Global Ultrasonic System for Autonomous Navigation of Indoor Mobile Robots

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Abstract: In this paper, we propose a global ultrasonic system for the self-localization and autonomous navigation of indoor mobile robots. The ultrasonic sensor is regarded as the most cost-effective ranging system among the possible alternatives, and it is widely used for general purpose, since it requires simple electronic drivers and has relatively high accuracy. The global ultrasonic system presented in this paper consists of four or more ultrasonic generators fixed at reference positions in the global coordinates of an indoor environment and two receivers mounted on the mobile robots. By using the RF (Radio Frequency) modules added to the ultrasonic sensors, the robot is able to control the ultrasonic generation and to obtain the critical distances from the reference positions, which are required in order to localize is position in the global coordinates. A kalman filter algorithm designed for the self-localization using the global ultrasonic system and the experimental results of the autonomous navigation are presented in this paper.

Keywords: global ultrasonic system, autonomous navigation, radio frequency module, extended kalman filter

1. INTRODUCTION

Paradigm of the robotics research is changing from the conventional repetitious and stand-alone type industrial robot to the human-friendly, intelligent robot e.g., a home service robot sharing the same environment with human in recent years. Together with the networking capability and the recognition using the artificial intelligence, the mobility is a main feature of the home service robot. The mobility implies the expansion of the work space of a robot. For autonomous navigation in the work space, a mobile robot should have the self-localization function to figure out where it is and the motion control to determine what direction it moves toward[1].

There are two sorts of sensors for the autonomous navigation in general; the internal sensors to control the angular velocity of wheels in the actuator level and the external sensors to localize the position of robot in work space. Since the trajectory error of the dead-reckoning navigation relying only on the internal sensors grows with time and distance, the external sensors such as the camera vision, laser sensor, or the ultrasonic sensor are necessary for the autonomous navigation to localize the current position and compensate the error.

The self-localization schemes using the external sensors can be divided into two groups again; the local scheme and the global scheme. (1) In the local scheme, a mobile robot makes the local object map using the distance data from the external sensors and matches the local map with the global map given in advance. (2) On the other hand in the global scheme, the mobile robot computes its position directly in the global coordinates directly using the distances from some reference positions.

The first scheme has some advantages that the collision-avoidance motion and the map-reconstruction for the changed environment are possible by using the distance sensors equipped on the robot as well as the self-localization. However, it requires the massive computations in the local map-making and the matching with the global map database instead. In the extreme case, the robot should stop moving momentarily to get the environmental information[2][3]. On the contrary in the second scheme, the local map-making and the matching processes are avoidable, so that the self-localization is computationally efficient and fast. The global localization scheme is exemplified by the well-known satellite GPS in which the localization is based on the triangulation using the distances between the GPS receiver on a mobile object and three or more signal transmitters i.e., satellites in the earth coordinates. Although the GPS gains increasing attentions in recent years, the GPS is still expensive to get enough positioning accuracy. Moreover, it is difficult to use the GPS in the indoor application as like the home service robot.

The global ultrasonic system in [4] has the GPS like structure for the self-localization of an indoor mobile robot. The ultrasonic sensor is regarded as the most cost-effective ranging system among the other alternatives and widely used for the general purposes since it requires a simple electronic drivers and has relatively high accuracy[8]. The global ultrasonic system consists of some ultrasonic generators fixed at the reference positions in the global coordinates and two receivers on the mobile robot. By controlling the ultrasonic generation through RF(Radio Frequency) modules added to the ultrasonic sensors, the robot is able to get the distances between the reference positions, so that to localize its position in the global coordinates.

Navigation algorithm of the autonomous mobile robot can divide into global path planning and local path planning. Global path planning is the method that is given information about surrounding environment to autonomous mobile robot previously and then makes a shortest way to the goal posture. However, this algorithm needs to exact information about surrounding environment and in the case of given wrong information or occurring changes of surrounding environment, it has a demerit which is difficult to navigate to the goal posture safely. Local path planning is the method that, under the condition which is no information about surrounding environment, navigates to the goal posture safely with only information which gets from the sensor. And under the real environment, an environment change such as the movement of the people or object can possibly occur even if autonomous mobile robot has whole information about surrounding environment. Therefore, local path planning is the necessary function which is considered to making an autonomous mobile robot with high autonomy and intelligence

In this paper, it is aimed to propose a new kalman filter algorithm for the self-localization under the global ultrasonic system and to verify the performance of the autonomous navigation based on the self-localization by experiments.

2. THE GLOBAL ULTRASONIC SYSTEM

In this section, the overall structure of the global ultrasonic system in [4] is summarized for the completeness of this paper. As depicted in Fig. 1, the ultrasonic generators are fixed at a priori known positions, $T_i=\left[x_i,\ y_i, z_i\right]$, $i=1,....,4$ in the work space, e.g., each corner of ceiling. Using the ultrasonic sensors at $\mathbf{P}_f$ and $\mathbf{P}_r$, a mobile robot receives the ultrasonic signal and computes the distances by counting the TOF(Time Of Flight) of the signal. It is conveniently assumed in Fig. 1 that the number of the ultrasonic generators are four, which can be increased as needed in consideration of the work space size and the environmental objects. In order to avoid the cross-talk between the ultrasonic signals and to synchronize the ultrasonic receivers with the generators, the RF transmitter, $\mathbf{TX}$ and the RF receiver modules, $\mathbf{RX}_1\sim\mathbf{RX}_4$ are added to the corresponding ultrasonic sensors respectively. By using the RF channel, the mobile robot calls in sequence to activate one of the ultrasonic generators for each time slot. Assuming that the delivery time for the RF calling signal is ignorable, the ultrasonic signal generation occurs simultaneously with the RF calling signal transmission and it is possible to synchronize the ultrasonic generators and the receivers. In Fig. 1, $h_{f,1}\sim h_{f,4}$ denote the distance between $\mathbf{T}_1\sim\mathbf{T}_4$ and $\mathbf{P}_f$ .The distances, $h_{r,1}\sim h_{r,4}$ between $\mathbf{T}_1\sim\mathbf{T}_4$ and P_r are omitted for brevity. The positions of the ultrasonic receivers on the robot, $\mathbf{P}_f=\left[x_f,\ y_f,\ z_f\right]^t$ and $\mathbf{P}_r=\left[x_r,\ y_r,\ z_r\right]^t$ with respect to the center position of the mobile robot, $\mathbf{P}=\left[x,\ y,\ z\right]^t$ can be described as follows:

$$\mathbf{P}_f=\begin{bmatrix} x+l\cos\theta \\ y+l\sin\theta \\ z_c \end{bmatrix}, \qquad \mathbf{P}_r=\begin{bmatrix} x-l\cos\theta \\ y-l\sin\theta \\ z_c \end{bmatrix} \tag{1}$$

where l represents the distance between the center position of the mobile robot and the ultrasonic receiver and θ denotes the heading angle of the mobile robot. It is assumed that the moving surface is flat, so that the Z component of the position vectors is constant as z_c in Eq.(1).

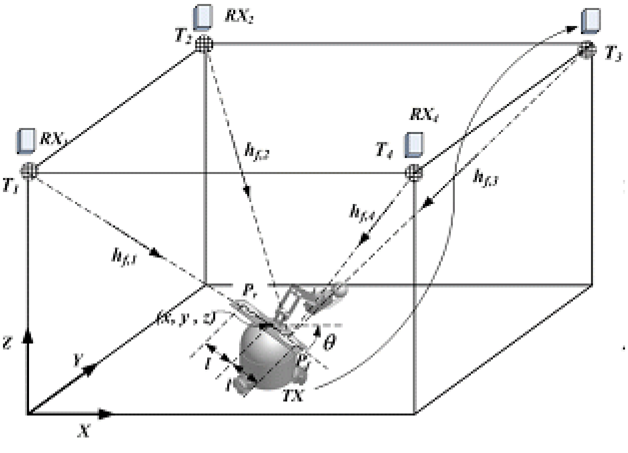


Fig. 1. The global ultrasonic system

3. THE EXTENDED KALMAN FILTER FOR THE SELF-LOCALIZATION AND THE AUTONOMOUS NAVIGATION ALGORITHM

The position vector in $x-y$ plane, $\mathbf{r}=\left[x,\ y\right]^t$ of a mobile robot having the omnidirectional wheels, together with the heading angle, θ follows the state Eq.(2) in discrete-time domain[9]:

$$\begin{bmatrix} x(k+1) \\ y(k+1) \\ \theta(k+1) \end{bmatrix} = \begin{bmatrix} x(k)+T(-\frac{1}{3}r\omega_{1,k}-\frac{1}{3}r\omega_{2,k}-\frac{2}{3}r\omega_{3,k}) \\ y(k)+T(-\frac{1}{\sqrt{3}}r\omega_{1,k}-\frac{1}{\sqrt{3}}r\omega_{2,k}) \\ \theta(k)+T(\frac{1}{3b}(r\omega_{1,k}+r\omega_{2,k}+r\omega_{3,k})) \end{bmatrix} \tag{2}$$

where the subscript k is the time index, T denotes the sampling interval, r is radius of the wheels, b is distance between wheel and c.g.(center of gravity), ω_i is the angular velocity of the wheel. In the sequel, the position vector and the heading angle are augmented into $\mathbf{p}=[x,\ y,\ \theta]^t$, which is referred as the robot posture. The bold and the normal symbols represent the vector and the scalar variables respectively.

As a consequence of Eq.(2), the state equation for the ultrasonic receivers on the robot can be described as follows:

$$\mathbf{r}_{f,k+1}=\mathbf{f}(\mathbf{r}_{f,k},\ \mathbf{u}_k,\ \mathbf{q}_k)$$

$$=\begin{bmatrix} x_{f,k}+T(-\frac{1}{3}r\omega_{1,k}-\frac{1}{3}r\omega_{2,k}-\frac{2}{3}r\omega_{3,k}) \\ -l\left[1-\cos\left(T\left\{\frac{1}{3b}(r\omega_{1,k}+r\omega_{2,k}+r\omega_{3,k})\right\}\right)\right]+q_{1,k} \\ y_{f,k}+T(-\frac{1}{\sqrt{3}}r\omega_{1,k}-\frac{1}{\sqrt{3}}r\omega_{2,k}) \\ -l\sin\left(T\left\{\frac{1}{3b}(r\omega_{1,k}+r\omega_{2,k}+r\omega_{3,k})\right\}\right)+q_{2,k} \end{bmatrix} \tag{3-1}$$

$$\mathbf{r}_{r,k+1}=\mathbf{f}(\mathbf{r}_{r,k},\ \mathbf{u}_k,\ \mathbf{q}_k)$$

$$=\begin{bmatrix} x_{r,k}+T(-\frac{1}{3}r\omega_{1,k}-\frac{1}{3}r\omega_{2,k}-\frac{2}{3}r\omega_{3,k}) \\ +l\left[1-\cos\left(T\left\{\frac{1}{3b}(r\omega_{1,k}+r\omega_{2,k}+r\omega_{3,k})\right\}\right)\right]+q_{1,k} \\ y_{r,k}+T(-\frac{1}{\sqrt{3}}r\omega_{1,k}-\frac{1}{\sqrt{3}}r\omega_{2,k}) \\ +l\sin\left(T\left\{\frac{1}{3b}(r\omega_{1,k}+r\omega_{2,k}+r\omega_{3,k})\right\}\right)+q_{2,k} \end{bmatrix} \tag{3-2}$$

Where $\mathbf{r}_f=[x_f,\ y_f]^t$ and $\mathbf{r}_r=[x_r,\ y_r]^t$ represent the positions of the front and the rear ultrasonic receivers respectively and $\mathbf{q}_k=[q_{1,k},\ q_{2,k}]^t$ is the gaussian random noise with zero mean and $\mathbf{Q}$ variance.

The measurement equation at the ultrasonic receivers can be modeled as follows:

$$z_{f,k}=h_{f,i}(\mathbf{r}_{f,k},\ v_k)$$

$$=\sqrt{\left(x_{f,k}-x_i\right)^2+\left(y_{f,k}-y_i\right)^2+\left(z_c-z_i\right)^2}+v_k \tag{4-1}$$

$$z_{r,k}=h_{r,i}(\mathbf{r}_{r,k},\ v_k)$$

$$=\sqrt{\left(x_{r,k}-x_i\right)^2+\left(y_{r,k}-y_i\right)^2+\left(z_c-z_i\right)^2}+v_k \tag{4-2}$$

Where the measurement noise, v_k is assumed to be gaussian with zero mean and G variance, and the subscript, i denotes one of the ultrasonic generators at $\mathbf{T}_1 \sim \mathbf{T}_4$ called by the mobile robot at time k.

With the state Eq.(3) and the measurement Eq. (4-1), the following set of equations are the EKF estimation for the front ultrasonic receiver position:

$$\bar{\mathbf{r}}_{f,k+1} = f_f(\hat{\mathbf{r}}_{f,k}, \mathbf{u}_k, \mathbf{0})$$

$$\bar{\mathbf{V}}_{f,k+1} = \mathbf{A}_{f,k}\mathbf{V}_{f,k}\mathbf{A}^t_{f,k} + \mathbf{Q} \tag{5}$$

$$\mathbf{K}_{f,k} = \bar{\mathbf{V}}_{f,k}\mathbf{H}^t_{f,k}(\mathbf{H}_{f,k}\bar{\mathbf{V}}_{f,k}\mathbf{H}^t_{f,k} + G)^{-1}$$

$$\mathbf{V}_{f,k} = (\mathbf{I} - \mathbf{K}_{f,k}\mathbf{H}_{f,k})\bar{\mathbf{V}}_{f,k}$$

$$\hat{\mathbf{r}}_{f,k} = \bar{\mathbf{r}}_{f,k} + \mathbf{K}_{f,k}(z_{f,k} - h_f(\bar{\mathbf{r}}_{f,k}, \mathbf{0})) \tag{6}$$

where $\mathbf{K}_{f,k}$ is the kalman filter gain, $\bar{\mathbf{r}}_{f,k}$ and $\hat{\mathbf{r}}_{f,k}$ imply a priori and a posteriori estimations for $\hat{\mathbf{r}}_{f,k}$ respectively and $\bar{\mathbf{V}}_{f,k}$ and $\mathbf{V}_{f,k}$ represent a priori and a posteriori error covariance matrices as defined in Eq.(7).

$$\bar{\mathbf{V}}_{f,k} = \mathbf{E}[(\mathbf{r}_{f,k} - \bar{\mathbf{r}}_{f,k})(\mathbf{r}_{f,k} - \bar{\mathbf{r}}_{f,k})^t]$$

$$\mathbf{V}_{f,k} = \mathbf{E}[(\mathbf{r}_{f,k} - \hat{\mathbf{r}}_{f,k})(\mathbf{r}_{f,k} - \hat{\mathbf{r}}_{f,k})^t] \tag{7}$$

where $\mathbf{E}(\cdot)$ denote the expectation of the corresponding random variables. The jacobian matrices, $\mathbf{A}_{f,k}$ and $\mathbf{H}_{f,k}$ in (6) are given as follows:

$$\mathbf{A}_{f,k} = \frac{\partial \mathbf{f}_f}{\partial \mathbf{r}_f}(\hat{\mathbf{r}}_{f,k}, \mathbf{u}_k, \mathbf{0})$$

$$= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{8}$$

$$\mathbf{H}_{f,k} = \frac{\partial h_{f,i}}{\partial \mathbf{r}_f}(\hat{\mathbf{r}}_{f,k}, \mathbf{0})$$

$$= \begin{bmatrix} \dfrac{x_{f,k} - x_i}{D_{f,i}} & \dfrac{y_{f,k} - y_i}{D_{f,i}} \end{bmatrix} \tag{9}$$

where $D_{f,i}$ mean the followings:

$$D_{f,i} = \sqrt{\left(x_{f,k} - x_i\right)^2 + \left(y_{f,k} - y_i\right)^2 + \left(z_c - z_i\right)^2} \tag{10}$$

The EKF estimation, $\hat{\mathbf{r}}_{r,k}$ for the rear ultrasonic receiver position is similar and omitted here for brevity.

From $\hat{\mathbf{r}}_{f,k}$ and $\hat{\mathbf{r}}_{r,k}$, posture estimation for the mobile robot can be described as follows:

$$\hat{x}_k = \frac{\hat{x}_{f,k} + \hat{x}_{r,k}}{2}$$

$$\hat{y}_k = \frac{\hat{y}_{f,k} + \hat{y}_{r,k}}{2} \tag{11}$$

$$\hat{\theta} = \tan^{-1}\frac{\hat{y}_{f,k} - \hat{y}_{r,k}}{\hat{x}_{f,k} - \hat{x}_{r,k}}$$

Assuming that the estimation error covariances for the front and the rear ultrasonic receivers are same, the error covariances of the posture estimation shown in Fig. 2 are given in (12).

$$\mathbf{V}_k = \mathbf{E}[(\mathbf{r}_k - \hat{\mathbf{r}}_k)(\mathbf{r}_k - \hat{\mathbf{r}}_k)^t]$$

$$= \mathbf{V}_{f,k} \ (= \mathbf{V}_{r,k})$$

$$\mathbf{V}_{\theta,k} = E[(\theta - \hat{\theta}_k)^2] \tag{12}$$

$$\approx \tan^{-1}\frac{\mathbf{V}_{f,k}}{l}$$

Eq. (12) implies that the estimation for the heading angle becomes more accurate according to the distance between the two ultrasonic receivers.

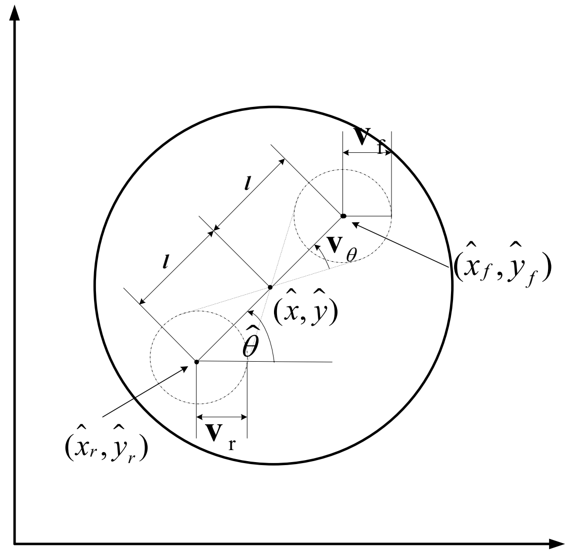


Fig. 2. Error covariances of the posture estimation

If the working-space extend, we have to increase the number of ultrasonic sensor for making whole space to active space with ultrasonic sensor which has a limited range. At this moment, to active all ultrasonic sensors are not only that consume an excessive sampling time but also that needed number of available data are decreased too. Therefore mobile robot calculates a distance of each ultrasonic sensor then increase available data by activating only module in the range to measure and can make a convergence speed of posture data fast by extended Kalman filter. Fig. 4 shows us to active only ultrasonic module in the range to measure with mobile robot as its center.

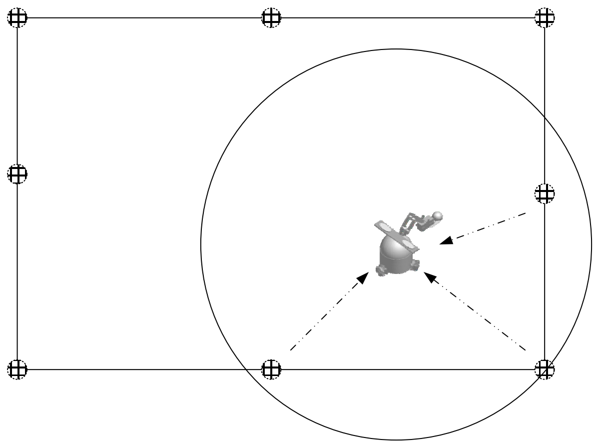


Fig. 3. Selective activation

4. EXPERIMENTS AND DISCUSSION

In order to verify the autonomous navigation under the global ultrasonic system, a simple experimental set up is established as in Fig. 4 which has 2,600 mm and 5,200 mm in width and length and 5,400 mm in height.

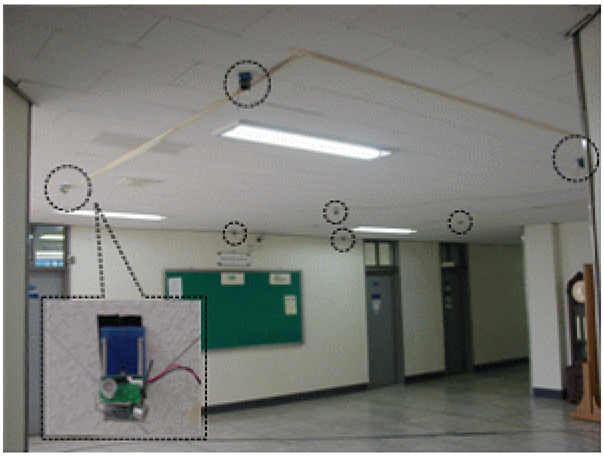
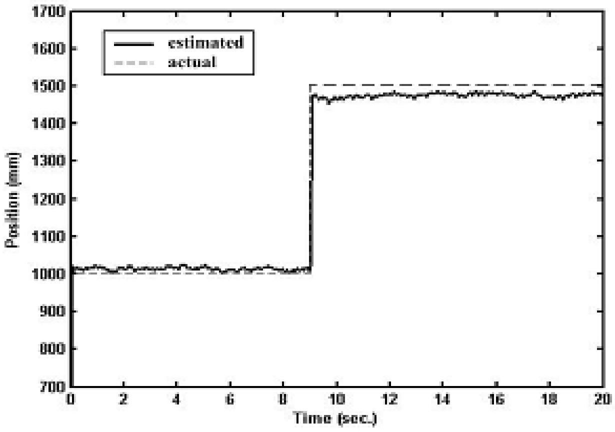


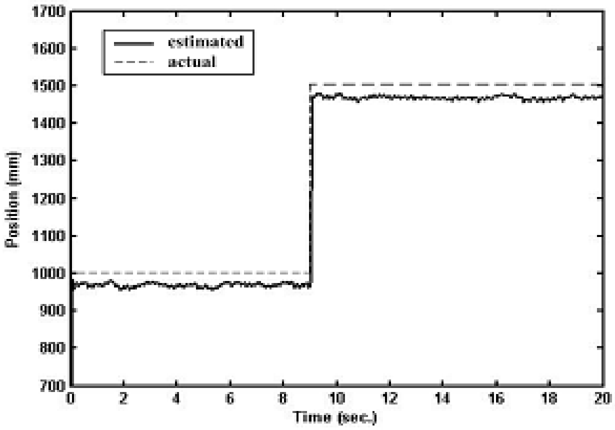
Fig. 4. Experimental setup

The mobile robot that used in the experiment made with 3 omni-directional wheel which arranged each 120 degrees for maximum utilization of assigned working space. It has more difficulties than mobile robot which has two wheels in solving the robot's kinematics, but has an advantage about space utilization. We use dc-motors with encoder for each wheel, and AVR as a client controller to move it wanted-speed. We also use a DSP board as a host controller to detect the position by measure the TOF(time of flight) and control the position of the mobile robot. The ultrasonic generators with the RF receiver modules shown in Fig. 4 are fixed near the nine corners of ceiling. We use a SRF04 ultra-sonic module as an ultra sonic generator, combine it with the TX, RX module to use a micro-processor PIC16F873. SRF04 ultra sonic sensor has a 40kHz operation frequency and 5m maximum detection distance.

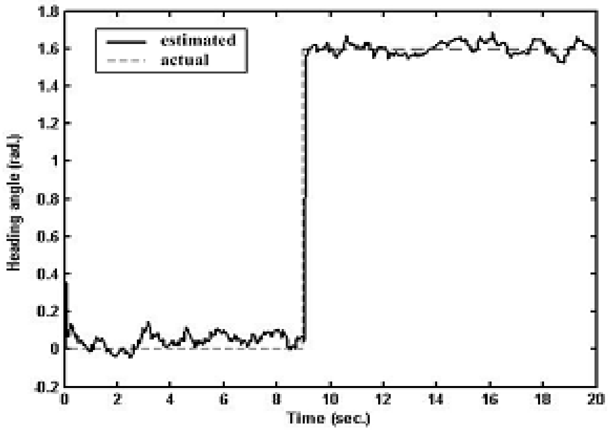
At first, the experiment to verify the self-localization is carried out and the results are presented in Fig. 5. The robot is moved manually from the initial posture, $(x, y, \theta)=(1000, 1000, 0)$ to $(1500, 1500, \frac{\pi}{2})$ at 45 sec. The initial value of the posture estimation are set arbitrary as $(500,500,0)$. The distance and the heading angle are described in mm and rad respectively. As shown in the figure, the position errors in x and y axes are within 30 mm in the steady-state. Since the distance between the center position of the robot and the ultrasonic receiver is designed as $l = 133\,mm$, the estimation error of the heading angle becomes $tan^{-1}\frac{30}{133} \approx 0.221$ as in Fig. 5 (c).



(a) Position estimation in x axis



(b) Position estimation in y axis



(c) Estimation in heading angle

Fig. 5. The self-localization of mobile robot

The state noise, $\mathbf{Q}$ and the measurement noise, G in the EKF estimation imply the measure of the relative confidence. In case of $\|\mathbf{Q}\| > G$ for example, the measurement data given in (4-1) and (4-2) from the external sensors are more credible than the state value from the motion equations, (3-1) and (3-2). In this experiment, the variances of the state noise and the measurement noise are set as $G = 1.80$ and $\mathbf{Q} = [100.0, 100.0]'$ intentionally to give the more confidence to the measurements in the global ultrasonic system.

The autonomous navigation under the global ultrasonic system is compared to the dead-reckoning navigation on the straight line connecting the initial posture, $(500, 500, 0)$ and the goal posture, $(3500, 2500, \frac{\pi}{2})$ in the work space. The following Fig. 6 shows the results of the dead-reckoning navigation without the global ultrasonic system, in which the mobile robot cannot reach to the goal posture due to the uncertainties in the state equation.

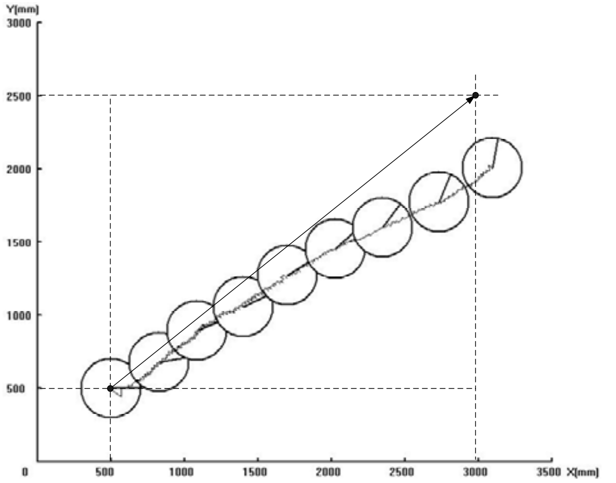


Fig. 6. Navigation without global ultrasonic system

Extend Kalman Filter algorithm is follow the exact current position by measuring a signal which came from ultrasonic generator, but some ultrasonic receiver modules detect only a part of ultrasonic signal cause the ultrasonic maximum range problem. In the case of occurring these kind of problems, convergence of the position value is delayed. Cause of it, we can not find the exact position of mobile robot or error range is increase. The convergence of many positions is delayed, because of the all of the ultrasonic generator does not exist under the detection range. For solving this kind of problems, we use a selective activation method that is only receive a signal from ultrasonic generator which can be detected by the mobile robot.

The ultrasonic sensor(SRF04) which used this experiment has a beam width of $\pm30^\circ$ from the center, and depends on the angles, it has distance range of 5m ~ 3.5m. Therefore, we measure an angle between mobile robot and ultrasonic sensor, and if there is an ultrasonic generator which is out of range, we don't active it. And mobile robot doesn't receive a signal from non-active ultrasonic generator, so the convergence speed is more faster.

The results of the autonomous navigation based on the self-localization with selective activation of the global ultrasonic system are presented in Fig. 7 for the same initial and the goal posture.

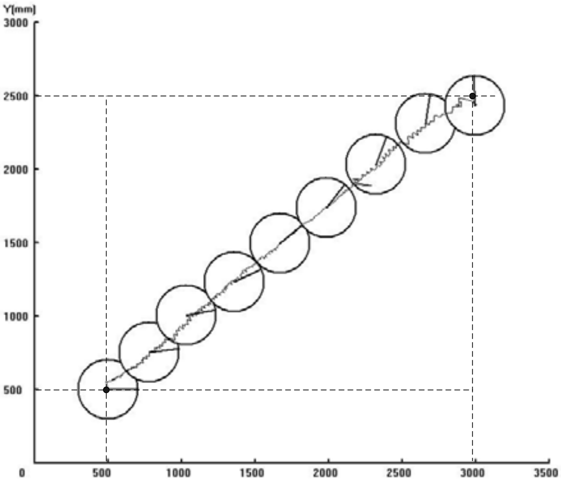


Fig. 7. Navigation with global ultrasonic system

As shown in the figure, the mobile robot reaches to the goal posture within the error of 50mm under the same situation like experiment of Fig. 6. Also during the driving from initial to goal posture, there is no heading angle error. As a result of this experiment, we can recognize that not only that convergence speed is getting increase cause of we only receive the efficient data by using a selective activation method but also that change ratio of data is regular.

5. CONCLUSIONS

In this paper, it is presented a new EKF algorithm for the self-localization using the global ultrasonic system and the successful autonomous navigation based on the self-localization. The global ultrasonic system consists of some ultrasonic generators fixed at known positions in the work space, two receivers on the mobile robot, and RF modules added on the ultrasonic transducers. By controlling the ultrasonic signal generation through the RF channel, the robot can synchronize and measure the distance between the ultrasonic generators and the receivers, thereby estimate its own position and heading angle. It is shown through experiment that the estimation errors are within $30mm$ in position and less than $0.22rad$ in heading angle, and the autonomous navigation using the global ultrasonic system is superior to the dead-reckoning navigation. Since the estimation error of the heading angle is dependant on the distance between two ultrasonic receivers on the robot, it is possible to get more accurate heading angle estimation by setting the distance.

It is assumed in this paper the ideal environment without any objects in the work space. The environmental objects may cause the shading region, where the ultrasonic signals can not reach. It is possible to overcome the problems in the obstacle environments by increasing the number of ultrasonic generators in the work space as needed which is under study.

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