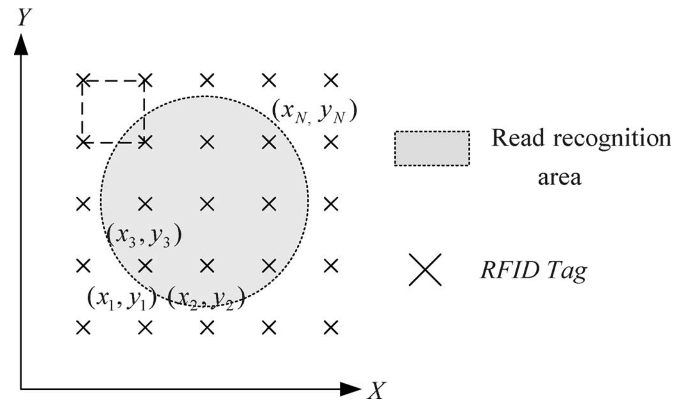


Fig. 3. Recognition area of the RFID reader.

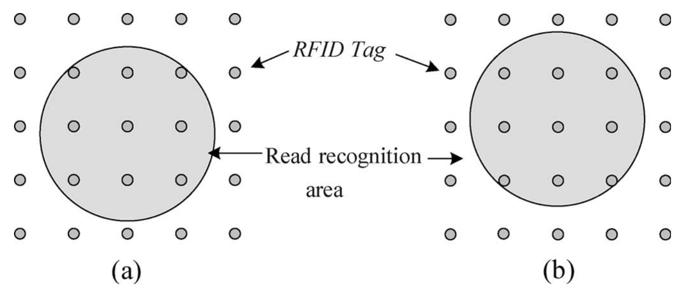


Fig. 4. Estimation error in the RFID sensor space.

In this paper, the localization error for a specific allocation pattern of the RFID tags has been modeled and analyzed to show the superiority of the triangular pattern. When the tags are arranged in a square pattern, the recognition area of the tag reader can be represented as a circle, as shown in Fig. 3. Notice that the antenna of the RFID has, generally, a circular shape.

The position of the mobile robot $(x_{\text{est}}, y_{\text{est}})$, which carries a reader antenna on the bottom, can be estimated through the position data of the tags within the recognition area of the reader as

$$x_{\text{est}} = \frac{\max\{x_1, \cdots, x_N\} + \min\{x_1, \cdots, x_N\}}{2} \quad (1)$$

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

where N represents the number of tags detected by the reader, and x_1, x_2,y_1, y_2, etc. represents the coordinates of the tags.

B. Position-Estimation Error

In the procedure of the mobile-robot position estimation, there always exists an estimation error, as shown in Fig. 4. The position of the antenna—the coordinates of the mobile robot—is estimated to be the same for Fig. 4(a) and (b) by (1) and (2), since the tags in the read-recognition area are the same.

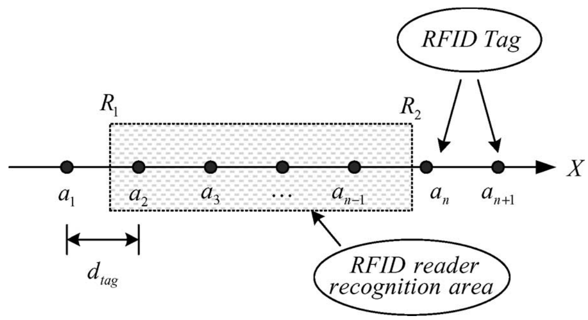


Fig. 5. Estimation error and the gap of the tags.

However, the real position of the mobile robot, which is the center of the circle, is not the same. From this observation, it is clear that the estimation error is directly related to the gap between the RFID tags.

Fig. 5 illustrates the relationship between the estimation error and the gap between the RFID tags along the x-axis. Each tag from left to right has coordinates of a_1, a_2, and a_{n+1}, and the gap between the tags is constant as d_{tag}.

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 the tags between R_1 and R_2. From Fig. 5, the estimated coordinates $R_{\mathrm{est\_}x}$ and the real center position of the reader $R_{\mathrm{real\_}x}$ are represented, respectively, as follows:

$$R_{\mathrm{est\_}x} = \frac{a_2 + a_{n-1}}{2} \tag{3}$$

$$R_{\mathrm{real\_}x} = \frac{R_1 + R_2}{2}. \tag{4}$$

Therefore, the x-directional estimation error $e_{\mathrm{est\_}x}$ is

$$e_{\mathrm{est\_}x} = |R_{\mathrm{est\_}x} - R_{\mathrm{real\_}x}| = \left| \frac{R_1 + R_2}{2} - \frac{a_2 + a_{n-1}}{2} \right| \tag{5}$$

where the ranges of R_1 and R_2 can be limited by the tag data as

$$\begin{cases} a_1 < R_1 < a_2 \\ -d_{\mathrm{tag}} < R_1 - a_2 < 0 \end{cases} \tag{6-a}$$

$$\begin{cases} a_{n-1} < R_2 < a_n \\ 0 < R_2 - a_{n-1} < d_{\mathrm{tag}} \end{cases}. \tag{6-b}$$

From (5) and (6), now, the range of the estimation error can be represented as

$$e_{\mathrm{est\_}x} = \left| \frac{(R_1 - a_2) + (R_2 - a_{n-1})}{2} \right| \le \frac{1}{2} |d_{\mathrm{tag}}|. \tag{7}$$

Equation (7) shows that the maximum estimation error is proportional to the tag interval along the x-axis and reaches to half of the tag interval. Therefore, the maximum estimation error in the $x - y$ Cartesian coordinates is

$$e_{\mathrm{est\_max}} = \frac{1}{2}\sqrt{d_{\mathrm{tag}}^2 + d_{\mathrm{tag}}^2} \cong 0.707 d_{\mathrm{tag}}. \tag{8}$$

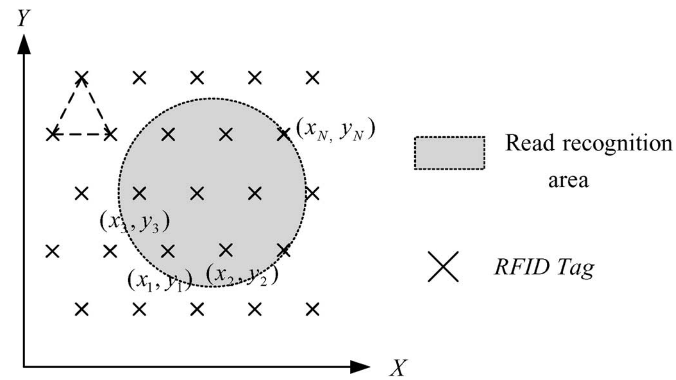


Fig. 6. RFID tags and the recognition area in the triangular pattern.

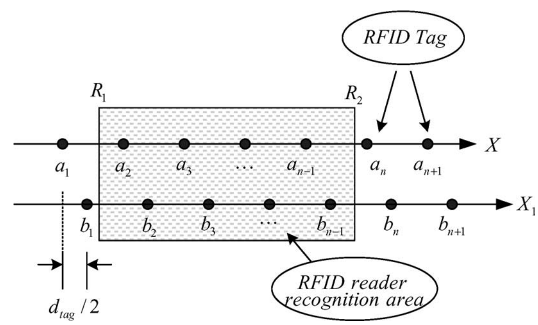


Fig. 7. Estimation error in a triangular pattern.

C. New RFID Tag Arrangement

When the distance between the tags is reduced, the estimation accuracy is improved, as described in the previous section. However, the solution increases the system cost because it increases the number of tags. A new RFID tag arrangement is proposed in this paper to improve the position-estimation accuracy without increasing the number of tags. That is, a triangular pattern (Fig. 6) is proposed to decrease the estimation error of the square pattern (Fig. 4) without increasing the number of tags.

Fig. 7 illustrates the tag arrangement in a triangular pattern. The ranges for R_1 and R_2 are represented as follows:

$$\begin{cases} b_1 < R_1 < a_2 \\ -\frac{d_{\mathrm{tag}}}{2} < R_1 - a_2 < 0 \end{cases} \tag{9-a}$$

$$\begin{cases} b_{n-1} < R_2 < a_n \\ 0 < R_2 - b_{n-1} < \frac{d_{\mathrm{tag}}}{2} \end{cases}. \tag{9-b}$$

When the RFID tags are arranged in the triangular pattern, the estimation error along the x-direction can be described as follows:

$$\begin{aligned} e_{\mathrm{est\_}x} &= |R_{\mathrm{est\_}x} - R_{\mathrm{real\_}x}| \\ &= \left| \frac{R_1 + R_2}{2} - \frac{a_2 + b_{n-1}}{2} \right| \end{aligned} \tag{10}$$

$$e_{\mathrm{est\_}x} = \left| \frac{(R_1 - a_2) + (R_2 - b_{n-1})}{2} \right| \le \frac{1}{4} |d_{\mathrm{tag}}|. \tag{11}$$

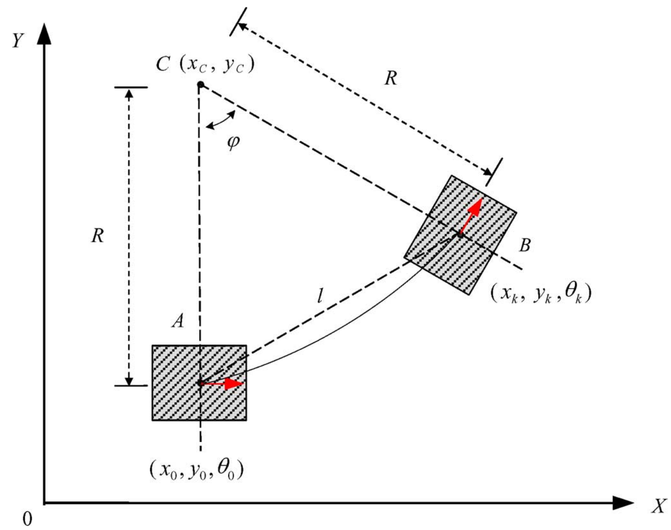


Fig. 8. Orientation estimation while the robot is moving.

Therefore, the maximum estimation error in the $x - y$ Cartesian coordinates is

$$e_{\text{est\_max}} = \frac{1}{4}\sqrt{4 \cdot d_{\text{tag}}^2 + d_{\text{tag}}^2} \cong 0.58 d_{\text{tag}} \tag{12}$$

which is about 82% of the error in the square pattern given in (8).

III. Orientation Estimation and Enhancement

To estimate the orientation of the mobile robot using a reader instead of using two readers for the conventional approach, multiple sets of the estimated positions are necessary. For the estimation, first of all, the mobile-robot motion is modeled, and two different orientations, initial and traveling orientations, are defined by the two sets of position data.

With the model, the orientation of the mobile robot can be estimated by the single RFID reader.

A. Modeling of a Mobile-Robot Motion

1) Initial Orientation: The initial orientation of the mobile robot can be estimated by the position data of A and B in Fig. 8.

Location A is denoted as $P_0 = [x_0 \quad y_0]^{\mathrm{T}}$ and Location B as $P_1 = [x_1 \quad y_1]^{\mathrm{T}}$ when $k = 1$ in Fig. 8. The initial orientation of the robot can be obtained as follows:

$$\tan\theta_{\text{Robot}} = \frac{y_1 - y_0}{x_1 - x_0} = \frac{dy}{dx} \tag{13}$$

$$\theta_{\text{Robot}} = \tan^{-1}\left(\frac{y_1 - y_0}{x_1 - x_0}\right) = \tan^{-1}\left(\frac{dy}{dx}\right). \tag{14}$$

Note that this orientation estimation works for only a small variation of x, dx. That is, the sampling time should be kept small enough for this estimation. Now, the initial state of the robot can be represented as a vector with a position and orientation as follows:

$$P_0 = [x_0 \quad y_0 \quad \theta_{\text{Robot}}]^{\mathrm{T}} = \left[x_0 \quad y_0 \quad \tan^{-1}(dy/dx)\right]^{\mathrm{T}}. \tag{15}$$

2) Traveling Orientation: With the preestimated initial position and orientation of the mobile robot, the consecutive orientation and position of the robot are estimated while it is moving. When the mobile robot moves from Location A to B, as shown in Fig. 8, the positions of the robot at Position A and B can be measured using the RFID system. With the initial-orientation estimation, the later states of the mobile robot can be estimated consecutively.

The traveling orientation of the mobile robot θ_k can be represented as the summation of the initial orientation and the rotation angle φ as

$$\theta_k = \theta_0 + \varphi. \tag{16}$$

To obtain the rotation angle φ, the rotation radius of the robot R is represented as

$$\begin{aligned} R &= \sqrt{(x_0 - x_C)^2 + (y_0 - y_C)^2} \\ &= \sqrt{(x_k - x_C)^2 + (y_k - y_C)^2} \end{aligned} \tag{17}$$

with the instantaneous center of curvature (ICC) of the mobile robot, C. The coordinates of the ICC can be determined as

$$\begin{bmatrix} x_C \\ y_C \end{bmatrix} = \begin{bmatrix} x_C \\ -\frac{1}{\tan(\theta_0)}(x_C - x_0) + y_0 \end{bmatrix} \tag{18}$$

where $\theta_0 \neq 0$. When $\theta_0 = 0$, $x_c = x_0$ and $y_c = y_0 + R$, as shown in Fig. 8.

Notice that, from the initial values (x_0, y_0, θ_0) and the measured values (x_k, y_k), the ICC coordinates (x_c, y_c) can be calculated from (17) and (18). With (x_c, y_c), R is calculated directly from (17).

Now, the rotation angle of the robot can be calculated as

$$\varphi = \cos^{-1}\left(1 - \frac{l^2}{2R^2}\right) \tag{19}$$

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

From (16)–(19), the state of the mobile robot can be represented as

$$\begin{aligned} P_k &= [x_k \quad y_k \quad \theta_k]^{\mathrm{T}} \\ &= \left[x_k \quad y_k \quad \theta_0 + \cos^{-1}\left(1 - \frac{l^2}{2R^2}\right)\right]^{\mathrm{T}}. \end{aligned} \tag{20}$$

B. Proposed Algorithm to Preestimate the Orientation

Since it takes quite a long time to read all the tags within the read-recognition area, in order to calculate the position and estimate the orientation, there exists a large error in the position and orientation data for the mobile robot. Notice that the continuously moving mobile robot is not waiting stationary at a place while the reader is reading the tags in the read-recognition area. To reduce this estimation error based on the RFID readings, a new orientation-estimation algorithm is proposed in this paper based on the motion continuity [12], which is an intrinsic property of a differential-driving mobile robot.

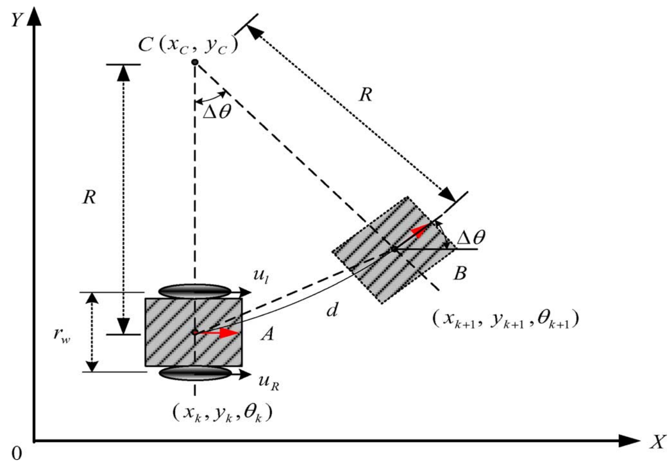


Fig. 9. Measurement and prediction model.

1) Step 1—Motion Model: The states of the mobile robot are represented as the position and orientation, as shown in Fig. 9. After k steps of time, a new state of the mobile robot $P_k = [x_k \quad y_k \quad \theta_k]^{\mathrm{T}}$ is calculated by the RFID tags. For the compensation model derivation, the motion characteristics of the differential-driving mobile robot are observed and extracted as follows: 1) The orientation variation of the mobile robot comes from the velocity difference between the left wheel and the right wheel. 2) The rotation radius is not changing rapidly for the accurate trajectory motion. 3) When the rotation radius is changing, the velocity should be lowered to reduce slippage of the mobile robot. These properties are named as the motion continuity of the mobile robot, and it is also shown that a single curvature motion is the most stable and precise for the differential-driving mobile robots.

Now, the angular velocity of the mobile robot ω can be expressed by the instantaneous angular increment and the sampling period T as

$$\omega = \frac{\Delta\theta}{T}. \tag{21}$$

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

$$d = R\Delta\theta = \int_{t}^{t+T} \nu_l \, dt = \int_{t}^{t+T} \frac{u_L + u_R}{2} dt, \tag{22}$$

where ν_l is the linear velocity, which is represented by the left-wheel velocity u_L and the right-wheel velocity u_R of the mobile robot. The rotation radius R is represented through the relation between the wheel velocities and the width of the mobile robot as

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

2) Step 2—Preestimation: The velocity, rotation angle, and driving distance of the robot can be measured at k^{th} time step as $P_k = [x_k \quad y_k \quad \theta_k]^{\mathrm{T}}$. Based upon the motion-continuity property, the state of the mobile robot at time $t = k+1$, $\hat{P}_{k+1} = [x_{k+1} \quad y_{k+1} \quad \theta_{k+1}]^{\mathrm{T}}$ can be preestimated as

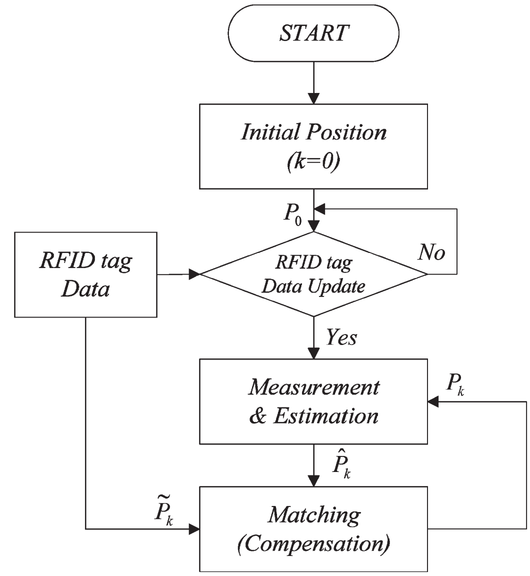


Fig. 10. Procedure of the error compensation.

$$\hat{x}_{k+1} = x_k + R\{\sin(\theta_k + \Delta\theta) - \sin(\theta_k)\} \tag{24-a}$$

$$\hat{y}_{k+1} = y_k + R\{\cos(\theta_k + \Delta\theta) - \cos(\theta_k)\} \tag{24-b}$$

$$\widehat{\theta}_{k+1} = \theta_k + \Delta\theta. \tag{24-c}$$

Using this predicted location, $\hat{P}_{k+1} = [x_{k+1} \quad y_{k+1} \quad \theta_{k+1}]^{\mathrm{T}}$ of the robot in time $t = k+1$; the measured location by the RFID tags is filtered and compensated for.

C. Compensation Algorithm

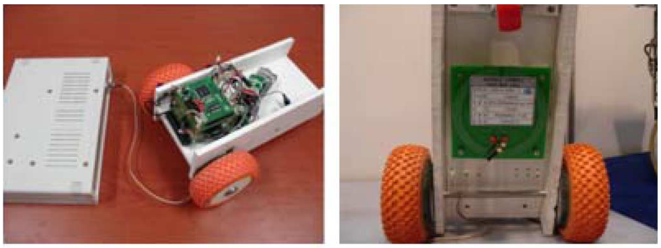
When the preestimated value is used as a measured value for the kth step continuously, it aggregates the dead-reckoning error. Therefore, even though the orientation-preestimation algorithm provides precise orientations for a couple of steps, it gets worse with time. Remember that one of the advantages of the RFID system is that it provides absolute position data. Therefore, in this approach, to take advantage of both the fast and precise estimation and the absolute measurement, a matching and compensation procedure in Fig. 10 is introduced with a threshold value ε. That is, the position/orientation of the kth step is determined as

$$P_k = \begin{cases} \widetilde{P}_k, & if \ |\widetilde{P}_k - \hat{P}_k| \le \varepsilon \\ \hat{P}_k, & \text{otherwise} \end{cases} \tag{25}$$

where $\widetilde{P}_k$ is the absolute position value measured by the RFIDs.

When it has more discrepancy from the estimated value, $\hat{P}_k$, which is based on the motion continuity, is considered as a malicious value. The localization procedure is summarized and illustrated in Fig. 10.

Note that the threshold value ε can be selected heuristically based on the observation of the experimental data.



(a) (b)

Fig. 11. Mobile robot and RFID antenna for the experiments. (a) Mobile robot. (b) RFID antenna.

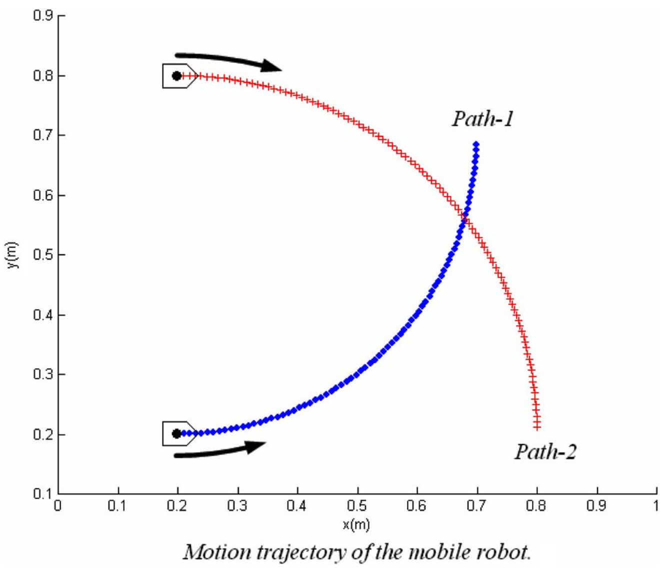
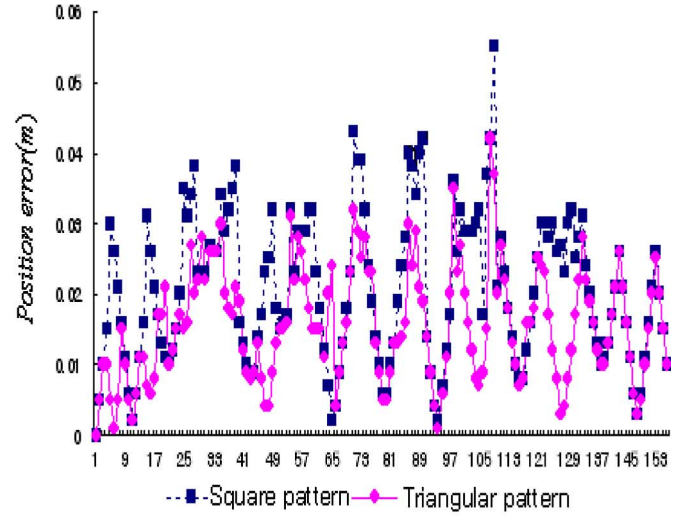
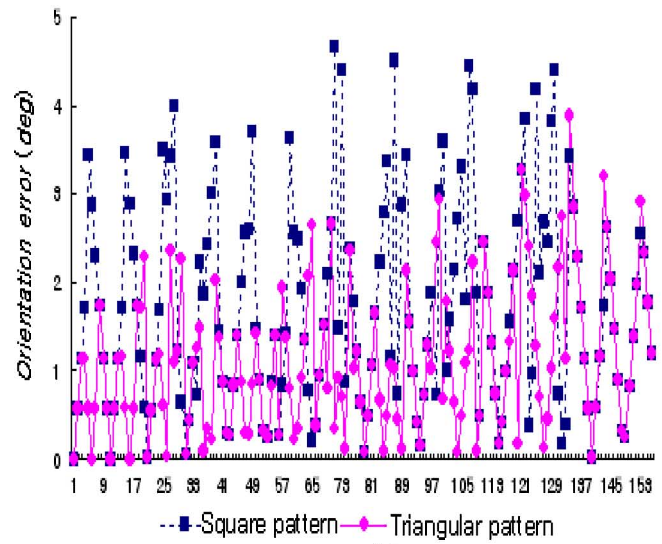


Fig. 12. Two different paths (Path-1 and Path-2) for the mobile-robot navigation.



(a)



(b)

Fig. 13. Estimation errors of Path-1 depending on the tag-arrangement patterns. (a) Position-estimation error. (b) Orientation-estimation error.

IV. Experiments and Results

For the localization of a mobile robot, it is assumed that the mobile robot moves precisely along a designated path. The mobile robot carries an RFID reader at the bottom of the chassis, which reads the positions of the tags when the reader passes over the tags.

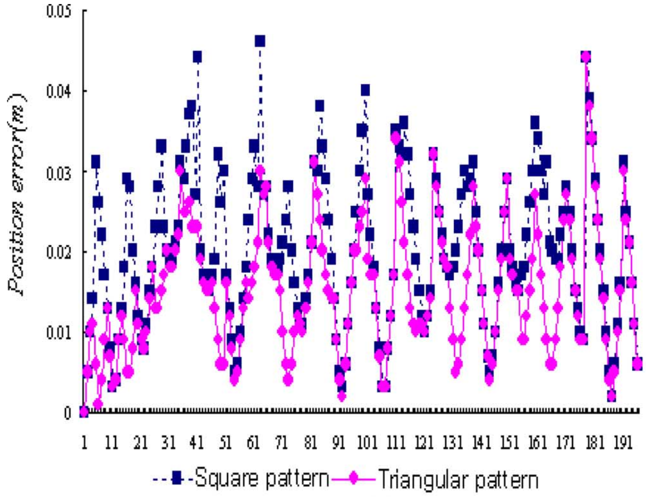
A. Experimental Environment

The RFID reader and the passive tags are used for the real experiments. The tags are regularly arranged at the specific locations following a design pattern, which keep the pre-stored absolute-position coordinates. The main frequency of the RFID system is 13.56 MHz. For the precise control of the mobile robot, an encoder is installed at each wheel. And using the encoder data, the mobile robot is controlled by the TMS320LF2407 with the control cycle of 10 μs. Since the mobile robot is following a single-curvature trajectory, there is no recognizable slippage in the control. The tags are allocated at every 0.05 m in a row for both the square and triangular patterns. However, the starting position is shifted to the right by $d_{\rm tag}/2$ in the even rows for the triangular pattern. The size of the RFID reader antenna is 0.1×0.1 m and that of the epoxy tags is 3×3 cm. Fig. 11 shows the mobile robot and RFID antenna for this paper. The mobile robot moves in the 1×1 m space along the designated path. The command velocities for the right wheel and the left wheel are sent through a wireless LAN of 2.4 GHz from the main computer to the robot that has the differential-driving mechanism. As shown in Fig. 11(b), the reader antenna used to recognize the RFID tag is at the bottom of the robot and is connected to the reader, as shown in Fig. 11(a). The reader is interfaced to the control and the communication microprocessor through the RS-232 serial-communication channel.

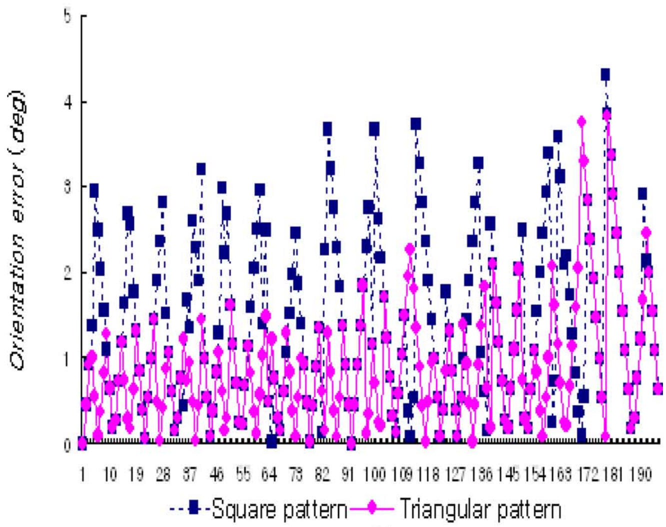
B. Experimental Results

The first experiment aims at the comparison of the robot localization accuracies in the triangular and square patterns of the tag arrangement. The mobile robot follows Path-1 and Path-2 while the RFID reader gathers the position data from the tags (see Fig. 12). The velocity of the robot is 0.25 m/s along Path-1 and Path-2, and the sampling time for the localization is 0.04 s.

The estimation errors are illustrated in Figs. 13 and 14. As shown in the comparison of errors, the estimation errors in the



(a)



(b)

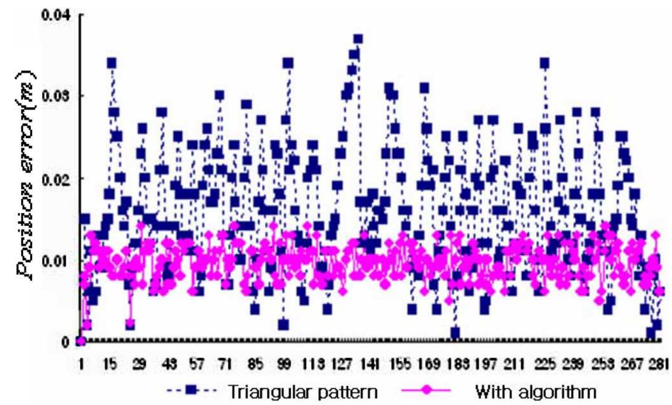
Fig. 14. Estimation errors of Path-2 depending on the tag-arrangement patterns. (a) Position error. (b) Orientation error.

TABLE I
AVERAGE OF THE POSITION AND ORIENTATION ERROR BY THE TAG-ARRANGEMENT PATTERNS

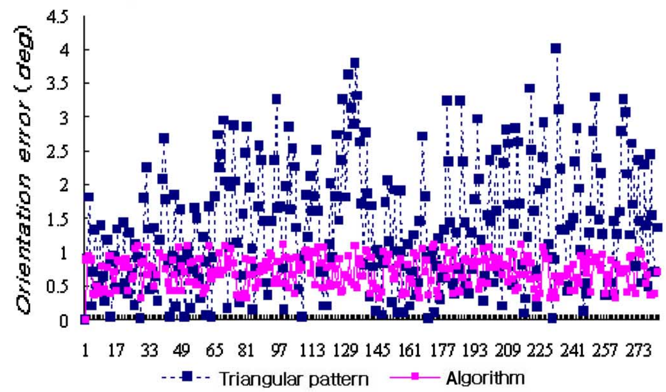
	Path-1		Path-2	
	Position Error(m)	Orientation Error(deg)	Position Error(m)	Orientation Error(deg)
Square Pattern	0.02	1.72	0.02	1.42
Triangle Pattern	0.016	1.12	0.015	0.89

triangular pattern are a lot smaller than in the square pattern for both Path-1 and Path-2. To compare the errors globally, the average position and orientation errors are represented in Table I. The fact that the triangular pattern of the RFID tag arrangement reduces the estimation error is mathematically shown in Section II by using the error model, and it is well demonstrated by these experiments.

The object of the second experiment is to show the effectiveness of the orientation-preestimation (Section III-B) and compensation (Section III-C) algorithms in reducing the localization error, which is the other contribution of this paper. In this paper, the mobile robot follows Path-1 in Fig. 14 and estimates its own position and orientation using the single RFID reader. To provide a better condition for the estimation, the RFID sensor space is formed by the tags in the triangular pattern.



(a)



(b)

Fig. 15. Error reduction by the compensation algorithm. (a) Position-error reduction. (b) Orientation-error reduction.

TABLE II
AVERAGE ERRORS OF THE POSITION AND ORIENTATION ESTIMATIONS

	Position Error(m)		Orientation Error(deg)	
	W/O algorithm	With algorithm	W/O algorithm	With algorithm
Error	0.016	0.0 09	1.36	0.70

Through Fig. 15 and Table II, it is clearly shown that the estimation error of the mobile-robot orientation is decreased to about 50% by the orientation preestimation and compensation described in Section III. Not only the orientation accuracy but also the position accuracy is improved.

V. CONCLUSION

This paper proposes an efficient and precise localization scheme in an RFID sensor space, which is derived from the new ideas on the tag arrangement and on the preestimation and compensation of the mobile-robot states. 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 sensor space. To illustrate the improved accuracy and efficiency of the mobile-robot localization, the square and triangular tag-arrangement patterns have been compared. The triangular pattern has shown better performance than the square pattern for the position/orientation estimation of a mobile robot. When the mobile robot moves in the RFID sensor space, the orientation of the robot is preestimated and compensated to reduce the estimation error and to implement a precise localization system. Based on the approach described over the RFID sensor space, the absolute position of a mobile robot can be estimated precisely without any interference from the environment. Therefore, this scheme is very effective for the position/orientation estimation of any object in the sensor space and it could be a good tool to form a ubiquitous environment.

REFERENCES

[1] D. Hahnel, W. Burgard, D. Fox, K. Fishkin, and M. Philipose, "Mapping and localization with RFID technology," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2004, vol. 1, pp. 1015–1020.
[2] J. L. M. Flores, S. S. Srikant, B. Sareen, and A. Vagga, "Performance of RFID tags in near and far field," in *Proc. IEEE Int. Conf. Pers. Wireless Commun.*, 2005, pp. 353–357.
[3] O. Kubitz, M. O. Berger, M. Perlick, and R. Dumoulin, "Application of radio frequency identification devices to support navigation of autonomous mobile robots," in *Proc. IEEE Veh. Technol. Conf.*, 1997, vol. 1, pp. 126–130.
[4] V. Kulyukin, C. Gharpure, J. Nicholson, and S. Pavithran, "RFID in robot-assisted indoor navigation for the visually impaired," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2004, pp. 1979–1984.
[5] K. Yamano, K. Tanaka, M. Hirayma, E. Kondo, Y. Kimuro, and M. Matsumoto, "Self-localization of mobile robots with RFID system by using support vector machine," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 28–Oct. 2, 2004, vol. 4, pp. 3756–3761.
[6] K. Ohno, T. Tsubouchi, B. Shigematsu, S. Maeyama, and S. Yuta, "Outdoor navigation of a mobile robot between buildings based on DGPS and odometry data fusion," in *Proc. IEEE Int. Conf. Robot. Autom.*, Sep. 2003, pp. 1978–1984.
[7] K. Komoriya and E. Oyama, "Position estimation of a mobile robot using optical fiber gyroscope," in *Proc. IEEE/RSJ/GI Int. Conf. Intell. Robots Syst.*, Sep. 12–16, 1994, vol. 1, pp. 143–149.
[8] K. Nagatani, Y. Iwai, and Y. Tanaka, "Sensor-based navigation for car-like mobile robots using generalized Voronoi graph," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2002, vol. 3, pp. 3068–3073.
[9] J.-H. Lee and H. Hashimoto, "Controlling mobile robots in distributed intelligent sensor network," *IEEE Trans. Ind. Electron.*, vol. 50, no. 5, pp. 890–902, Oct. 2003.
[10] S. Shenoy and J. Tan, "Simultaneous localization and mobile robot navigation in a hybrid sensor network," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Aug. 2–6, 2005, pp. 1636–1641.
[11] H. Chae and K. Han, "Combination of RFID and vision for mobile robot localization," in *Proc. IEEE Int. Conf. Intell. Sensors, Sensor Netw. Inf. Process.*, 2005, pp. 75–80.
[12] B. S. Choi and J. M. Lee, "A moving object capturing algorithm using the single curvature trajectory," *J. ICASE*, vol. 12, no. 2, pp. 145–153, 2006.
[13] E. D. Sharp, "A triangular arrangement of planar-array elements that reduces the number needed," *IEEE Trans. Antennas Propag.*, vol. AP-9, no. 2, pp. 126–129, Mar. 1961.
[14] D. Lee and W. Chung, "Discrete-status-based localization for indoor service robots," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1737–1746, Oct. 2006.
[15] D. Hahnel, W. Burgard, D. Fox, K. Fishkin, and M. Philipose, "Mapping and localization with RFID technology," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2004, pp. 1016–1020.

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