Autonomous Mobile Robot Navigation Using Passive RFID in Indoor Environment

Sunhong Park and Shuji Hashimoto

Abstract—**This paper proposes an efficient method for localization and pose estimation for mobile robot navigation using passive radio-frequency identification (RFID). We assume that the robot is able to identify IC tags and measure the robot's pose based on the relation between the previous and current location according to the IC tags. However, there arises the problem of uncertainty of location due to the nature of the antenna and IC tags. In other words, an error is always present which is relative to the sensing area of the antenna. Many researches have used external sensors in order to reduce the location errors, with few researches presented involving purely RFID driven systems. Our proposed algorithm that uses only passive RFID is able to estimate the robot's location and orientation more precisely by using trigonometric functions and the IC tags' Cartesian coordinates in a regular gridlike pattern. The experimental results show that the proposed method effectively estimates both the location and the pose of a mobile robot during navigation.**

Index Terms—**Autonomous mobile robot, localization, navigation, passive radio-frequency identification (RFID), pose estimation.**

I. Introduction

AUTONOMOUS mobile robots need localization technology to move about and perform assigned tasks. In particular, in the proliferation of navigation technologies, both the location information and pose information of a mobile robot in a given environment are indispensable. In general, these have been classified by the three questions of mobile robots. Those are "Where am I?", "Where am I going?", and "How do I go there?". Some widely used localization algorithms utilize dead reckoning (DR) [1], [2], which makes it possible to estimate the total distance traveled from a starting point. However, DR is problematic in that the estimation error accumulates over time since no external reference signals are employed for correction. Recently, in order to improve the accuracy of localization, many approaches combine external sensors; such as cameras, laser range finders, sonar, GPS, etc. Hahnel *et al.* [3] build 3-D models with a laser scanner mounted vertically on the mobile robot equipped with a horizontal 2-D localization system. Moravec [4] used evidence grids in 3-D space based on stereo vision. There are also methods to revise the accumulated errors by external sensors using landmarks [5]–[7]. These methods estimate the location and pose of the robot from the observation of landmarks established in environment. However, the landmarks are not always observable due to the influence of ambient light and shielding obstacles.

One of the most well-known localization systems in outdoor environments is the Global Positioning System (GPS), a satellite-based navigation system made up of a network of 24 satellites in orbit [8]. GPS is widely used to track moving objects located outdoors. However, the receiver is not synchronized with the satellite transmitters and, thus, cannot precisely measure the time that it took the signal to reach the ground from space. Additionally, ultrasonic systems, like the Active Bat localization systems [9], use an ultrasound time-of-flight measurement technique to provide location information. In order to determine pose information of a mobile robot, many approaches have used external sensors such as cameras providing 2-D and 3-D information about the environment [10], [11].

In this paper, we propose a method for estimating both location and pose information of a mobile robot using only passive radio-frequency identification (RFID). According to the conventional approach, two antennas are necessary to identify the orientation of the mobile robot. However, furthermore, our proposed algorithm that uses only passive RFID is able to estimate the robot's location and orientation more precisely by using trigonometric functions and the IC tags' Cartesian coordinates in a regular gridlike pattern. Using our approach, we are able to acquire robust environment information.

Although RFID systems can provide location information of a robot, it is difficult to accurately calculate location of the robot due to the nature of the antenna, which can only detect if a IC tag is present or not. Therefore, a mobile robot normally requires other sensors for estimating its precise location and pose. We present the improved algorithm that estimates the pose of robot dynamically from the record of acquired location information. In order to examine its validity, we implemented it on an autonomous mobile robot. The IC tags are small and inexpensive, making them easily installed in a human living environment. They can even be installed under carpets or other flooring materials, since unlike barcodes they are identified by radio frequency. Moreover, IC tags are durable against dirt, vibration, and wear.

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II. Related Work

Recently, RFID has been used for localization and navigation of mobile robots. RFID is also useful in mobile robotics as a substitute for other forms of landmark detection as a basis for navigation [12]. Lionel *et al.* [13] presented LANDMARC, a location sensing prototype system that used active RFID for locating objects inside buildings. Han *et al.* [14] present localization scheme for an indoor mobile robot using RFID system. They adopted triangular pattern of arranging the RFID tags on the floor in order to reduce the estimation error of the conventional square pattern. This method also uses encoder at each wheel for the precise control of the mobile robot, while it estimates localization using single antenna. Chon *et al.* [15] used an RFID system along with GPS and a gyroscope to produce highly accurate location information. They installed active IC tags which stored accurate location information on roads. Yamano *et al.* [16] proposed a method that performs self-localization with an RFID system using Support Vector Machines. In RFID technology, there is little research on both localization and pose estimation of a robot. Matsumoto *et al.* [17] combined RFID and GPS to estimate both localization and pose of robot. In these researches, generally, only the location is estimated with the RFID system, while pose estimation is performed by other sensors. Additionally, some methods which use active IC tags require maintenance by humans, such as periodic battery exchange.

Contrary to the aforementioned methods, we have proposed a method that is able to estimate localization and pose of a robot while navigating [18]. Tsukiyama [19] developed a navigation system for mobile robots using RFID tags, however, their system assumed perfect signal reception and measurement and do not deal with uncertainty. On the other hand, we proposed a method that, by using an anticollision function, is able to read plural tags at the same time [20]. From this experimental result, we could estimate a more precise location and pose estimation of the robot. However, it is not economical because of the increased number of required tags. The two methods given in [18] and [20] differ in their experiment environments. In [18], we proposed navigation in gridlike pattern of IC tags, while in [20], we used anticollision to be able to read multiple IC tags at once in order to reduce localization error. Recently, Gueaieb and Miah [21] proposed navigation method based on processing analog features of an RFID signal without a vision system and building a map of the robot workspace. This method used signal strength of active RFID. It may occurs problem such as signal unstable according to environment situation. Furthermore, although it used real-world data sampled from a real RFID system, the results are based on computer simulations. Here, proposed method focuses on the localization error from the RFID system. We propose a method that reduces the localization error by using trigonometric functions and the Cartesian coordinates of IC tags in a regular distribution.

This paper is organized as follows. In Section III, a brief overview of the autonomous mobile robot [UBIquitous RObot (UBIRO)] and RFID system. In Section IV, the localization and pose estimation algorithms are described. We performed a series of experiments with the developed algorithms, the results of which are presented in Section V. Finally, conclusion and future works are described in Section VI.

Fig. 1. Mobile robot (UBIRO).

III. Mobile Robot and RFID System

A. UBIRO

In this section, we describe the robot system named UBIRO used in the experiment. UBIRO consists of three main parts: the PC for control, the RFID system for obtaining the location information of robot, and the mobile base for navigation. UBIRO was developed based on an electric wheelchair (EMC-230) for the elderly and disabled persons as a mobility device. The PC mounted on the electric wheelchair acts as a central controller that handles information of IC tags from the RFID system and sends command to mobile base in order to reach the goal. The RFID system reads IC tags on the floor which allows the PC to roughly deduce the location and pose of the robot based on the proposed algorithms. Finally, the mobile base is controlled by the PC based on calculations result from information provided by the RFID system. UBIRO has external sensors such as distance sensors and touch sensors (bumper switches) for detection of obstacles. The robot's front wheels are free rotating casters, causing some instability when moving. UBIRO is shown in Fig. 1 and the specifications are given in Table I.

B. RFID System

RFID systems usually consist of a reader, an antenna, IC tags, and software such as drivers and middleware. The main function of the RFID system is to retrieve information (serial number) from an IC tag (also known as a transponder) and to send it to the PC. An antenna is sometimes regarded as a separate part of an RFID system. The communication between

TABLE I
SPECIFICATIONS OF UBIRO

Feature	Description
Size	800(W)×1100(D)×1050(H)[mm]
Weight	110kg
Battery Weight	SS-SEB35-T 30kg (Two 12V 35A)
Operation System	Windows XP (Pentium III 850MHz / 512MB)
Velocity	Min. 2.5km/h and Max. 6.0km/h
Range of Travel	30Km

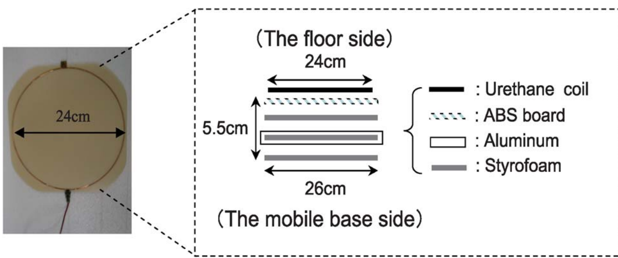

Fig. 2. Picture and structure of the antenna for 13.56 MHz.

an antenna and IC tags uses inductive coupling, and each has a coil. The energy is transferred from an antenna to IC tags by means of mutual inductance between the two circuits. The frequency for the RFID system is 13.56 MHz.

C. Reader

In the RFID system, we adopted the compact and inexpensive RFID reader (Midrange Reader Module) made by Texas Instrument. It operates at a frequency of 13.56 MHz and handles all RF and digital functions in order to communicate with Tag-it HF, Tag-it HF-I, and all other ISO 15693 devices. Moreover, it has an anticollision function that makes it able to read plural IC tags simultaneously.

D. Antenna

The size of the antenna in the RFID system must be adjusted in accordance with the distance between IC tags. We constructed an experimental circular antenna shown in Fig. 2 that is able to read IC tags on the 13.56-MHz frequency band by using the S6350 Midrange Reader Module (Texas Instruments).

It is possible to read IC tags within 6 cm under the antenna. Thus, we assume that the IC tags are laid on the floor where the robot explores, attach the antenna to the underside of the mobile base, keeping the distance from the antenna to the floor approximately 5 cm. Since the batteries of mobile base are equipped near the antenna, we covered the antenna with Styrofoam, aluminum sheeting, and Acrylonitrile Butadiene Styrene (ABS) material board to block the magnetic field, as shown in the Fig. 2. Although the diameter of the antenna is 24 cm, the antenna is able to read IC tags which exist within about 17 cm from the center of the antenna.

E. IC Tag

Generally, IC tags for RFID systems can be classified as one of three types: passive, semipassive (also known as semiactive), and active.

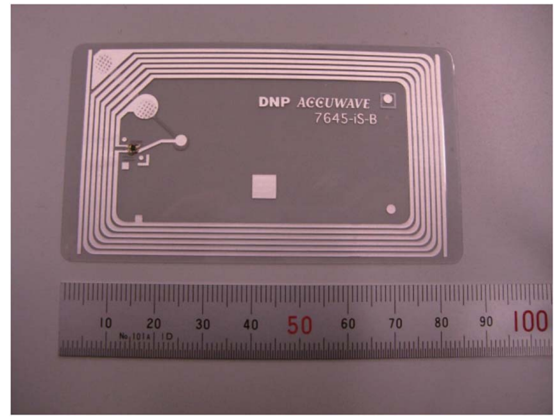

Fig. 3. Passive IC tag.

TABLE II
SPECIFICATIONS OF PASSIVE IC TAG

Feature	Description
IC Chip	I – CODE SLI (ISO15693)
Size	76(W)×45(D) ×0.23(H)[mm]
Weight	1.5g
Communication range	13.56MHz
Memory	1KB

1) Passive: Passive-type IC tags have no internal power supply. The minute electrical current induced in the antenna by the incoming radio frequency signal provides power for the IC in the tag to power up and transmit a response. Although communication range of passive tag is short, this is compact and requires no battery maintenance.

2) Semipassive: Semipassive IC tags are similar to passive tags except for the addition of small battery. This battery allows the IC tag to be powered when the tag is activated by the reader. Semipassive IC tags are faster in response and can produce a stronger signal compared to passive tags.

3) Active: Unlike passive and semipassive IC tags, active IC tags have their own internal power source which is used to power the IC and generate the outgoing signal. They are often called beacons because they broadcast their own signal. They may have longer range and larger memories than passive tags, as well as the ability to store additional information sent by the transceiver. However, its size is increased due to the need for a power supply and requires regular maintenance for battery exchange.

In consideration of no maintenance, cost, and indoor environment, we adopted the passive tags shown in Fig. 3. The specifications of the IC tag are given in the Table II.

Each IC tag is programmed to send a serial number that is related to the 2-D coordinate of the tag position in a database stored on the robot. Moreover, the IC tag is recognized only when it stays within the reception area of the antenna for more than 50 μs.

F. Tag Arrangement

There are two tag arrangement patterns: random distribution and the regular distribution. In case of the regular distribution method, the robot can sense at least one IC tag at any location. Although we must arrange IC tags maintaining the regular

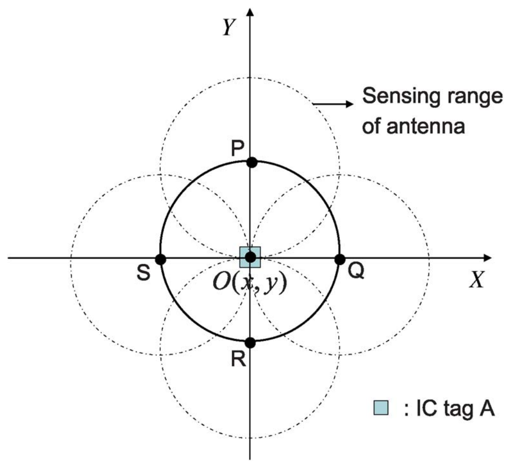

Fig. 4. Uncertainty of robot location.

distance and pattern in environment, it is easy to get the location information without an additional special algorithm. In this paper, we use the regular distribution method and arrange the IC tags in the square gridlike pattern.

G. Reduction of Localization Error

The localization error in navigation based on the RFID system is proportional to the sensing range of the antenna. As mentioned before, many researches had been used external sensors such as the DR, vision systems, and sonar in order to reduce the localization error. In using the RFID system, some research introduces the method which raises the arrangement density of IC tags. However, the system cost is also increased because it increases the number of IC tags. Moreover, a problem with detection collisions arises, as sometimes the antenna senses more IC tags than it can handle at once. In this paper, we use trigonometric functions and the Cartesian coordinates of the IC tags to reduce the localization error of the RFID system. We can reduce the location error that results from antenna sensing range and raise the accuracy of localization, as shown through the experimental results.

IV. Localization and Pose Estimation Algorithm

In navigation of a mobile robot, there are two important factors: localization and pose estimation. Therefore, we aimed to estimate accurately the location and pose of a robot in navigation through the use of trigonometric functions and the Cartesian coordinates in regular distribution of IC tags. Although the RFID system dramatically simplifies the process of tracking parts, it cannot estimate physical location of an IC tag in the antenna's sensing range, as shown in Fig. 4.

Let us assume that IC tag A is at the origin O of the $X{-}Y$ coordinates. When the robot is at O, the robot reads the current location as $O(x, y)$. However, when the robot is at P, Q, R, S, they also read the current location as the same, $O(x, y)$. Therefore, there is a localization error proportional to the sensing range of the antenna, as in

$$X - \text{axis} : 0 \leq x_{\text{localization\_error}} \leq D \tag{1}$$

$$Y - \text{axis} : 0 \leq y_{\text{localization\_error}} \leq D. \tag{2}$$

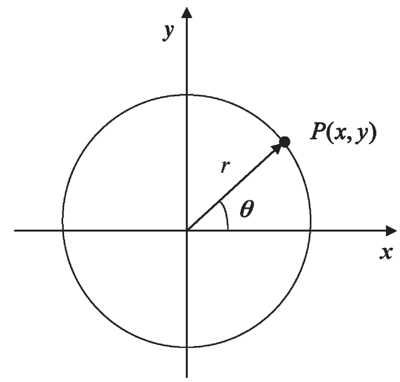

Fig. 5. Polar coordinates at P.

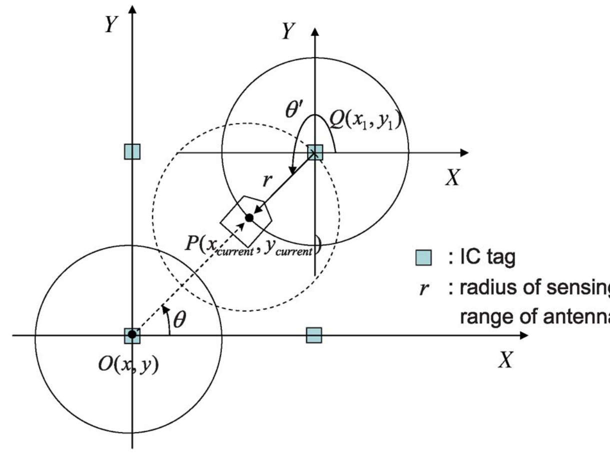

Fig. 6. Proposed method of localization.

In this equation, D is the diameter of the sensing range of the antenna.

We used trigonometric functions and the Cartesian coordinates of the IC tags in regular distribution in order to reduce the uncertainty of localization for situations, as shown in Fig. 5.

In general, as shown in Fig. 5, the polar coordinates (r, θ) are defined in terms of Cartesian coordinates (x, y) by

$$x = r \cos\theta \tag{3}$$

$$y = r \sin\theta \tag{4}$$

$$r = \sqrt{x^2 + y^2} \tag{5}$$

$$\theta = \tan^{-1}\left(\frac{y}{x}\right) \tag{6}$$

where r is the radial distance from the origin, and θ is the counter clockwise angle from the positive X-axis.

When the robot detects a new IC tag, as shown in Fig. 6, we can calculate robot's location $x_{\text{current}}, y_{\text{current}}$ as in IC tags field like (7) and (8) using the above equations

$$x_{\text{current}} = r \cos\theta' + x_1 \tag{7}$$

$$y_{\text{current}} = r \sin\theta' + y_1. \tag{8}$$

Radius r is 17 cm, the same as the radius of the sensing range of the antenna. Let angle (θ') denote an incident angle against the newly detected IC tag. The θ' is given by the accumulation

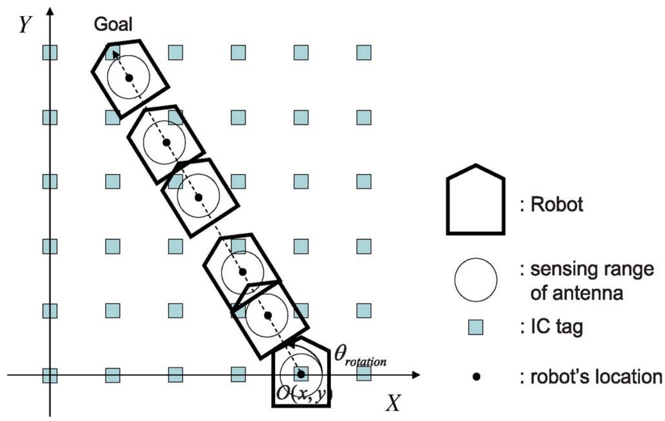

Fig. 7. Overall concept of proposed method.

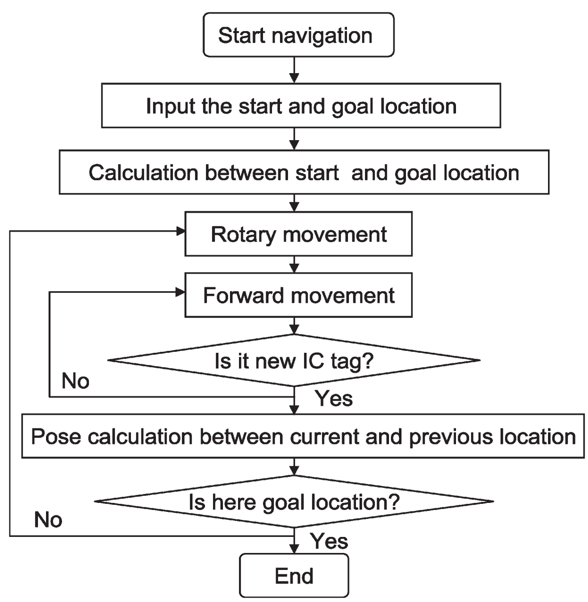

Fig. 8. Procedure of navigation.

of the rotation angle of the robot. Equations (7) and (8) are also used in the procedure for navigation. Unlike conventional method that used single antenna without considering pose of a robot, our proposed algorithm reflected pose of a robot whenever newly detected IC tag. Consequently, proposed method can estimate precisely location and pose. Fig. 7 describes the overall concept of the proposed algorithm, and Fig. 8 shows the procedure of the navigation using proposed algorithm.

Initially, the robot is given the initial location and goal location by the user. Then, it starts to navigate toward goal based on a calculated rotation angle between the start and goal. The initial pose of robot is 0°, representing the positive Y-axis. Next, the robot estimates the orientation angle from the current and previous location information. The robot recalculates the orientation of the goal location and determines the rotation angle of robot to reach the goal again. The antenna reads new IC tags at an interval of 0.2 s, and the robot rotates according to the calculated rotation angles periodically. Otherwise, the robot keeps moving forward. The robot speed is determined by antenna sensing ability; if the robot moves too quickly, some tags will fail to be read. In the event the robot reads the same tag after a rotation, the robot proceeds in the same direction without a course adjustment.

Utilizing the aforementioned described approach, we calculate the rotation angle for navigation to the goal by the following method. First, the robot starts to move without considering the initial pose. The orientation of the goal $\theta_{\mathrm{start}\rightarrow\mathrm{goal}}$: is derived from the initial and goal location by

$$\theta_{\mathrm{start}\rightarrow\mathrm{goal}} = \arctan\left(\frac{y_{\mathrm{goal}} - y_{\mathrm{init}}}{x_{\mathrm{goal}} - x_{\mathrm{init}}}\right). \tag{9}$$

In this equation, $(x_{\mathrm{goal}}, y_{\mathrm{goal}})$ represents the coordinate of the goal location. Likewise, $(x_{\mathrm{init}}, y_{\mathrm{init}})$ represents the coordinate of the start location. The robot obtains the coordinates of new IC tags from the antenna when it moves. We assumed that the robot moves straightly, so that the incident angle (θ') equals the pose of the robot: $(\theta_{\mathrm{previous}\rightarrow\mathrm{current}})$ as following:

$$\theta_{\mathrm{previous}\rightarrow\mathrm{current}} = \arctan\left(\frac{y_{\mathrm{current}} - y_{\mathrm{previous}}}{x_{\mathrm{current}} - x_{\mathrm{previous}}}\right) \tag{10}$$

where $(x_{\mathrm{previous}}, y_{\mathrm{previous}})$ and $(x_{\mathrm{current}}, y_{\mathrm{current}})$ denote the coordinates of the location scanned previous and current, respectively.

According to (11), we obtain the angle $(\theta_{\mathrm{current}\rightarrow\mathrm{goal}})$ between the current location

$$\theta_{\mathrm{current}\rightarrow\mathrm{goal}} = \arctan\left(\frac{y_{\mathrm{goal}} - y_{\mathrm{current}}}{x_{\mathrm{goal}} - x_{\mathrm{current}}}\right). \tag{11}$$

From (10) and (11), the rotation angle $(\theta_{\mathrm{rotation}})$ toward the goal is provided by (12). The current location and orientation are updated in real time

$$\theta_{\mathrm{rotation}} = \theta_{\mathrm{previous}\rightarrow\mathrm{current}} - \theta_{\mathrm{current}\rightarrow\mathrm{goal}}. \tag{12}$$

Accordingly, the rotation $\theta_{\mathrm{rotation}}$ is also updated by (12).

Fig. 9 describes the example of a rotation and forward movement of the robot when the value of $\theta_{\mathrm{rotation}}$ is zero, positive, and negative. The robot repeats a forward and rotation movement autonomously until it reaches the goal. The forward movement speed of the robot is about 12.2 cm/s in the experiment. In any navigation system using RFID, reliable detection of RFID tags is important for accuracy in estimating the location of the robot. For this reason, we set the speed of the mobile robot to about 12.2 cm/s. The speed of robots using RFID systems depend on the read rate of the RFID reader. If we use an RFID reader that can detect tags more quickly, the speed of the robot can be raised without any change to the proposed algorithm.

V. Experiments

To evaluate the validity of localization and pose estimation using the proposed algorithm for mobile robot navigation, we conducted experiments under three kinds of conditions. In the condition 1, the initial pose of the mobile robot was 0°, i.e., the positive Y-axis. Condition 2 was 90°. Finally, condition 3 was $-90°$. The experimental environment is shown in Fig. 10. We

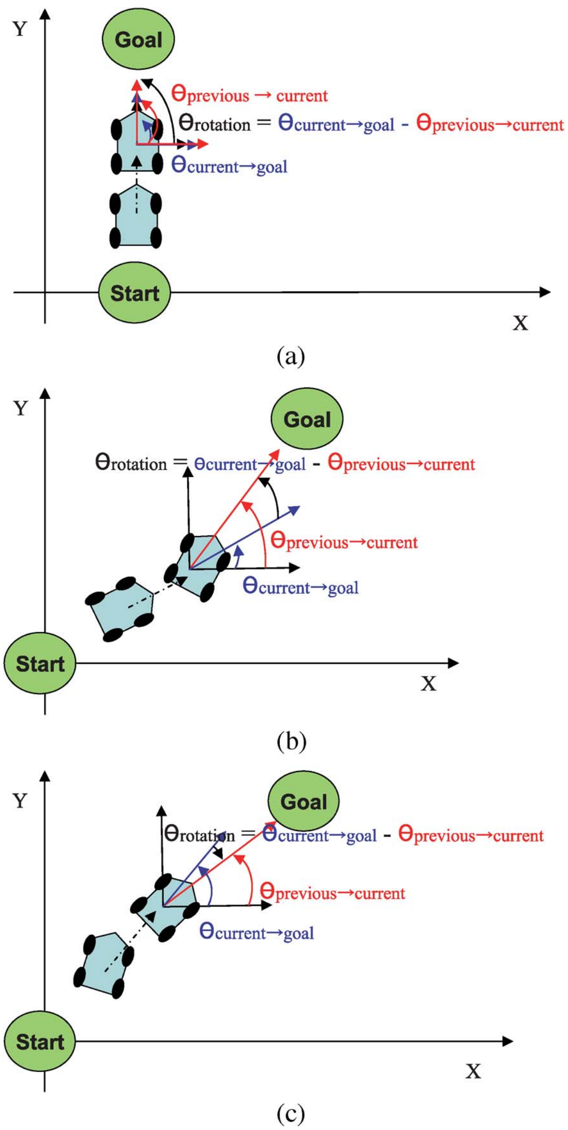

Fig. 9. Patterns of robot movement (a), (b), and (c). (a) Forward: $\theta_{\text{rotation}} = 0$. (b) Turn left: $\theta_{\text{rotation}} > 0$. (c) Turn right: $\theta_{\text{rotation}} < 0$.

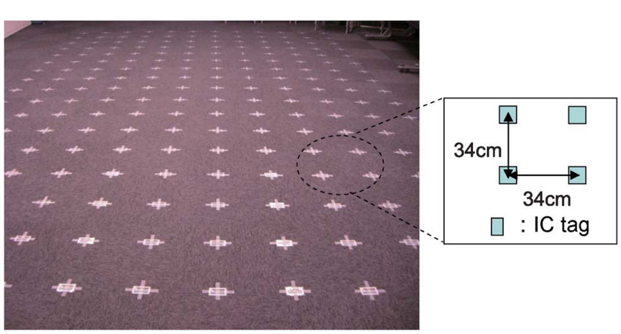

Fig. 10. Experimental environment.

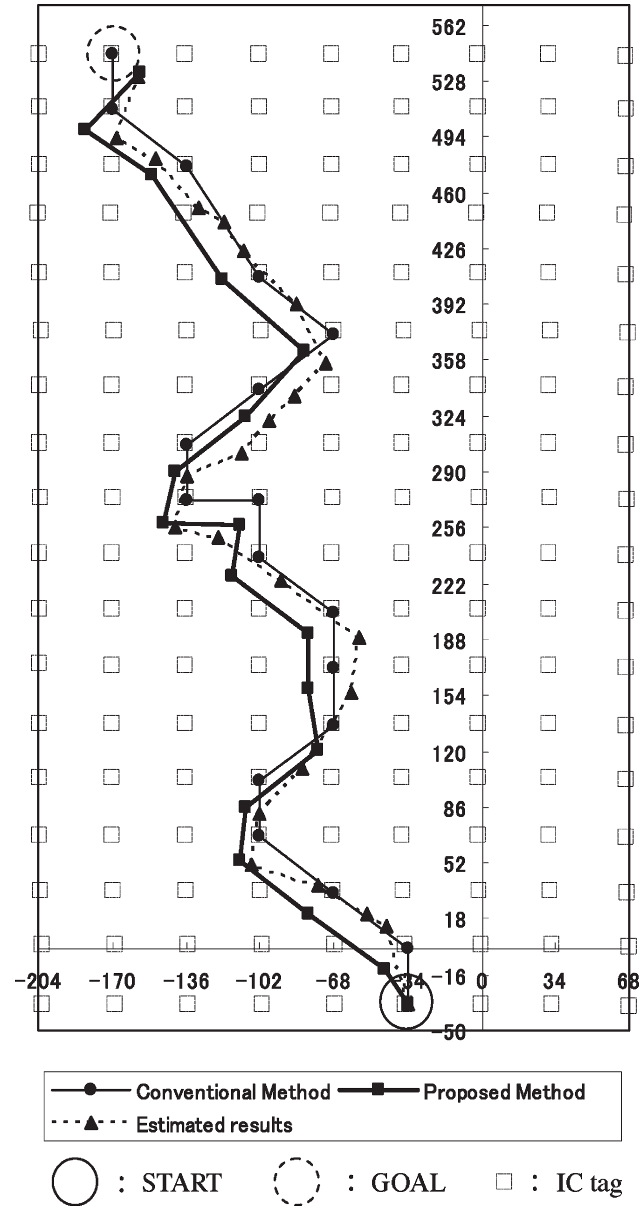

Fig. 11. Path trajectories under the condition 1.

assumed the environment as an indoor field where the IC tags were deployed. The 198 passive IC tags were laid on the floor in a gridlike pattern over an area measuring 420 cm × 620 cm, with a spacing of 34 cm. The field was free of obstacles. The robot stops navigating when the antenna detects the IC tag of the goal area (within 34 cm × 34 cm).

The result of the condition 1, the condition 2, and the condition 3 are shown in Figs. 11–13, respectively. Three figures show the start location, the goal location, and the path trajectories. Here, we compared with the conventional method without the proposed error reduction [18] and the proposed method for each condition. The robot stops and ends navigation in case that the antenna detected the IC tag of the goal. Moreover, we arranged the IC tags around the field in order to prevent the robot going out of IC tag field.

In general, conventional method acquired an intermediate location of the IC regardless of pose of robot which detected IC tag. Moreover, the moving distance of the robot relies on the direction of the front wheel, which is a free caster, and changes from 0 to 60 cm, approximately. On the other hand, the proposed method could measure more accurately localization and pose of robot in real time. Table III illustrates localization error between the conventional method and proposed method.

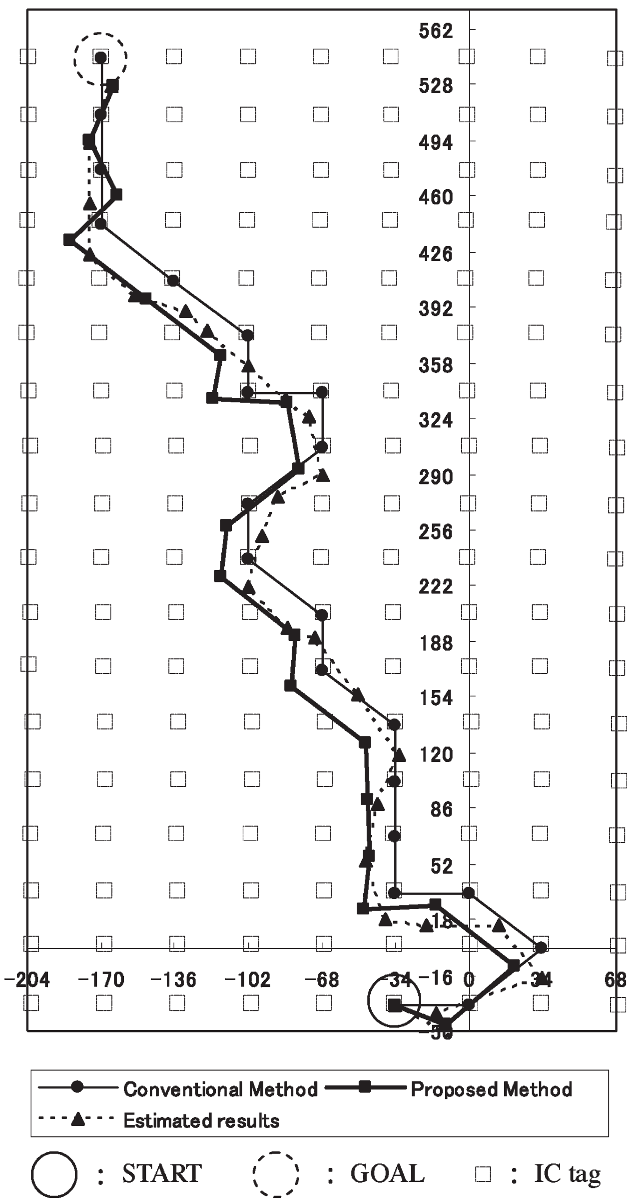

Fig. 12. Path trajectories under the condition 2.

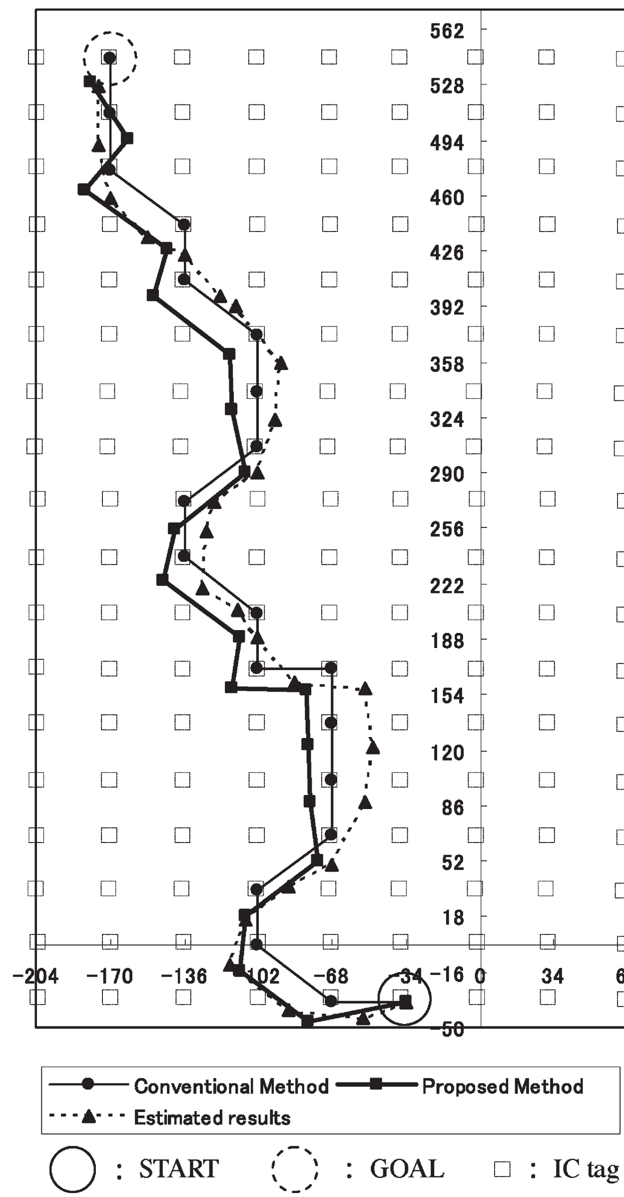

Fig. 13. Path trajectories under the condition 3.

While localization error in the proposed method has 13.3 cm at X-axis and 5.7 cm at Y-axis in the average, conventional method has 17 cm at $X-Y$ coordinates.

According to the results of experiments, when sufficient IC tags are deployed in environment, the mobile robot was able to reach the goal without relation to initial pose. In path trajectories under each condition, the proposed method showed that it was able to estimate more precisely both the location and the pose of a mobile robot during navigation. However, there are problems such as the wheel slippage and drift, as mentioned in Section III. The front wheel of robot is free caster so it is difficult to move as we command. From these reasons, estimation of location and pose of robot are sometime unstable.

We realized through Figs. 11 and 13 that the X-axis error is larger when the robot makes a wider turn form left to right, and vice versa. Due to this reason, the Y-axis error is relatively smaller than that of the X-axis. Although the mobile robot using the proposed method navigated sometime zigzag toward goal location, the movement of robot was seen smoothly like Fig. 14. On the average, the robot was able to reach the goal within 85 s. The total time of navigation using the proposed method is shorter than the conventional method (97 s). From this result, we can decrease the time that took total navigation by placement pattern of IC tags suitable to purpose.

TABLE III
COMPARISON OF LOCALIZATION METHODS

Localization error	X-axis [cm]	Y-axis [cm]
Conventional Method [18]	17	17
Proposed Method	13.3	5.7

VI. CONCLUSION AND FUTURE WORK

In this paper, we have described an efficient method that considers uncertainty for estimating the location and orientation of a mobile robot using a passive RFID system. The aim of our

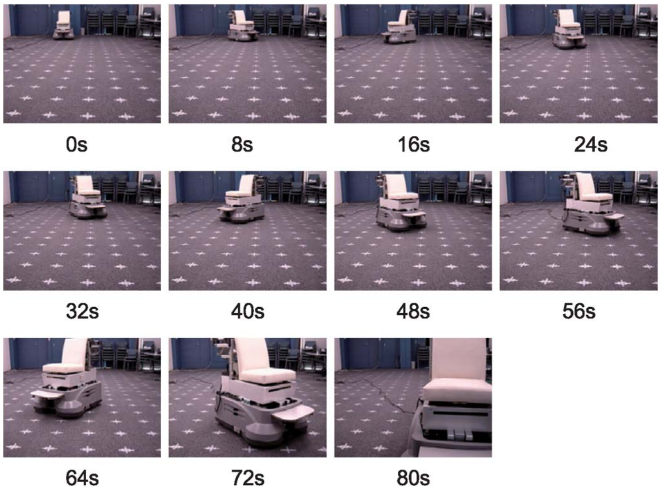

Fig. 14. Movie capture under the condition 1.

approach is to precisely acquire the location and orientation of the robot based on information of the placement of the IC tags. Using proposed algorithm, we can estimate precisely location and pose of a robot with consideration of an incidence angle to IC tags.

Unlike many conventional approaches, our approach does not require any sensors in order to acquire or modify the position of the robot. We examined the efficiency of the algorithm through indoor experiments with the mobile robot. After examining the recorded trajectories, we determined that using our approach the robot was able to navigate autonomously and estimate successfully its location and the orientation more precisely than previous researches on that topic. Our results show that the placement pattern of the IC tags should be adapted through experiments to suit different applications. The IC tags can be identified robustly despite of any covers, dirt, wear, or vibration, and so we conclude that the IC-tagged-room is a feasible option for real-life applications. We believe that our approach would be adequate for providing mobility for elderly and disabled people.

In the near future, we aim at improving the navigation algorithm to identify the IC tags which will allow the mobile robot to navigate through more dynamic environments with obstacles. We are going to continue experimenting with different placing patterns and distances between the IC tags. The accuracy of the location depends on the incident angle (θ') and is unstable due to the rotation angle error that arises when the robot makes wide turns. We plan on redesigning the front wheels of the robot to allow us more precise motion control. We also plan to incorporate time measurements of the interval between detecting and loosing an IC tag in order to determine the location and orientation of the robot relative to that tag.

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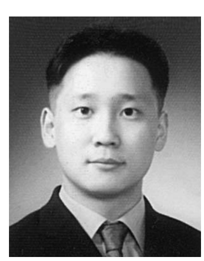

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