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Mobile Robot Localization in Indoor Environment using RFID and Sonar Fusion System

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Abstract—**Localization of indoor environment is a fundamental issue for mobile robot. In this paper, we proposed the localization scheme to fusion the RFID localization system, ultrasonic sensor and wheel encoder. The uncertainty is factor caused by each localization system, and the estimation error is affected by this uncertainty. The sensor system for mobile robot localization is technical limitation such as sensing range, operation feature. Therefore we focus on sensor fusion scheme. When the mobile robot moves, certain data combination set to fuse is selected according to the environmental factor. The performance and simplicity of the approach is demonstrated with the result produced by experiments using mobile robot.**

I. Introduction

THE localization problem of mobile robots is considered as most fundamental issue in the field of robotics. In recent year, the concern about mobile robots such as service robot, and entertainment robot is increasing. Therefore, many methods for mobile robot localization have been researched and developed so far [1]-[8]. Localization problem can be defined as recognize robot's own position in given environment. There are several localization methods.

Recently, RFID (Radio Frequency Identification) system [9] is applied to mobile robot localization problem [10]-[15]. And also, efficient sensor fusion method is used in order to reduce the uncertainty in RFID localization system. The sensors such as ultra-sonic sensor, laser sensor, and CCD camera sensor are employed with RFID localization system.

We found the some problem in existing researches, which suggest the RFID fusion localization scheme. The first problem is the deficiencies from technical limitations of RFID localization system. For example, we are not able to know the exact location of a passive tag within RFID reader recognition area. And also, the distance between the RFID reader and the RFID passive tags cannot be measured using time of flight methods. The second problem is the environmental constriction from distance measurement sensor, which is used with RFID localization system. For example, the distance measurement sensor such as ultra-sonic and laser sensor cannot obtain the distance data if there are no obstacles within sensing range.

Therefore, we propose a novel scheme for mobile robot localization to solve the problem in RFID fusion localization system. This research is based on RFID localization system. We focus on a sensor system that fuses an RFID localization system, ultra-sonic sensors, and wheel encoder of mobile robot. The RFID localization system provides us with convenient and robust approach to location data under environmental changes. The ultra-sonic sensors provide us with continuous environmental information from distance measurements using obstacle. It partially compensates the technical limitations in the RFID localization system. The wheel encoder of mobile robot can measure the displacement from reference position. Because the wheel encoder provides us with location data irrespective of obstacle, the problem of ultra-sonic sensor based on obstacle is solved using wheel encoder. This paper adds wheel encoder system to previous RFID localization system which fuses that fuses an RFID localization system and ultra-sonic sensors. Therefore, effective mobile robot localization was also conducted for space, which has no obstacle.

This paper is organized as follows. Section 2 addresses the related work and problems to solve. In Section 3, the localization architecture and each localization system are explained. In Section 4, the localization algorithm to fuse systems is addressed. In Section 5, the experiment and result are is explained Finally, the conclusion is presented in Section 6.

II. Related Work

In recent research, RFID system is used for mobile robot localization. However, this system is subject to uncertainty from technical limitation. In order to reduce the estimation error in RFID localization system, localization system based on fusion sensor is proposed using ultra-sonic senor, laser sensor, and camera sensor.

H.-H. Lin *et al*. [16] proposed the mobile robot localization method using laser scanner and active RFID system. P. Kamol *et al*. [17] used the camera on ceiling in order to complement the shortcoming of RFID based localization system. S. Jia *et al*. [18] applied fusion system, stereo vision and RFID technology, to mobile robot localization. However, CCD cameras are often hampered by illumination problems. B.-S. Choi *et al*. [19] proposed the mobile robot localization algorithm using ultra-sonic sensor and RFID technology. The

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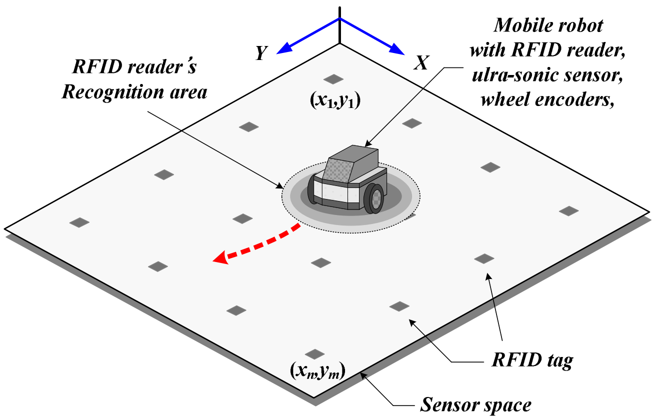

Fig. 1. RFID localization system based on tag-floor.

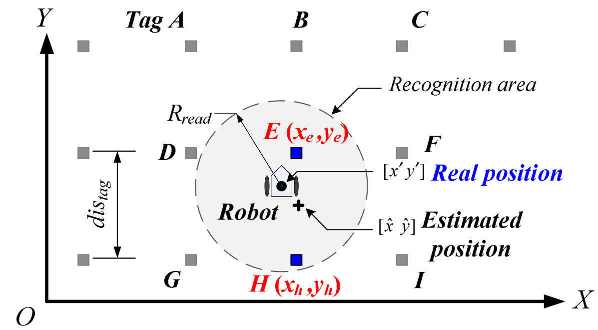

Fig. 2. Uncertainty about the recognition area in RFID localization system.

ultra-sonic sensor and laser sensor launch the sensor-beam, and then measure the distance data from the obstacle to robot. Therefore, ultra-sonic and laser sensor are widely used for localization, because we obtain comparatively accurate distance measurement data. However, the performance may not be guaranteed in special case. If the obstacles don't exist around the robot or sensing range, distance data between robot and obstacle is not obtained. Therefore, the uncertainty of RFID localization system is not be reduced.

We focus the fusion system with RFID localization system and ultra-sonic sensor. The continuous localization system is addressed using additional wheel encoder installed in mobile robot irrespective of obstacle.

III. Localization System

A. System Architecture

In this paper, the localization system is basically organized using RFID system (reader and tags) [19]. Fig. 1 shows the proposed system for mobile robot localization. The mobile robot moves in sensor space, where passive RFID tag (sensor agent) is arranged. 2-D coordinates, (x_1, y_1)~(x_m, y_m), is pre-stored in the passive tag. Mobile robot has RFID reader to obtain the coordinate data from passive tag. And also, the ultra-sonic sensors and wheel encoders are installed in the mobile robot.

B. Principle of RFID Localization System

1) Basic localization model: The RFID tag-floor localization system estimates the coordinates of the mobile robot through the coordinate data contained in passive tags that are within the RFID reader recognition area. Fig. 1 show the area shaped by the electromagnetic wave (RFID reader's recognition area) from RFID reader. If RFID tags exist within the recognition area, the tags are activated and can send the ID and data stored to RFID reader. The RFID reader antenna is installed on the bottom of the mobile robot. Therefore, the position of the mobile robot can be estimated using the coordinate data stored in the passive tags.

The state estimation value, $(\hat{x}(k),\ \hat{y}(k))$, of the mobile robot at time k in the 2-D coordinate is represented as follows:

$$\hat{P}(k) = [\hat{x}(k) \quad \hat{y}(k)]^T = [g_x(z(k)) \quad g_y(z(k))]^T . \tag{1}$$

The observer function, G, including the observer data, $z(k)$, is defined as follows:

$$G = \begin{bmatrix} g_x(z(k)) \\ g_y(z(k)) \end{bmatrix} = \begin{bmatrix} 0.5(\max\{x_1,\cdots,x_N\} + \min\{x_1,\cdots,x_N\}) \\ 0.5(\max\{y_1,\cdots,y_N\} + \min\{y_1,\cdots,y_N\}) \end{bmatrix}, \tag{2}$$

where N represents the number of tags detected by the reader and x_1, …, x_N, y_1, …, y_N represents the coordinate's information of the tags.

2) Uncertainty modeling: Note that the RFID reader in the passive RFID localization system cannot obtain precise location information from the tags. Only the existence of tags within the recognition area is checked—the distance measurement between RFID reader and tags are not available in the localization process (fig. 2). We represent the state estimation value including an estimation error, which is caused by the gap between tags and recognition area.

$$\hat{P}(k) = [\hat{x}(k) \quad \hat{y}(k)]^T = [x'(k) + v(k) \quad y'(k) + w(k)]^T \tag{3}$$

where $(x'(k),\ y'(k))$ is the real position of the mobile robot, and $(v(k),\ w(k))$ is the associated uncertainty. The gap between tags is dis_{tag}. If the coordinate data stored in tag E is $(x_e,\ y_e)$, the following equation is obtained.

$$\begin{aligned} & x_e - dis_{tag} < x'(k) - R_{read} < x_e \\ & x_e < x'(k) + R_{read} < x_e + dis_{tag} \end{aligned} \tag{4}$$

Using (4), the uncertainty with respect to X-coordinate and Y-coordinate can be represented as follows:

$$\begin{aligned} v(k) &= | x'(k) - \hat{x}(k) | \le 0.5\, | dis_{tag} | \\ w(k) &= | y'(k) - \hat{y}(k) | \le 0.5\, | dis_{tag} | \end{aligned} . \tag{5}$$

We consider uncertainties about measurement noise in RFID localization system. Real RFID systems are often hampered by some phenomenon such as time lag of

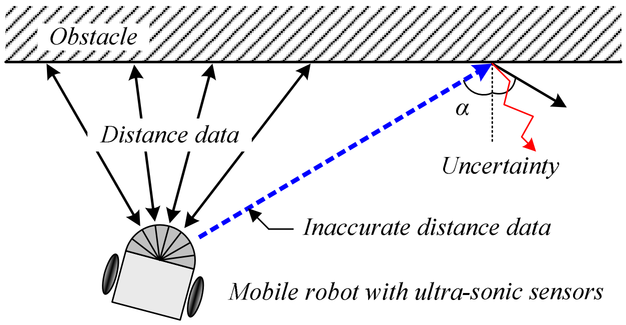

Fig. 3. Principle and uncertainty of ultra-sonic sensor.

communication system caused by unspecified reason. This case is regarded as the uncertainty about measurement noise. The estimated position of the mobile robot at time, k, is shown as (6).

$$\hat{P}(k)=[\hat{x}(k)\quad \hat{y}(k)]^T=[x'(k)+a(k)\quad y'(k)+b(k)]^T \tag{6}$$

If $\hat{P}(k-1)$ is equal to $\hat{P}(k)$ in spite activation of the new tags, the error, $a(k)$, and, $b(k)$, represent uncertainties about measurement noise, and is larger than the uncertainty about position estimation error caused by RFID reader's recognition area.

$$\begin{aligned} a(k) &= |x'(k)-\hat{x}(k-1)| > 0.5\,|dis_{tag}| \\ b(k) &= |y'(k)-\hat{y}(k-1)| > 0.5\,|dis_{tag}| \end{aligned} \tag{7}$$

C. Principle of Ultra-sonic Sensor System

1) Basic localization model: The ultra-sonic sensors installed the mobile robot can measure the distance between the mobile robot and obstacles within the environment (fig. 3).

The localization system with ultra-sonic sensor is applied from [19]. It is assumed that the search space of the mobile robot is well-structured indoor environment for effective mobile robot localization. The procedure is consist of three steps.

Step 1: Platform modeling

When the obstacles exist in the traveling space of the mobile robot, the position of the mobile robot and the position off the obstacles are described in 2-D coordinates. We define that the numbers of ultra-sonic sensors in the mobile robot is n and the position of the sensors, s_j, start from the front right-hand side with counter clockwise direction ($1 \le j \le n$). The distance R represents the distance from center of robot to sensors. The angle φ_{ij} represents the sensor placement angle, and each placement angle between two consecutive sensor is defined as α.

$$\alpha = 2\pi/(n-1) \tag{8}$$

$$\varphi_{ij} = (j-i)\alpha \tag{9}$$

The distance data for obstacles within environment is obtained and the mobile robot has the distance data every sampling period. The position is geometrically estimated using accumulated distance data. The distance data is defined as $d_j(k)$ from ultra-sonic sensor, s_j, at time k . The accuracy of the distance data from ultra-sonic sensor decreases when the distance data is larger, and the incidence angle of beam for the obstacle is larger. The data when incidence angle of beam is large, therefore, is excluded for the exact distance data.

Step 2: Propagation modeling

The distance vector is defined with magnitude and direction using the measured distance data and position of the sensors. If the initial position of the mobile robot is known, the measurement value for environment elements using ultra-sonic sensor. As shown in fig. 5, the position of the obstacle measured by ultra-sonic sensor s_j at time k is represented in X-Y robot coordinates as follows:

$$\begin{bmatrix} x_{ob}(k) \\ y_{ob}(k) \end{bmatrix}_j = \begin{bmatrix} R\cos\varphi_{1j} + d_j(k)\cos\varphi_{1j} \\ R\sin\varphi_{1j} + d_j(k)\sin\varphi_{1j} \end{bmatrix}. \tag{10}$$

The magnitude and direction of the distance vector for obstacle is represented as follows:

$$P_{ob}(k)_j = \begin{bmatrix} d_j(k) \\ \theta_{ob}(k) \end{bmatrix} = \begin{bmatrix} \sqrt{x_{ob}^2(k)+y_{ob}^2(k)} \\ \tan^{-1}(y_{ob}(k)/x_{ob}(k)) \end{bmatrix}. \tag{11}$$

Using the state vector, the position and orientation of the mobile robot at time k is represented as follows:

$$\hat{P}(k) = [\hat{x}(k)\quad \hat{y}(k)\quad \hat{\theta}(k)]^T. \tag{12}$$

At time k+1 after sampling period, the position of the mobile robot is represented including the current state and noise as follows:

$$\hat{P}(k+1) = H(\hat{P}(k), u(k)) + e(k), \tag{13}$$

where the position and orientation displacement of the mobile robot, $u(k)$, is defined using the position and orientation displacement, $u(k) = (\Delta x,\ \Delta y,\ \Delta\theta)$.

Step 3: Obstacle Estimation Modeling

It is assumed that the surface of obstacle is consisting of the combination of the straight line and curve.

In case of straight obstacle, at time k and k+1, the obstacle state, which is made from jth ultra-sonic sensor, s_j, in the robot is represented as follows:

$$P_{ob}(k)_j = [x_{ob}(k)\quad y_{ob}(k)\quad \theta_{ob}(k)]_j^T,\ 1 \le j \le n \tag{14-a}$$

$$P_{ob}(k+1)_j = [x_{ob}(k+1)\quad y_{ob}(k+1)\quad \theta_{ob}(k+1)]_j^T, 1 \le j \le n \tag{14-b}$$

where curvature is infinite for straight obstacle. Therefore, $\theta_{ob}(k) = \theta_{ob}(k+1)$.

In case of circular obstacle, at time k, k+1, and k+2, the obstacle state, which is made from jth ultra-sonic sensor, s_j, in the robot is represented as follows:

$$P_{ob}(k)_j = [x_{ob}(k)\quad y_{ob}(k)\quad \theta_{ob}(k)]_j^T,\ 1 \le j \le n \tag{15-a}$$

$$P_{ob}(k+1)_j = [x_{ob}(k+1) \quad y_{ob}(k+1) \quad \theta_{ob}(k+1)]_j^T, 1 \le j \le n \quad \text{(15-b)}$$

$$P_{ob}(k+2)_j = [x_{ob}(k+2) \quad y_{ob}(k+2) \quad \theta_{ob}(k+2)]_j^T, 1 \le j \le n \quad \text{(15-b)}$$

where the curvature for circular obstacle is described as $\theta_{ob}(k) \ne \theta_{ob}(k+1)$.

The incidence angle, β, of ultra-sonic sensor beam for obstacle is defined, and the state of the obstacle for s_j is only considered if the incidence angle is smaller than γ in order to reduce the uncertainty.

$$\beta = |\varphi_{1j} + \theta_R - \theta_{ob} - 180^o| < \gamma \quad (16)$$

The shape of the obstacle is estimated if the follow equation is satisfied in order to reduce the error, $e(k)$,

$$\min e(k) = \sum_{j=1}^{n} \left(\sqrt{(x'_{ob}(k)_j - \hat{x}_{ob}(k)_j)^2 + (y'_{ob}(k)_j - \hat{y}_{ob}(k)_j)^2} \right) \quad (17)$$

The inclination of the straight obstacle is represented as follows:

$$\theta_{ob} = \tan^{-1}\left(\frac{y_{ob}(k+1) - y_{ob}(k)}{x_{ob}(k+1) - x_{ob}(k)} \right). \quad (18)$$

The straight obstacle is represented as follows:

$$y = \tan\theta_{ob}(x - x_{ob}(k)) + y_{ob}(k) \quad (19)$$

The circular obstacle is represented using the following equations and the local map is obtained.

$$x_{ob}{}^2(k)_j + y_{ob}{}^2(k)_j + lx_{ob}(k)_j + my_{ob}(k)_j + n = 0 \quad \text{(20-a)}$$

$$x_{ob}{}^2(k+1)_j + y_{ob}{}^2(k+1)_j + lx_{ob}(k+1)_j + my_{ob}(k+1)_j + n = 0 \quad \text{(20-b)}$$

$$x_{ob}{}^2(k+2)_j + y_{ob}{}^2(k+2)_j + lx_{ob}(k+2)_j + my_{ob}(k+2)_j + n = 0 \quad \text{(20-c)}$$

The equation of the circular obstacle with the center position and radius is represented as follows:

$$(x - x_c)^2 + (y - y_c)^2 = R_c^2, \quad (21)$$

where (x_c, y_c) is the center of the obstacle and R_c is the radius of the obstacle.

2) Uncertainty modeling: The ultra-sonic sensor measure the distance data from the obstacle to robot. If the obstacles don't exist around the robot or sensing range, distance data between robot and obstacle is not obtained.

D. Principle of Wheel Encoder System

1) Basic localization model: In two dimensional *X-Y* Cartesian coordinates, the state of mobile robot in time k is represented as follows:

$$P(k) = [x(k) \quad y(k) \quad \theta(k)]^T, \quad (22)$$

where $x(k)$, $y(k)$ are position and $\theta(k)$ is orientation.

The velocity of robot is consist of linear velocity, v_1, and angular velocity, v_2.

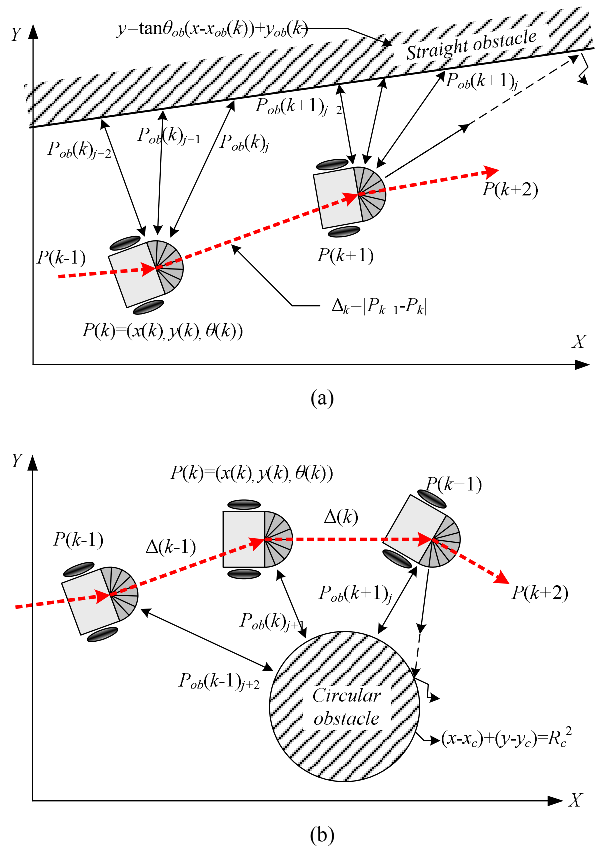

Fig. 4. Obstacle estimation model: (a) Straight obstacle ;(b) Circular obstacle.

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} (u_R + u_L)/2 \\ 2(u_R - u_L)/l \end{bmatrix} \quad (23)$$

where, u_R, u_L is angular velocity of right and left wheel, and l is the distance between two wheels. The state in time k+1 is defined as (3) using $P(k)$ for sampling period, T.

$$P(k+1) = \begin{bmatrix} x(k+1) \\ y(k+1) \\ \theta(k+1) \end{bmatrix} = \begin{bmatrix} x(k) \\ y(k) \\ \theta(k) \end{bmatrix} + T \begin{bmatrix} \dot{x}(k) \\ \dot{y}(k) \\ \dot{\theta}(k) \end{bmatrix} \quad (24)$$

where, $\begin{bmatrix} \dot{x}(k) \\ \dot{y}(k) \\ \dot{\theta}(k) \end{bmatrix} = \begin{bmatrix} \cos\theta(k) & 0 \\ \sin\theta(k) & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$

Wheel encoders read the velocity, u_R, u_L, of each wheel

2) Uncertainty modeling [20]: Measurement error and slippage during the movement may cause the position estimation uncertainty. The general state equations are described by current state, input, and error terms as follows:

$$\hat{P}(k+1) = f(P(k), u(k)) + \omega(k), \quad (25)$$

Where, $P(k)$ is current sate, $u(k)$ is observation value, $w(k)$ is noise affecting the state.

The estimated position of a mobile robot and covariance matrix equation are represented as follows:

$$\hat{P}(k+1) = f(\hat{P}(k), u(k))^T \tag{26}$$

$$\hat{P}(k+1) = A(k)P(k)A(k)^T + F(k)V(k)F(k)^T + W(k) \tag{27}$$

Where,

$$A(k) = \frac{\partial f}{\partial \hat{P}} = \begin{bmatrix} 1 & 0 & -T\dfrac{u_R(k)+u_L(k)}{2}\sin\hat{\theta}(k) \\ 0 & 1 & T\dfrac{u_R(k)+u_L(k)}{2}\cos\hat{\theta}(k) \\ 0 & 0 & 1 \end{bmatrix}$$

$$F(k) = \frac{\partial f}{\partial u} = T\begin{bmatrix} \frac{1}{2}\cos\hat{\theta}(k) & \frac{1}{2}\cos\hat{\theta}(k) \\ \frac{1}{2}\sin\hat{\theta}(k) & \frac{1}{2}\sin\hat{\theta}(k) \\ \frac{1}{l} & -\frac{1}{l} \end{bmatrix}$$

The zero-mean variance of the position estimation error is a critical factor for precise robot-position estimation. Using this covariance matrix, the position estimation uncertainty can be represented as a hyper-ellipsoid. That is, the uncertainty hyper-ellipsoid can be defined from the singular value decomposition (SVD) of the covariance matrix.

IV. Localization Algorithm

According to environmental case, useful data combination sets are selected. Because the previous algorithm used the combination of RFID and ultra-sonic sensor, it was not proper under open space. In this paper, if there are obstacles in space, RFID localization system and ultra-sonic sensors system are fused. On the contrast, if there are not obstacles in space, RFID localization system and wheel encoders are fused. We estimate the position of the mobile robot through the matching of the above data sets.

In case of fusion system with RFID localization system and wheel encoders, the uncertainty from accumulation error of wheel encoder system is reduced by absolute coordinate from RFID localization system

Using the position from RFID localization system, $\hat{P}_R(k)$, the position from ultra-sonic sensor, $\hat{P}_S(k)$, the position from wheel encoder $\hat{P}_E(k)$, the effective corresponding position value is obtained . The set, $v(k)$, consists of the difference between two values (of position) and the covariance matrix, $s(k)$, is represented as follows:

$$v(k) = \begin{cases} \hat{P}_R(k) - \hat{P}_S(k) & \text{if RFID and ultra-sonic} \\ \hat{P}_R(k) - \hat{P}_E(k) & \text{if RFID and wheel encoder} \end{cases} \tag{28}$$

$$S(k) = E[v(k)v^T(k)] \tag{29}$$

Processing for localization of the mobile robot is then repeated until the following condition is satisfied.

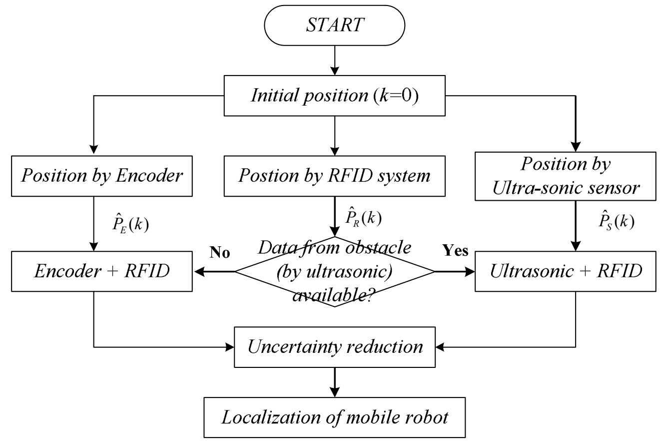

Fig. 5. Flow of the localization of the mobile robot from GPE and LEC.

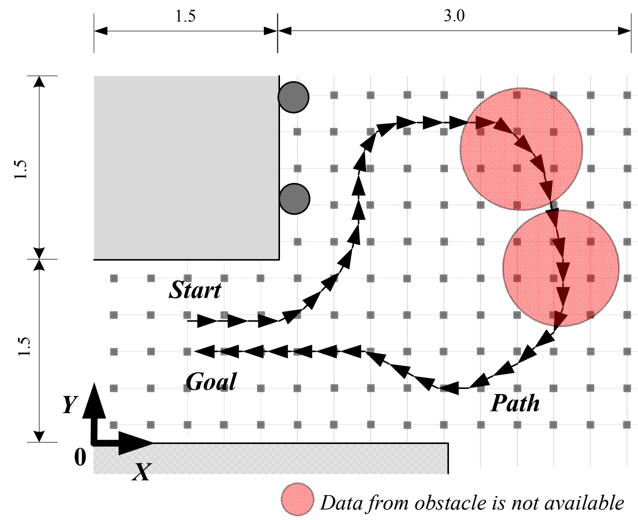

Fig. 6. The path of the mobile robot.

$$v(k)S^{-1}(k)v^T(k) < e^2 \tag{30}$$

This procedure is detailed in fig. 11.

V. Experiments

A. Environment for Experiments

For the localization of a mobile robot, it is assumed that the mobile robot moves along the designed path. *FiBot* is used for experiments, which is about 0.3 *m* × 0.5 *m* and car drive type. RFID reader's antenna is installed in bottom of the mobile robot and the nine ultra-sonic sensors are separately installed with 22.5 degree angle in front of the robot. And also, two wheel encoder which can measure 1024 pulses are installed. The RFID system, KISR300H, use the passive type and 13.56 *MHz* operating frequency and reader's antenna size is 0.15 *m* × 0.15 *m* and the tag made by epoxy is 0.03 *m* × 0.03 *m*. The module of ultra-sonic sensor is HRC01, measure the distance to 6 *m*.

TABLE I
COMPARISON OF AVERAGE ESTIMATION ERROR WITH EACH ALGORITHM

dis_{tag}	Algorithm	Average error
Red zone	Classic RFID localization system	6.19 *cm*
	RFID localization system + Ultrasonic	5.31 *cm*
	Proposed system with algorithm	2.13 *cm*
Total path	Classic RFID localization system	7.03 *cm*
	RFID localization system + Ultrasonic	3.57 *cm*
	Proposed system with algorithm	2.25 *cm*

B. Experiment and Result

To verify the proposed algorithm, the estimation error between real robot state and estimated robot state is measured. The initial position and goal position of the mobile robot were set as (0.75, 1, 0^o) and (0.75, 0.75, -90^o), respectively. Fig. 6 shows the path of the mobile robot. The object of the experiment is to show reduction of the estimation error by the proposed algorithm in this paper. The experiments results show that estimation error of robot position decreases when the proposed algorithm is applied as shown in table I.

VI. CONCLUSION

This paper addressed the effective localization scheme of the mobile robot using the RFID fusion localization system. This scheme overcomes the problem in previous RFID localization system. The uncertainty of localization is reduced. For localization, the position by RFID localization system, ultra-sonic sensor, and wheel encoder is used. This method to separate the situation according to obstacle is proposed for uncertainty reduction. Using matching algorithm of the data, the estimation error and uncertainty is reduced.

In the future, the localization of the mobile robot in outdoor environment and the localization for the dynamic environment will be considered.

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