Development of an Accurate Low-cost Ultrasonic Localization System for Autonomous Mobile Robots in Indoor Environments

Yong-hwi KIM, Ui-kyu SONG, Byung-kook KIM
(*Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon* 305-701, *Korea*)

Abstract – An accurate low-cost ultrasonic localization system is developed for automated mobile robots in indoor environments, which is essential for automatic navigation of mobile robots with various tasks. Although ultrasonic sensors are more cost-effective than other sensors such as Laser Range Finder (LRF) and vision, but they are inaccurate and directionally ambiguous. First, the matched filter is used to measure the distance accurately. For resolving the computational complexity of the matched filter, a new matched filter algorithm with simple computation is proposed. Then, an ultrasonic localization system is proposed which consists of three ultrasonic receivers and two or more transmitters for improving position and orientation accuracy was developed. Finally, an extended Kalman filter is designed to estimate both the static and dynamic positions and orientations. Various simulations and experimental results show that the proposed system is effective.

Key words – *localization*; *ultrasonic sensor*; *matched filter*; *extended Kalman filter*

Manuscript Number: 1674-8042(2010)01-0065-06

dio: 10.3969/j.issn.1674-8042.2010.01.15

1 Introduction

Nowadays, researches on an automated mobile robot have become one of the important issues for improvement of human welfare and quality of life. The automated robot performs various tasks according to the user's instruction, which essentially includes navigation. Hence the localization capability of the robot is essential for independent navigation of the automated mobile robot in indoor environments.

The dead-reckoning method has been extensively utilized to calculate the current location of the automated mobile robot, but suffers from the accumulation errors caused by wheel slippage, or by mechanical tolerances and surface roughness. Hence, the robot may fail to keep track of its true location over long traveling distances[1]. External sensors are necessary for estimating the locations and orientations of the mobile robots.

Laser Range Finders (LRF) are widely used and have shown many successful results in indoor localization and Simultaneous Localization and Mapping (SLAM)[2], due to high accuracy. However LRF is very high-cost, and hence not cost effective.

Ultrasonic sensors have been widely applied to the development of cost-efficient sensing systems for localization with a beacon positioning system. An ultrasonic sensing system is composed of a transmitter and a receiver. The ultrasonic transmitter generates high frequency sound waves and the ultrasonic receiver evaluates the received ultrasonic signals. The receiver measures the time interval between sending and receiving the signals to determine the distance. An ultrasonic transmitter becomes a beacon with a known position, and several ultrasonic receivers can be placed on top of a mobile robot. Several transmitters are placed on the ceiling. The robot selects a transmitter for generating signal, and then calculates the time interval between the transmitter and the receiver, and then converts into distance data between the transmitter and the receiver. From the distances, the robot can calculate to position and orientation by itself. Cricket[3] system developed by MIT is a representative ultrasonic beacon positioning system. Nevertheless, despite various researches about an ultrasonic beacon positioning system, such localization system is still inaccurate.

In this paper, an ultrasonic localization system is developed, which is low-cost, easy to implement, and reliable to obtain accurate position and orientation information of the mobile robot. The system is composed of a set of transmitting beacons with known positions in the global coordinates. The mobile robot uses the estimated distance data from the several receiving beacons on top of the mobile robot. For determining its position and orientation with the beacons, there are different approaches such as using distance and angle, using signal signature, and visibility.

In practice, ultrasonic signals are received with noise, and hence the robot cannot figured out the accurate distance. Most of the ultrasonic systems use threshold for

* **Received**: 2010-02-05
Project supported: This research was supported by the MKE(The Ministry of Knowledge Economy, Korea), the ITRC (Information Technology Research Center) support program (IITA-2009-(C1090-0902-0007))
Corresponding author: Yong-hwi KIM(yhkim@rtcl.kaist.ac.kr)

the receiver to recognize the ultrasonic signals. Unfortunately, if the small threshold value is taken, to calculate the distance, it is affected by the noise sensitively, and so, the matched filter[4] is widely applied to high accurate ultrasonic distance system by reducing noise effects. In view of performance, however, the matched filter takes long computing time for convolution computation. To resolve the problem, a new matched filter computation algorithm is proposed to reduce time consumption. Besides, accuracy is also affected by the number of the receivers. Especially, for estimating position and orientation of a robot, the robot needs at least two receivers. If the robot has only a receiver, it can know the initial position, but cannot know the initial orientation. An ultrasonic localization system using three ultrasonic receivers is proposed to improve position and orientation error. Finally, the Extended Kalman Filter (EKF)[5-6] schemes are applied. The EKF has been widely applied to sensor fusion algorithms for nonlinear robot position estimation problems. If the EKF is applied to localization algorithm, the position and orientation error variation, which occurs due to noise variations in static and dynamic environments, is reduced.

2 Ultrasonic localization system

Recently, Lin[7] suggests a localization system where two transmitters are fixed as references and three receivers are on the mobile robot. This approach can determine uniquely the position of the robot in a 3-D environment. However, it can obtain an unreliable result of the position estimation for a certain orientation of the robot because of the poor numeric conditions[8]. Also it cannot be adopted to solve the robot's position when the robot observes the information from more than two transmitters. Therefore, a new localization system using three ultrasonic receivers with least square method is proposed.

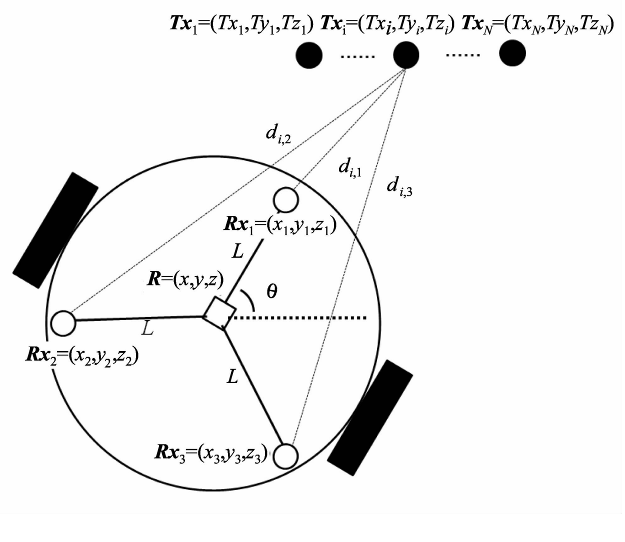

Fig. 1 Ultrasonic localization system

The ultrasonic localization system is described, as shown in Fig. 1. The N ultrasonic transmitters are placed on the ceiling at the known fixed points $\boldsymbol{TX}_1 \sim \boldsymbol{TX}_N$. The three ultrasonic receivers are placed on the robot. Each receiver is placed at the vertex of a regular triangle, and the center point of the triangle is located at the center point of the robot. Let a position of the robot be $\boldsymbol{R} = (x, y, z)$, and orientation of the robot be θ. In this system, $\boldsymbol{R}$ and θ can be figured out by using the distance data between transmitters and receivers(Assume $z = 0$).

To obtain the distance data between the ultrasonic transmitter and receiver, the robot selects and sends a RF message to one of the transmitter. After then, the transmitter sends an ultrasonic signal and a RF message to the robot. Receivers on the robot calculate the time interval between RF sending time and ultrasonic receiving time by using the matched filter. The time intervals are converted into distances, and then the position and orientation are found out. Furthermore, for reducing the error of the position of the moving robot, the EKF is applied by using dead reckoning data and velocity data of the motors.

2.1 Matched filter

Ultrasonic-based distance sensors measure the time-of-flight (TOF) of the ultrasonic signal between the signal source and the receiver. The received signal $m(t)$ is defined as

$$m(t) = as(t - t_d) + n(t), \tag{1}$$

where $s(t)$ is the transmitted signal from the transmitter, a is the amplitude attenuation of the transmitted signal, t_d is the time delay, and $n(t)$ is the noise signal. The distance d between the transmitter and the receiver is given by

$$d = ct_d, \tag{2}$$

where c is the speed of the ultrasonic sound in the air.

The threshold detection method is usually used to measure the time delay, which identifies the echo starting time. However, noise and shape distortions make it hard to detect the precise point. Also, the threshold detection method has worse performance as the distance to be detected becomes longer.

Hence the matched filter is used to measure the time difference. The matched filter is useful for maximizing the Signal to Noise Ratio (SNR) in the presence of additional noise. The SNR will have its maximum value at the signal arrival time.

The matched filter output is a convolution result between the transmitted signal and received signal, as shown in Eq. (3).

$$y(jT) = \sum_{k=0}^{\infty} s(kT)m((k-j)T), \tag{3}$$

where T is the sampling time. In fact, the transmitted signal is a pre-sampled signal which has no delay. This pre-sampled signal is used as a reference signal for every convolution operation.

The matched filter gives a considerably precise time delay even if the level of noise is high. However, the computational cost is too high to be implemented in an embedded board.

In order to reduce the computational cost, a matched filter with reduced calculation proposed in Ref. [11] is firstly used. If the envelope of the transmitted signal may be approximated by static signals within a period of the signal, the transmitted signal $s(t)$ can be expressed as

$$s(t) = e_i \sin(\omega t),$$
$$ip \leqslant t < (i+1)p, i = 0,1,\cdots,k,\cdots,L-1, \quad (4)$$

where ω is the angular velocity, e_i is the envelope of the transmitted signal, p is the period of the signal, and the meaningful period of the transmitted signal is limited by L , the number of pulses for ultrasonic transmission.

The received signal $m(t)$ with noise $n(t)$ is described as

$$m(t) = g_i \sin(\omega(t - t_d)) + n(t),$$
$$ip \leqslant t < (i+1)p, i = 0,1,\cdots,k,\cdots,M-1, \quad (5)$$

where g_i is the envelope of the received signal and M is the period for the maximum distance.

If the time delay t_d is divided by the period of the signal, t_d can be expressed with the integer quotient n and the fractional part φ , as shown in Eq. (6)

$$t_d = np + \varphi. \quad (6)$$

Certainly, φ is a real number less than p , and the phase delay is obtained by the multiplication of ω and φ . C_i and S_i for each i -th period of the received signal is defined as

$$C_i = \frac{1}{p}\int_{ip}^{(i+1)p} m(t)\sin(\omega t)\mathrm{d}t,$$
$$S_i = \frac{1}{p}\int_{ip}^{(i+1)p} m(t)\cos(\omega t)\mathrm{d}t. \quad (7)$$

Since the frequency of the noise $n(t)$ is not related to ω , Eq. (7) is simplified by substituting Eq. (5), as in

$$C_i = \frac{g_i}{p}\int_{ip}^{(i+1)p} \sin(\omega(t - ip - \varphi)) \cdot \sin(\omega t)\mathrm{d}t = \frac{g_i}{2}\cos(\omega\varphi),$$
$$S_i = \frac{g_i}{p}\int_{ip}^{(i+1)p} \sin(\omega(t - ip - \varphi))\cos(\omega t)\mathrm{d}t = \frac{g_i}{2}\sin(\omega\varphi). \quad (8)$$

Hence the envelope g_i and the phase delay $\omega\varphi_i$ for each period are given by

$$g_i = \sqrt{C_i^2 + S_i^2}, \quad (9)$$
$$\omega\varphi_i = a\tan2(S_i, C_i). \quad (10)$$

If the sampling period is chosen to be a constant multiple of the period of the ultrasonic signal (i.e. $p = NT$, N is an integer), C_i and S_i can be expressed in the discrete-time domain as

$$C_i = \frac{T}{p}\sum_{j=0}^{N-1} m(iN + j)T)\sin(j\omega T),$$
$$S_i = \frac{T}{p}\sum_{j=0}^{N-1} m(iN + j)T)\cos(j\omega T). \quad (11)$$

Especially, if the sampling period is four times the period of the ultrasonic signal (i.e. $N = 4$), Eq. (11) is further simplified as

$$C_i = \frac{1}{4}[m((4i+1)T) - m((4i+3)T)],$$
$$S_i = \frac{1}{4}[m((4i)T) - m((4i+2)T)]. \quad (12)$$

Considering the phase delay obtained in Eq. (10), the envelope of the received signal can be revised, as in

$$h_i = g_i \times (1 - \varphi_i/p) + g_{i+1} \times \varphi_i/p, \quad (13)$$

Thus, the result of the matcied filter with reduced calculation is

$$y(j) = \sum_{k=0}^{M-k-j} e_k h_{k+j}. \quad (14)$$

This matched filter reduces! the computational cost by $1/N^2$ with respect to the conventional matched filter given in Eq. (3), which becomes a strong aspect in embedded implementation.

To get the quotient n in Eq. (6), find the maximum value of $y(jT)$ as

$$n = \arg\max_j y(j). \quad (15)$$

Besides, in order to reduce the computational cost, a threshold is set to the received signal so that the convolution operation should be applied only to the meaningful range in which the ultrasonic signal is presented. The received signal are sampled for 30 ms, which covers 10 m in range. Since the ultrasonic signal takes about 1 ms, the computational cost can be reduced by 2/30.

2.2 Ultrasonic localization system with three receivers

For estimating the robot's position and orientation, the robot first estimates the position of the receivers ($\boldsymbol{Rx}_1, \boldsymbol{Rx}_2, \boldsymbol{Rx}_3$) by using the distance data obtained by matched filter. For estimating $\boldsymbol{Rx}_1$, $\boldsymbol{Rx}_2$, and $\boldsymbol{Rx}_3$, a quadratic equation is used[9] if the robot observes only two transmitters, and least square methods are used[10] if the robot observes information from more than three transmitters.

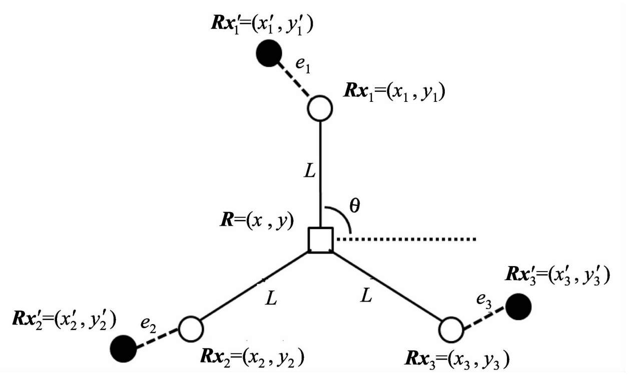

Fig. 2 Proposed system with three receivers

From the estimated positions of the receivers, the position and the orientation of the robot are found. Unfortunately, the estimated positions of the receivers are different from the actual positions of the receivers. That is, there are some errors between an actual position and an estimated position, as shown in Fig.2.

Let the estimated positions of the receivers be $\boldsymbol{Rx}_1'$, $\boldsymbol{Rx}_2'$, $\boldsymbol{Rx}_3'$, and the actual positions of the receivers be $\boldsymbol{Rx}_1, \boldsymbol{Rx}_2, \boldsymbol{Rx}_3$. Therefore, the errors e_1, e_2, e_3 can be described as the following equations:

$$\begin{aligned} e_1 &= \| \boldsymbol{Rx}_1' - \boldsymbol{Rx}_1 \|_2 = \sqrt{(x_1' - x_1)^2 + (y_1' - y_1)^2}, \\ e_2 &= \| \boldsymbol{Rx}_2' - \boldsymbol{Rx}_2 \|_2 = \sqrt{(x_2' - x_2)^2 + (y_2' - y_2)^2}, \\ e_3 &= \| \boldsymbol{Rx}_2' - \boldsymbol{Rx}_2 \|_2 = \sqrt{(x_3' - x_3)^2 + (y_3' - y_3)^2}. \end{aligned} \quad (16)$$

Furthermore, $\boldsymbol{Rx}_1, \boldsymbol{Rx}_2, \boldsymbol{Rx}_3$, are represented by $\boldsymbol{R}$, L, and θ respectively, as follows:

$$\begin{aligned} x_1 &= x + L\cos\theta, \\ y_1 &= y + L\sin\theta, \\ x_2 &= x + L\cos(\theta + 120°), \\ y_2 &= y + L\sin(\theta + 120°), \\ x_3 &= x + L\cos(\theta - 120°), \\ y_3 &= y + L\sin(\theta - 120°). \end{aligned} \quad (17)$$

The errors of the receiver's locations are

$$\begin{aligned} e_1 &= \sqrt{(x_1' - x - L\cos\theta)^2 + (y_1' - y - L\sin\theta)^2}, \\ e_2 &= \sqrt{(x_2' - x - L\cos(\theta + 120°))^2 + (y_2' - y - L\sin(\theta + 120°))^2}, \\ e_3 &= \sqrt{(x_3' - x - L\cos(\theta - 120°))^2 + (y_3' - y - L\sin(\theta - 120°))^2}. \end{aligned} \quad (18)$$

The position and orientation are, in fact, (x, y, θ) minimizing the sum of the square errors, and the solution of minimization can be acquired from the least square problem

$$\begin{aligned} &\text{Find } (x, y, \theta) \text{ such that } \min E, \\ &\text{where } E = \sum_{i=1}^{N} e_i^2, \\ &\frac{\partial E}{\partial x} = 0, \ \frac{\partial E}{\partial y} = 0, \ \frac{\partial E}{\partial \theta} = 0. \end{aligned} \quad (19)$$

Hence it is easy to estimate the point (x, y, θ) by using least square problem (19) as follows:

$$\begin{aligned} x &= \frac{x_1' + x_2' + x_3'}{3}, \\ y &= \frac{y_1' + y_2' + y_3'}{3}, \\ \theta &= \operatorname{atan} 2(\beta, \alpha), \\ \alpha &= (x_1' - x) - \frac{1}{2}(x_2' - x) + \frac{\sqrt{3}}{2}(y_2' - y) - \\ &\quad \frac{1}{2}(x_3' - x) - \frac{\sqrt{3}}{2}(y_3' - y), \\ \beta &= (y_1' - y) - \frac{\sqrt{3}}{2}(x_2' - x) - \frac{1}{2}(y_2' - y) + \\ &\quad \frac{\sqrt{3}}{2}(x_3' - x) - \frac{1}{2}(y_3' - y). \end{aligned} \quad (20)$$

From Eq. (20), the position of the robot is equal to the center of mass of the triangle composed of estimated positions of three receivers. This method provides almost accurate results if the robot estimates the accurate positions of the three receivers. Moreover, although the robot does not estimate the exact positions, the localization system is more accurate than a localization system with two receivers.

2.3 EKF for dynamic localization

To improve the localization accuracy in a dynamic environment, the EKF[5-6] is applied, which fuses the measurements from the ultrasonic localization system and the robot's odometry data. The wheel velocity is used to predict the states of the system at time k based on the predicted state at time $k-1$.

The state vector with robot's position and orientation is defined as

$$\boldsymbol{X}(k) = [x_r(k) y_r(k) \theta_r(k)]^{\mathrm{T}}. \quad (21)$$

The process model for the differential wheeled mobile robot is described as

$$\begin{aligned} \boldsymbol{X}(k+1) &= f(\boldsymbol{X}(k), u(k), k) + v(k), \\ f(\boldsymbol{X}(k), u(k), k) &= \boldsymbol{X}(k) + \\ &\quad T_s \begin{bmatrix} \cos\theta_r(k) u_1(k) \\ \sin\theta_r(k) u_1(k) \\ u_2(k) \end{bmatrix}, \end{aligned} \quad (22)$$

where T_s is the sampling time. $\boldsymbol{u}(k) = [u_1(k) u_2(k)]^{\mathrm{T}}$ is the control input, where $u_1(k)$ and $u_2(k)$ denote the forward and angular velocities of the robot, respectively. The process noise $v(k)$ is assumed to be zero-mean white Gaussian noise with covariance matrix $\boldsymbol{V}(k)$.

Since the robot's position and orientation are obtained from the ultrasonic localization system, the measurement model can be described as

$$\begin{aligned} &\boldsymbol{Y}(k) = h(\boldsymbol{X}(k), k) + w(k), \\ &\text{where} \quad h(\boldsymbol{X}(k), k) = [x_r(k) y_r(k) \theta_r(k)]^{\mathrm{T}}, \end{aligned} \quad (23)$$

and $w(k)$ is the measurement noise which is assumed to be zero-mean white Gaussian random vector with covariance matrix $\boldsymbol{W}(k)$. The values of the diagonal elements are the variances of the measurement noises, as in

$$\boldsymbol{W}(k) = \begin{bmatrix} \sigma_{x_{us}}^2 & 0 & 0 \\ 0 & \sigma_{y_{us}}^2 & 0 \\ 0 & 0 & \sigma_{\theta_{us}}^2 \end{bmatrix}, \quad (24)$$

At time k, the EKF estimates the state at time $k+1$ by using the odometry data, so called prediction step. The equations for the prediction step are

$$\begin{aligned} \hat{\boldsymbol{X}}(k+1 \mid k) &= f(\hat{\boldsymbol{X}}(k \mid k), u(k), k), \\ \boldsymbol{P}(k+1 \mid k) &= \boldsymbol{F}(k) P(k \mid k) \boldsymbol{F}(k)^{\mathrm{T}} + \boldsymbol{V}(k), \end{aligned} \quad (25)$$

$$\text{where} \quad \boldsymbol{F}(k) = \left. \frac{\partial f}{\partial \boldsymbol{X}} \right|_{X = \hat{X}(k \mid k)} = \begin{bmatrix} 1 & 0 & -T_s \sin\theta_r(k) u_1(k) \\ 0 & 1 & T_s \cos\theta_r(k) u_1(k) \\ 0 & 0 & 1 \end{bmatrix},$$

$\hat{\boldsymbol{X}}(k+1|k)$ is the prediction of the state for time $k+1$ given odometry data from time k and knowledge of the state at time k. $\boldsymbol{P}(k+1|k)$ is the covariance matrix of the predicted state. The covariance matrix of the process noise, $\boldsymbol{V}(k)$, has the same form as $\boldsymbol{W}(k)$, but the values of the diagonal elements are the variances of the process noise.

To estimate the state optimally, the Kalman gain $\boldsymbol{R}_k$

is calculated, as shown in Eq. (26).

$$
\boldsymbol{R}_k = \boldsymbol{P}(k+1 \mid k)\boldsymbol{H}(k+1)^{\mathrm{T}} S_1^{-1},
$$

where

$$
\boldsymbol{S}_1 = \boldsymbol{H}(k+1)\boldsymbol{P}(k+1 \mid k)\boldsymbol{H}(k+1)^{\mathrm{T}} + \boldsymbol{W}(k+1). \qquad (26)
$$

In the updated step, the EKF corrects the state and covariance estimates with the measurement from the ultrasonic localization system, $\boldsymbol{Y}(k) = [x_{us}(k) y_{us}(k) \theta_{us}(k)]^{\mathrm{T}}$. The equations for the updated step are

$$
\hat{\boldsymbol{X}}(k+1 \mid k+1) = \hat{\boldsymbol{X}}(\mathrm{k}+1 \mid \mathrm{k}) + \mathrm{R_k S_2},
$$

$$
\boldsymbol{P}(k+1 \mid k+1) = \boldsymbol{P}(k+1 \mid k) - \boldsymbol{R}_k \boldsymbol{H}(k+1)\boldsymbol{P}(k+1 \mid k),
$$

where

$$
S_2 = \boldsymbol{Y}(k+1) - h(\hat{\boldsymbol{X}}(k+1 \mid k), k+1),
$$

and

$$
\boldsymbol{H}(k+1) = \left.\frac{\partial h}{\partial X}\right|_{x=\hat{X}(k+1|k)} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \qquad (27)
$$

3 Experimental results

3.1 Simulation results

In this simulation, the localization error related to the number of ultrasonic receivers is analyzed. The simulation environment is set up to evaluate the performance of the proposed localization system. The size of the room is 800 cm (x -axis) by 600 cm (y -axis), and the height is 250 cm. The positions of the two transmitters are (0 cm, 0 cm) and (800 cm, 0 cm) as respectively transmitter 1 and transmitter 2 in the room. The receiver array′s radius is $L=25$ mm. The five real x positions are from 200 cm to 600 cm at 100 cm intervals and the four real y positions are from 170 cm to 410 cm at 80 cm intervals. The real orientation of the robot is 0 deg. Finally, the maximum distance error of the ultrasonic sensor is assumed to 1 cm, and the error distribution to uniform error.

Tab. 1 Localization error(simulation result): (a) Position and orientation error by using 2 receivers; (b) Position and orientation error by using proposed system (3 receivers)

	200	300	400	500	600
170	1.019	1.072	1.093	1.072	1.019
250	0.835	0.851	0.86	0.851	0.835
330	0.773	0.771	0.772	0.771	0.773
410	0.76	0.748	0.746	0.748	0.76

(a-1) RMSE of position

	200	300	400	500	600
170	1.689	1.814	1.855	1.814	1.689
250	1.263	1.324	1.345	1.324	1.263
330	1.064	1.091	1.1	1.091	1.064
410	0.956	0.961	0.962	0.961	0.956

(a-2) Average error of orientation

(a)

	200	300	400	500	600
170	0.84	0.886	0.904	0.886	0.841
250	0.684	0.698	0.705	0.698	0.684
330	0.632	0.631	0.632	0.631	0.632
410	0.621	0.612	0.609	0.612	0.621

(b-1) RMSE of position

	200	300	400	500	600
170	1.114	1.166	1.179	1.145	1.082
250	0.906	0.921	0.921	0.908	0.886
330	0.836	0.831	0.828	0.822	0.821
410	0.82	0.806	0.799	0.798	0.808

(b-2) Average error of orientation

(b)

From Tab. 1, the horizontal axis is the x value and the vertical axis is the y value. From the result, the proposed localization system has a smaller position and orientation error than the 2 receiver localization system for most of the positions. Therefore, the proposed localization system is accurate and robust compared to the localization system by using 2 receivers.

3.2 Experimental results

The ultrasonic sensor used for the experiment is Murata MA40S5. PXA255 ARM based microcontroller is used to evaluate the performance of the system. The calculation time about the three matched filter algorithms is shown in Tab. 2.

1) Conventional matched filter;

2) Matched filter + reduced calculation algorithm;

3) Matched filter + reduced calculation algorithm + threshold.

Tab. 2 Calculation time for matched filter

	Algorithm		
Operations	1)	2)	3)
Envelope/Phase (ms)	N/A	33	33
Convolution (ms)	1 095	68	6
Total (ms)	1 095	101	39

Each distance is measured 100 times from 2 m to 6 m and the average and the standard deviation of the measured distance are shown in Tab. 3. The average error of most distances is less than 1 cm, and the standard deviation is about 0.9 cm~1.4 cm.

Tab. 3 Distance statistics (100 iterations)

Distance between Tx and Rx (cm)	Average (cm)	Standard deviation (cm)
200	199.8	0.90
300	300.74	0.95
400	400.86	1.12
500	499.05	1.25
600	599.15	1.40

Tab. 4 Static localization error (100 iterations): (a) Localization error at (100, 50) and 180 deg; (b) Localization error at (100, 100) and 180 deg

(a)

The number of transmitters	2	3	4
Average position (cm)	(99.33,54.84)	(99.83,48.20)	(100.15,48.77)
Average position error (cm)	4.89	1.81	1.23
Average orientation (deg)	183.92	179.00	178.62
Orientation error (deg)	3.92	1	1.4

(b)

The number of transmitters	2	3	4
Average position (cm)	(99.44,97.95)	(99.80,97.34)	(99.12,98.52)
Average position error (cm)	2.12	2.66	1.72
Average orientation (deg)	177.43	178.08	178.84
Orientation error (deg)	2.56	1.92	1.15

The experimental results are shown in Tab. 4. From the results, according to the increasing number of transmitters, most of the position and orientation errors get smaller. Moreover, most of the position error is less than 3 cm, and most of the orientation error is less than 3 deg in the static environment including fixed-attached transmitters and unmoving robots.

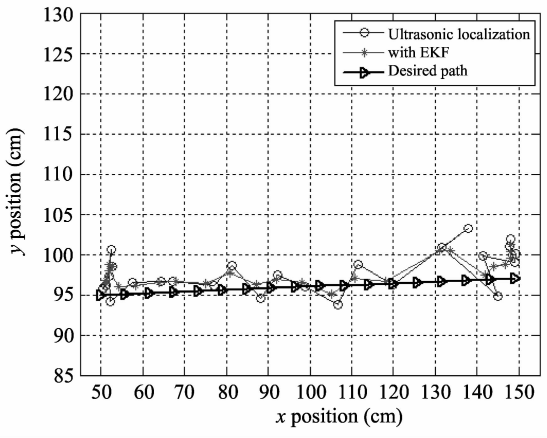

Fig. 3 Localization result in dynamic environment

In the dynamic situation, the position is estimated with the measurement from the ultrasonic localization system and the odometry information of the robot by using the EKF. Assume that the standard deviation of error of the ultrasonic localization system is $\sigma_{x_{us}}^2 = \sigma_{y_{us}}^2 = 1.5$ cm^2 and $\sigma_{\theta_{us}}^2 = 1$ deg^2. The standard deviation of error of the odometry information is also obtained, and the diagonal elements of $\boldsymbol{V}(k)$, as $\sigma_x^2 = \sigma_y^2 = 1$ cm^2 and $\sigma_\theta^2 = 1$ deg^2 experimentally. Let a mobile robot move from a point (50 cm, 95 cm) to a point (149 cm, 97 cm).

Tab. 5 Dynamic localization error

	Localization System without EKF	Localization System with EKF
Average position error (cm)	4.23	3.76

The EKF result is shown in Fig. 3. The average position error with respect to the desired path is summarized in Tab. 5. From the table, the result with the EKF is more accurate than the result without the EKF.

4 Conclusion

In this paper, an ultrasonic localization system is presented with three ultrasonic receivers and two or more ultrasonic transmitters. At first, the matched filter is used for calculating accurate distances in a noisy environment. Then, three ultrasonic receivers are placed on the mobile robot, which is more accurate than an ultrasonic localization system with two ultrasonic receivers. Finally, for the dynamic localization, the EKF is designed by using dead-reckoning and velocity data is designed. Various simulation and experimental results show that the proposed system is effective. However, an important factor to evaluate the performance of the localization system is not only an average error, but also a standard deviation of error. In this paper, the average errors of the position, the orientation, and the distance of the ultrasonic sensor are mainly analyzed. Hence, the improvement of the system to reduce the inaccuracy of error and the value of the standard deviation of error should be further studied.

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