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H. R. Beom and H. S. Cho

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H.R. Beom* and H.S. Cho†

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SUMMARY

This paper proposes a new method of estimating the position and heading angle of a mobile robot moving on a flat surface. The proposed localization method utilizes two passive beacons and a single rotating ultrasonic sensor. The passive beacons consist of two cylinders with different diameters and reflect the ultrasonic pulses coming from the sonar sensor mounted on the mobile robot. The sonar sensor, again, mounted on a pan-tilt device then receives the reflected pulses while scanning over a wide area. The geometric parameter set of beacon is acquired from the sonar scan data obtained at a single mobile robot location using a new data processing algorithm. The presented algorithm is especially suitable for processing the sonar scan data obtained by ultrasonic sensor with wide beam spread. From this parameter set, the position and heading angle of the mobile robot is determined directly. The performance and validity of the proposed method are evaluated using two beacons and a single sonar sensor attached at the pan-tilt device mounted on a mobile robot, named LCAR, in our laboratory.

KEYWORDS: Mobile robot; Sonar; Beacon; Localization.

I. INTRODUCTION

Ultrasonic sensors have been widely applied to robotic fields due to its low cost and fast processing time. Such applications to these fields may be divided into two categories: One is the area of map building by acquiring complete information about the unknown environment when mobile robot positions are given, and the other is the localization of mobile robot by using the sensory information about environment. These tasks involve extraction of range information from real world by taking into account noise and inaccuracy of sensor information which introduce uncertainty into environment map and increase difficulty of the navigation task. The map building method includes a certainty grid method[1] and an occupancy grid method.[2] In the methods, the map representing the position of obstacles is built under the assumption that the mobile robot position is completely known within the workspace.

The localization methods include a dead reckoning with a wheel encoder, an inertial navigation system using a gyro, a CCD camera and a landmark, and a beacon navigation system. The dead reckoning[3] and inertial navigation systems are used to measure the acceleration or velocity of the mobile robot at every sampling time. Thus, the current position is calculated by aggregating the increments over the time history of movements. These methods have the advantage in that the robot position can be continuously calculated, but they have drawback in that the position error accumulates due to wheel slippage and deformation when the mobile robot travels over a long distance. Therefore, it becomes necessary for the mobile robot to interact with its environment to decrease such positional uncertainty.

Recently, many studies have been made to find the robot position by using a CCD camera and a landmark.[4,5] Many algorithms have been proposed to reduce extensive computation time by using landmarks with simple shapes. As the camera is located farther away from the mark, the errors of the position variables tend to increase. Another limitation of this method is that its accuracy strongly depends on the resolution of image pixels, and this method may not be used in the environment such as too dark or bright, or smoky environment.

The beacon navigation system employs optical wave or sound wave. The beacon system using optical wave consists of a laser beam, three corner cubes and a photo detector.[6] The beacon navigation system using sound wave consists of one ultrasonic receiver and several ultrasonic transmitters.[7,8] The transmitters here acting as beacons fire the coded ultrasonic pulses, and these methods require additional transmitter controller. In this method, the measurement error grows as the area of the triangle formed by three corner cubes or three ultrasonic transmitters becomes larger. The position measurement by these methods becomes even unreliable when the mobile robot is located outside the triangle since they yield unacceptable amount of errors.

Several studies[9–12] have tried to localize a mobile robot using a matching technique, which compares the ultrasonic data with an environment model. Drumheller

* Research & Development Laboratory Gold Star Industrial Systems, CO., Ltd. Anyang (Korea).
† Center for Robotics and Automation Department of Precision Engineering and Mechatronics Korea Advanced Institute of Science and Technology 373-1 Kusong-dong, Taejeon, 305-701 (Korea).

et al.[9] modeled a room as a list of line segments indicating the position of walls and determined several candidates of the position and heading angle of a mobile robot by correlating the straight line segments extracted from sonar contour in range data with the room model. Leonard et al.[10,11] modeled a room using the map of the locations of geometric beacons, which can be observed by successively measuring the objects such as walls, corners and edges naturally existing in the environment. The position and heading angle are then determined by matching between observed geometric beacons and a priori map of beacon location. These model-based methods are, however, not suitable for dynamically changing environment or complex environment with many geometric beacons. Besides, these methods require sonar data obtained from multiple locations in order to determine the true position and heading angle of the mobile robot.

Even though various localization systems have been proposed, none of them have proven superiority over other methods, mainly because the sensors are subject to limited accuracy and degraded by disturbance and environmental conditions. The objective of this study is to develop an effective mobile robot localization system using a single sonar sensor and two beacons. Our method is different from the previous methods in that the position and heading angle can be determined solely from the sonar scan data obtained at a single mobile robot location. Furthermore, the proposed method does not require complicated environment model since the artificially designed cylinders are used as beacons. Using the above system, the problem of determining the position and heading angle of a mobile robot can be reformulated as to finding the center positions of two beacons from sonar scan data when the diameters and positions of two beacons with respect to the world coordinate frame are given. To realize this, first, the sonar scan data are obtained by scanning operation. Then, a data processing algorithm is developed to acquire the beacon's geometric parameter set. This parameter set is then used to determine the position and heading angle of the mobile robot.

This method can be not only economically implemented but also used to localize the mobile robot without a complete model of environment. Also, a new self-calibration method for ultrasonic sensors is presented for compensating for changes in environmental conditions. By the above proposed procedures, the mobile robot can estimate its position and heading angle. The performance and validity of the position estimation method are evaluated through analysis of the experimental results.

This paper is organized in following manner: section II describes the ultrasonic sensor system and beacons. A method of extracting the parameter sets associated with beacons from sonar data is presented in section III. The mobile robot localization is described in section IV. The experimental results and discussions are described in section V. Finally, the conclusions are presented in section VI.

II. THE SYSTEM DESCRIPTION

A. The mobile robot and ultrasonic sensor system

The proposed localization method is developed for a wheeled mobile robot named as LCAR shown in Figure 1(a). The robot has four wheels; two driven wheels are fixed at both sides of the mobile robot and two castors are attached at the front and rear side of the robot, respectively. The robot moves and changes its heading angle by the rotation of two driven wheels, which are actuated by DC servo motors. The pan-tilt device with a CCD camera and an ultrasonic sensor is mounted on the top of the mobile robot, as shown in Figure 1(b). It is driven by two servo motors: One is for panning (α_P) and the other is for tilting (α_T).

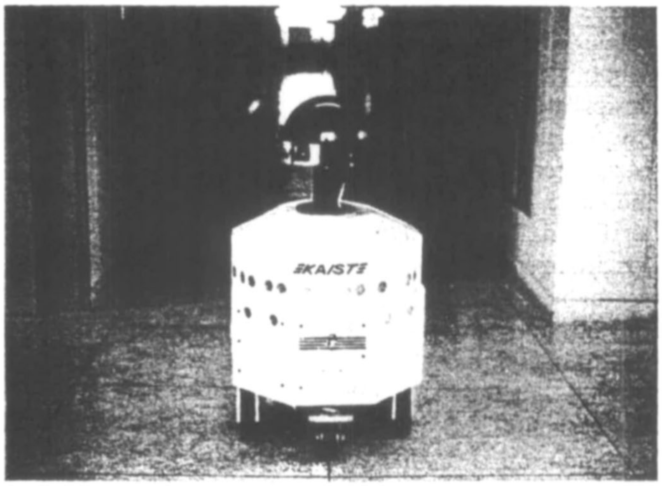

Fig. 1(a). The wheeled mobile robot, LCAR.

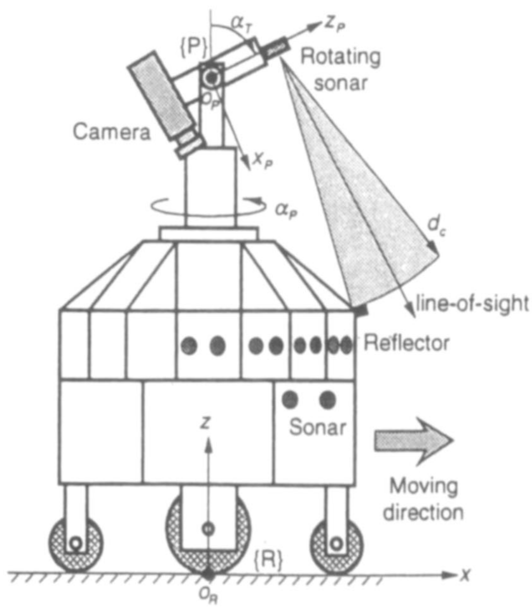

Fig. 1(b). An ultrasonic sensor for localization and sensor calibration.

The mobile robot frame {R} is fixed at the bottom center of the mobile robot and its origin is at the point o_R as shown in Figure 1(b). Its x-axis coincides with the moving direction of the mobile robot and its z-axis is perpendicular to floor plane and coincident with the central axis of the mobile robot. Also, the frame {P} is fixed at the point o_P on the pan-tile device. The x_P and z_P denote the x-axis and z-axis of the frame {P}, respectively. When $\alpha_P = 0$, its x-axis is parallel to that of the mobile robot frame {R} and when $\alpha_T = 0$, its z-axis is coincident to that of the frame {R}.

A TOF (time of flight) system produces a range value computed from the time, t_0, when the echo amplitude first exceeds a threshold value. A range value, δ, is obtained from the round-trip TOF, as per references 13 and 14.

$$\delta = \frac{v_s t_0}{2} \tag{1}$$

where v_s is the speed of sound in air. The speed of sound in air varies slightly with humidity; i.e. max. 0.35% at 20°C, and greatly with temperature; i.e. 7% variation from 0°C to 40°C.[15] The changes in environment temperature and humidity give inaccurate range values. Such an error can be compensated for by periodically calibrating the sonar sensor.

Use of ultrasonic sensor in the mobile robot navigation field may be divided into two categories: One is to detect the obstacle in the vicinity of the mobile robot and the other is to localize the mobile robot inside environment. Figure 1(b) shows a single rotating ultrasonic sensor mounted on the top of the pan-tilt device. This sensor is used not only to localize the mobile robot but also to calibrate the sensors for periodically compensating for the variation of environment conditions. The calibration is performed as shown in Figure 1(b) without using the temperature or humidity sensors. A small reflector, which produces the echo signal exceeding the threshold value, is attached at the front face of the mobile robot. As the pan-tilt device rotates at (α_P, α_T), the rotating sonar sensor aims at the reflector at a known position. When $\alpha_T = 53.1$ degrees and $\alpha_P = 0$, we can calculate the distance, d_c, from the rotating sonar to a small reflector. Therefore, we can find a parameter representing the relationship between the distance, $d_c = 0.515$ m, and the round-trip TOF.

In our mobile robot, eighteen ultrasonic sensors mounted in the front face of the mobile robot are used to detect the obstacles around the mobile robot. Figure 2 shows the arrangement of the ultrasonic sensors marked as dots in the figure. The distances d_j, $(j = 1, 2, \ldots, 18)$, from the z-axis of the robot frame {R} to an obstacle detected by jth sensor, S_j is defined as $d_j = \delta_j + R_r$. The relationship $\varphi_j = (j - 9.5)\bar{\varphi}$ can be deduced from this figure. Here, φ_j denotes the sensor orientation and $\bar{\varphi}$ is the angle between two adjacent sensors, and R_r is the radius of the robot and δ_j is the jth sensor reading drawn by the dashed line.

We use the Polaroid ultrasonic sensors as most of the other researchers did, and their technical specifications and beam pattern can be found in Polaroid.[15] These sensors act both as a transmitter and a receiver. In this study, they are controlled by a microcontroller, Intel 8031, communicated with PC/AT computer. Their control boards consist of a transmitter module to fire the ultrasonic pulses, a receiver/gain control module to receive the attenuated echo pulses and a switching module to arbitrarily select the activation of the sensor according to the sensing mode.

B. The environment and geometric beacon

It is assumed that the environment is a two-dimensional floor plane and composed of walls, corners, edges and cylinders. These elements may be used as reference elements for localizing the mobile robot inside the environment. In order to be used as one of the passive beacons, they must return strong echo independent of the measurement location of the sonar sensor and have a feature point to accurately determine their positions. Also, the feature point must not vary with the measurement location of the sonar sensor. The corner is not suitable for the reference since it is difficult to accurately find a feature point (corner point) from sonar scan data due to the multiple reflections. Also, the edges produce weak echo, and the wall does not have a feature point to uniquely determine its position. To solve this difficulty, we choose the cylinders as passive beacons, as

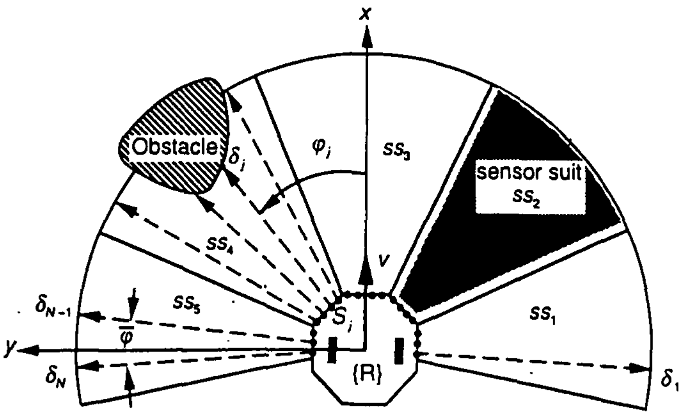

Fig. 2. The arrangement of ultrasonic sensors and sensor suits.

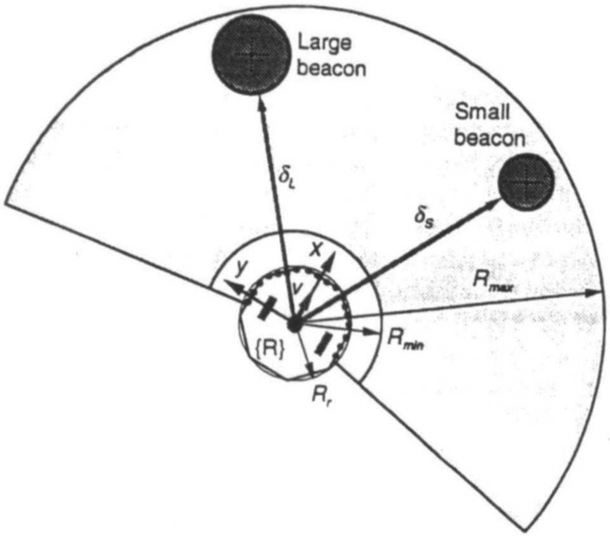

Fig. 3(a). The measurement ranges and relationship between two beacons and a mobile robot.

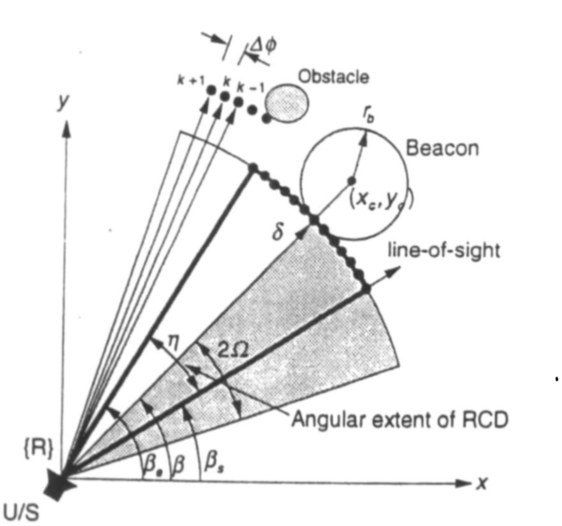

Fig. 3(b). The process of formation of a RCD by beacon.

shown in Figure 3(a). The cylinder has a feature point (its center) not to vary with measurement location. In order to localize the mobile robot by using only a sonar scan data obtained from one location, two cylinders with different diameters are required. Two cylinders can be distinguished by using the angular extents to be explained in section III. In this figure, $R_{\max}$ and $R_{\min} - R_r$ denote the maximum and the minimum range of sensors. The δ_L and δ_S denote the range values which are measured by a single rotating sonar sensor, produced by large and small beacons, respectively.

III. THE DETERMINATION OF LOCATION OF CYLINDRICAL BEACON

A. Extracting RCD's from sonar scan data

When the sonar scan data are obtained from the ultrasonic sensor with wide beam spread, the RCD (Region of Constant Distance) is a useful feature. Thus, in this section we will describe the procedure for extracting the RCD from sonar scan data.

Since a single sonar sensor is mounted on the top of the pan-tile device, as shown in Figure 1(b), the sensor rotates by the increments of $\Delta\phi$ degrees, transmits ultrasonic pulses and receives the echoes reflected by the object. The round-trip TOF is measured by 12 bit counter operating at frequency, $f_0 = 1/32$ MHz, and the rotating angles of the pan-tilt device are measured by two encoders. The round-trip TOF is converted into the range value using the parameter determined by sensor calibration. Scanning operation is conducted with the pan-tilt device, where the pan angle α_P varies within $(-\pi \leq \alpha_P < \pi)$ and the tilt angle α_T is fixed at zero degree. Let the angular increment be $\Delta\phi$ as shown in Figure 3(b). Then, the entire sonar scan data consists of $\{\delta(k\,\Delta\phi) | k = 1, 2, \ldots, 360/\Delta\phi\}$. Here, $\delta(k\,\Delta\phi)$ is the distance from a single rotating sensor to the object located in the direction of the angle $k\,\Delta\phi$.

Since the 50-kHz Polaroid sensor used in this study has the wavelength of 6.86 mm, the surfaces of the objects encountered in real environment can be considered to be specular. Let us consider the case of Figure 3(b). When the sonar sensor with beam spread 2Ω aims at the direction of the angle β_s with respect to {R}, the echo exceeding a threshold value just begins to occur. The TOF range dot is placed along the transducer orientation, β_s, at the measured range. As the sonar sensor continues to rotate, the cylinder continuously produces strong echoes enough to exceed the threshold value and the TOF dots are placed along the transducer orientation at the measured ranges. As can be seen from this figure, range dots produced by beacon form an arc and they are approximately identical within angular extent, $\beta_s \leq \beta \leq \beta_e$. This is because the ultrasonic sensor has the wide beam spread. Thus, we will define the arc as an RCD since the range values inside the region are approximately identical. Also, we will name the angle η as angular extent of the RCD and define the geometric parameter set of the RCD as $\chi = \{\delta, \beta, \eta\}$. Here, δ denotes the range value along the angle β with respect to {R}. We can easily deduce from this figure that the range values within the RCD are usually produced by the same object. Therefore, in order to find a group of range values produced by a beacon, extraction of the RCD's from sonar scan data is required. Also, the geometric parameter set of the RCD is directly used to determine the object location. The β and η are calculated by $\beta = (\beta_e + \beta_s)/2$ and $\eta = \beta_e - \beta_s$, respectively, where β_s and β_e denote the starting and end angles of the arc. If the geometric parameter set χ and the beacon radius r_b are given, the center position, (x_c, y_c) of the beacon with respect to {R} can be calculated by

$$(x_c, y_c) = \{(\delta + r_b)\cos\beta, (\delta + r_b)\sin\beta\}. \quad (2)$$

As can be deduced from the equation (2), in order to find the center position of the beacon, first, we must extract the geometric parameters of the RCD's from the sonar scan data. The RCD's can be extracted by using the following conditions. Let the $\delta((k-1)\,\Delta\phi)$, $\delta(k\,\Delta\phi)$ and $\delta((k+1)\,\Delta\phi)$ be the range values measured at the three consecutive discrete angles $(k-1)\,\Delta\phi$, $k\,\Delta\phi$ and

$(k+1)\,\Delta\phi$, respectively, as shown in Figure 3(b). The start angle of the RCD, β_s, becomes $k\,\Delta\phi$ if the above three range values obtained from sonar scan data satisfy the following condition:

$$|\delta(k\,\Delta\phi) - \delta((k-1)\,\Delta\phi)| \geq \varepsilon \quad \text{and} \quad |\delta((k+1)\,\Delta\phi) - \delta(k\,\Delta\phi)| < \varepsilon. \quad (3)$$

Here, ε denotes a measure of determining whether the three range values are produced by the same object or not. The ε depends on the resolution of the range finder and the object shapes and is determined by a series of experiments. The end angle of the RCD, β_e, becomes $k\,\Delta\phi$ if these range values satisfy the following condition:

$$|\delta(k\,\Delta\phi) - \delta((k-1)\,\Delta\phi)| < \varepsilon \quad \text{and} \quad |\delta((k+1)\,\Delta\phi) - \delta(k\,\Delta\phi)| \geq \varepsilon. \quad (4)$$

After increasing the index k, if the above two conditions are repeatedly applied to newly selected three consecutive range values, all the RCD's existing in sonar scan data and their parameter sets can be determined. The range value, $\delta(k\,\Delta\phi)$ within the RCD always satisfies the following condition:

$$|\delta(k\,\Delta\phi) - \delta((k-1)\,\Delta\phi)| < \varepsilon \quad \text{and} \quad |\delta((k+1)\,\Delta\phi) - \delta(k\,\Delta\phi)| < \varepsilon. \quad (5)$$

B. Data reduction using angular extent of RCD of the beacon

Once all the RCD's are obtained by the above conditions, the next step is to find the RCD's associated with the beacons. In this step, the angular extent condition is used to test whether the RCD's are associated with the passive beacons or not. The angular extents of the cylinders are experimentally obtained by using cylinders with various diameters. Figure 4 shows the experimental results about the angular extent of the RCD's formed by cylinders with different diameters. In the case where the diameters of the beacons are greater than 12.0 cm, the angular extents vary slightly from 24.0° to 25.5° with variation of the cylinder location. However, in the case where the diameters are smaller than 12.0 cm, the angular extents vary greatly from 20.0° to 24.0°. Thus, only the RCD's satisfying angular extent condition, $18.0 \leq \eta \leq 26.0$, will be used in the next data reduction steps while all others will be ignored. It is easily seen from this figure that, if two cylinders with small diameter ($d_b < 12.0$ cm) and large one ($d_b > 12.0$ cm) are used as geometric beacons, two cylinders can be distinguished from each other if the angular extents conditions are utilized.

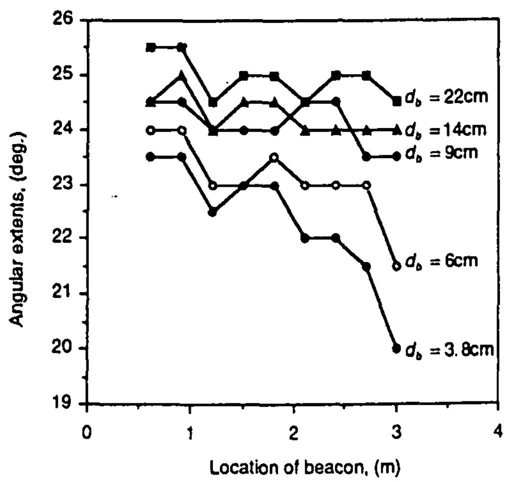

Fig. 4. Angular extent of the cylinders with various diameters: experiment.

C. Data reduction using symmetricity

Even though the RCD's satisfy the above angular extent condition, they may not turn out to be true beacons. If the RCD is formed by a cylindrical beacon, the range values within the RCD should be symmetric with respect to the line connecting the two centers of the beacon and sonar sensor. If this property is used, only the symmetric RCD can be considered to be those formed by beacon among the RCD's satisfying the angular extent conditions. We define a measure of this symmetricity by

$$\gamma = \frac{1}{M}\sum_{i=1}^{M}\left|\delta\left(\beta + \frac{i\cdot\eta}{2M}\right) - \delta\left(\beta - \frac{i\cdot\eta}{2M}\right)\right| \quad (6)$$

where M is INT$(N/2)$, N is the number of data forming the RCD and INT means integer operation. If the RCD is symmetric with respect to the line emanating at the angle β shown in Figure 3(b), γ approaches to zero. In this experiment, the cylinders with various diameters are used for determining the threshold value, γ_T. Figure 5 shows the experimental results when the cylinder with the diameter of 3.8 cm is located at 0.6 cm, 1.2 m, 1.8 m and 2.7 m, respectively. The y-axis denotes the differences between the range values consisting of RCD and a range value at angle β. It is easily seen from the figure that the profile is almost symmetric about the axis of $\beta = 0$. Hence, the RCD's with the value of the measure of the symmetricity smaller than γ_T will be used for the next data reduction step.

D. Data reduction using a priori known information

If this test applies to the RCD's satisfying the above steps, only the RCD's formed by passive beacons will remain. Let the geometric parameter set of RCD's be $\chi_n = \{\delta_n, \beta_n, \eta_n\}$, $(n = 1, 2, \ldots, m-1, m, \ldots, P)$. Here, the index, n denotes the nth RCD of the P RCD's which still remain after the above data reduction steps. As shown in Figure 6, since the coordinates of the centers of two cylinders, (x_L, y_L) and (x_S, y_S), are a priori given, the distance d_0 between the centers of two geometric beacons can be calculated. Let us consider that the $(m-1)$th and mth RCD's are formed by the small and large beacons. Using the geometric parameter sets of two RCD's, we can calculate the distance $\hat{d}_0$ between two beacons. In this case, the absolute estimation error between $\hat{d}_0$ and d_0 is calculated by

$$\Delta d_0 = |d_0 - \hat{d}_0| = \left|d_0 - \sqrt{d_S^2 + d_L^2 - 2d_L d_S \cos(\varphi_S - \varphi_L)}\right| \quad (7)$$

where if $\eta_m > \eta_{m-1}$, then $d_L = \delta_m + r_L$, $d_S = \delta_{m-1} + r_S$.

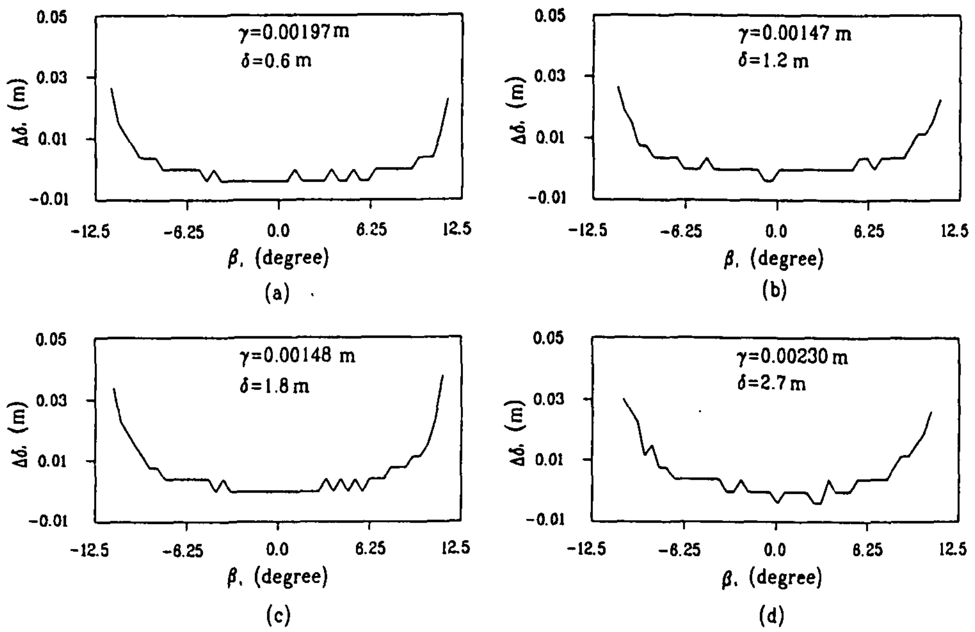

Fig. 5. The profiles of the range values when $d_b = 3.8$ cm.

$\varphi_L = \beta_m$ and $\varphi_S = \beta_{m-1}$, whereas if $\eta_m < \eta_{m-1}$, then $d_L = \delta_{m-1} + r_L$, $d_S = \delta_m + r_S$, $\varphi_L = \beta_{m-1}$ and $\varphi_S = \beta_m$. Also, if two angular extents are equal, the RCD with larger range value will be considered as the RCD formed by the large beacon. The above estimation error Δd_0 is calculated for all the combinations of RCD's and finally a pair with the smallest error within allowable error range will be used for localization of the mobile robot.

IV. MOBILE ROBOT LOCALIZATION

We extracted the geometric parameter sets of the RCD's of beacons from sonar scan data using the preceding data reduction steps. Once the parameter sets are determined, we can find the position and heading angle of mobile robot. The basic problem is shown in Figure 6. Let us consider that the mobile robot is located at an unknown point, (x_R, y_R), with respect to the world coordinate

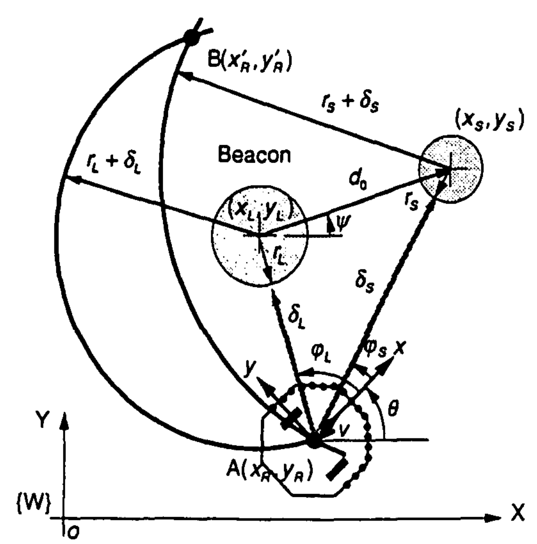

Fig. 6. Analytic geometry solution.

frame {W} fixed at a point o. The δ_L, δ_S, φ_L and φ_S can be obtained from geometric parameter sets of RCD's satisfying all the above data reduction steps.

The mobile robot positions correspond to the intersection points of two circles which are the loci of possible positions corresponding to the measured angles φ_L and φ_S. Analytic geometry may be used to solve for the common points, (x_R, y_R) and (x'_R, y'_R) of two circles

$$d_L^2 = (x_L - x_R)^2 + (y_L - y_R)^2 \tag{8}$$

$$d_S^2 = (x_S - x_R)^2 + (y_S - y_R)^2 \tag{9}$$

where $d_L = \delta_L + r_L$ and $d_S = \delta_S + r_S$. Using the equations (8) and (9), the intersection points of two circles are obtained by

$$y_R = \frac{-(x_L \tan\psi - L\tan\psi - y_L) \pm \sqrt{D}}{1 + \tan^2\psi} \tag{10}$$

$$x_R = y_R \tan\psi + L \tag{11}$$

$$D = (x_L \tan\psi - L\tan\psi - y_L)^2 - (\tan^2\psi + 1)((x_L - L)^2 + y_L^2 - d_L^2) \tag{12}$$

where

$$\tan\psi = \frac{y_L - y_S}{x_L - x_S}$$

and

$$L = \frac{(d_S^2 - d_L^2 + x_L^2 - x_S^2 + y_L^2 - y_S^2)}{2(x_L - x_S)}$$

As can be seen from equation (10), if $D < 0$, we can not determine the position and heading angle because we can obtain two imaginary solutions. The imaginary solutions result from inaccuracy of the ultrasonic sensor when the center points of the mobile robot and two beacons are colinear. However, by a priori calculating the value of D, we can decide whether or not the proposed method is suitable for updating the mobile robot position under the current situation. In general, as the value of D approaches zero, the estimation error of the proposed method increases due to inaccuracy of ultrasonic sensor.

As shown in this figure, two feasible positions, (x_R, y_R) and (x'_R, y'_R) of the mobile robot are determined. Then, the two angle differences, $\Delta\varphi = \varphi_S - \varphi_L$ and $\Delta\varphi' = \phi'_S - \varphi'_L$ are calculated, respectively, by

$$\begin{aligned}\Delta\varphi &= \varphi_S - \varphi_L \\ &= \tan^{-1}\left(\frac{y_S - y_R}{x_S - x_R}\right) - \tan^{-1}\left(\frac{y_L - y_R}{x_L - x_R}\right)\end{aligned} \tag{13}$$

$$\begin{aligned}\Delta\varphi' &= \phi'_S - \varphi'_L \\ &= \tan^{-1}\left(\frac{y_S - y'_R}{x_S - x'_R}\right) - \tan^{-1}\left(\frac{y_L - y'_R}{x_L - x'_R}\right)\end{aligned} \tag{14}$$

Using the β's of the geometric parameter sets of two beacons, we can determine one of two feasible solutions. The mobile robot position becomes then the position where the sign of $\Delta\varphi$ is the same as that of $\Delta\beta$, which is the angle differences $\Delta\beta = \beta_S - \beta_L$. Once the position of the mobile robot is determined, its heading angle can be calculated by

$$\theta = \tan^{-1}\left(\frac{y_L - y_R}{x_L - x_R}\right) - \varphi_L \tag{15}$$

where φ_L is the angle at which the larger beacon is located.

In this study, position and heading angle errors, E_{xy} and E_θ, are defined by

$$\begin{aligned}E_{xy} &= \sqrt{(x_R - x_T)^2 + (y_R - y_T)^2} \\ E_\theta &= |\theta - \theta_T|\end{aligned} \tag{16}$$

where (x_R, y_R) and θ denote the position and heading angle of the mobile robot estimated by a localization method, while (x_T, y_T) and θ_T denote the true position and heading angle of mobile robot.

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Experimental conditions

The proposed method was tested using the mobile robot, LCAR in order to show the effectiveness of this method. Currently, we are controlling the mobile robot motion by controlling the velocities of two wheels whereas its reference trajectory is given by a motion generating software program. In order to test the proposed localization method, we performed a series of experiments. The indoor environment where the mobile robot is located is shown in Figure 7. The sizes of environment and grid in this figure are $6.2\,\text{m} \times 5.0\,\text{m}$ and $0.5\,\text{m} \times 0.5\,\text{m}$, respectively. The small and large dark circles denote the positions, (2.85 m, −0.6 m) and (0.3 m, −1.5 m), of the small and large beacons, respectively.

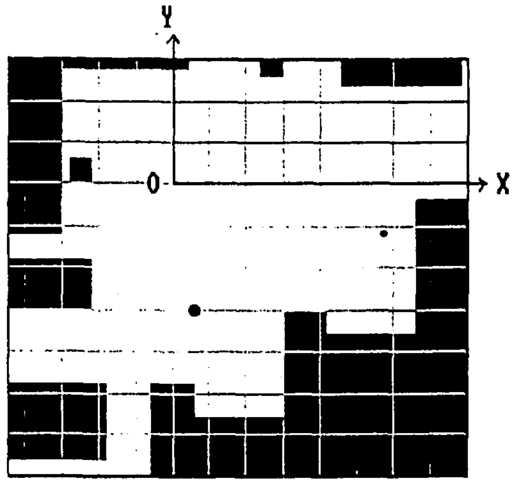

Fig. 7. The indoor environment for experiment of localization.

The distance between two beacons is 2.704 m. The small rectangle located at (−1.25 m, −0.2 m) denotes a hexahedral object. The environment is very cluttered, where walls, corners, edges, cylinders, and computers and monitors on the tables are located. Their positions are approximately drawn as shaded rectangles in the figure. All the parameters and physical dimensions used in the experiments are given in Table I.

B. Experimental procedure

The mobile robot drawn as an octagon in Figure 8(a) is located at the origin of the world coordinate frame shown in Figure 7. At this location the sonar scan data are obtained by rotating a single sonar. The sonar scan data shown in Figure 8(a) represent the positions of objects in environment and they should be represented by RCD's for next data processing. The RCD's are extracted by applying equations (3) through (5) to this sonar scan data and they are represented by arcs shown in Figure 8(b). By applying the angular extent condition, $18.0 \leq \eta \leq 26.0$, the number of RCD's dramatically decreases and consequently only four RCD's shown in Figure 8(c) remain. Their geometric parameter sets are listed in Table II. Again, if we apply the symmetricity condition to the four RCD's, we can obtain the values of symmetricity measure shown in Table II. The RCD with the value of symmetricity measure larger than γ_T will be ignored in the next data reduction step using a priori known information. Therefore, the RCD's except the third one in Figure 8(c) will be used in the next data

Table I. Physical dimensions and parameters

Parameters & dimensions	Values
Angle between adjacent sensors, $\bar{\varphi}$	11.25°
Radius of mobile robot, R,	0.3 m
Radius of small beacon, r_S	0.0382/2 m
Radius of large beaxon, r_L	0.14/2 m
Minimum sensing range of sensor, $R_{\min}$	0.3 m
Maximum sensing range of sensor, $R_{\max}$	4.0 m
Threshold value of symmetricity measure, γ_T	0.005
Measure determining RCD, ε	0.02 m
Incremental rotational angle, $\Delta\phi$	1.0°

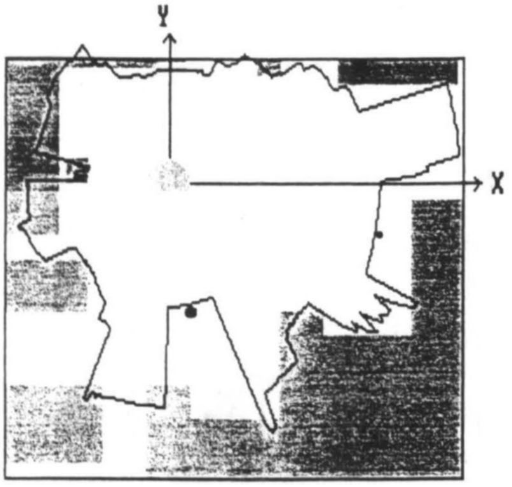

Fig. 8(a). The sonar scan data obtained at origin of world coordinate frame.

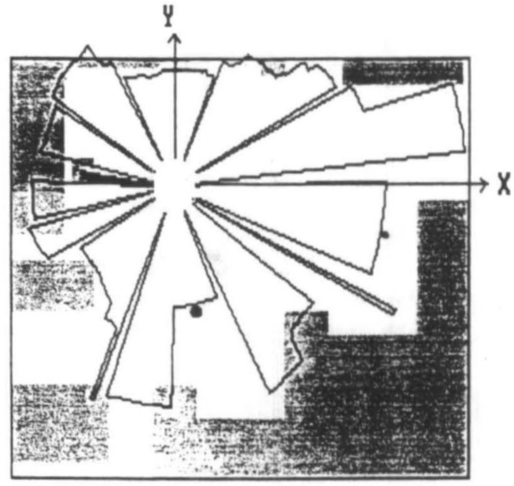

Fig. 8(b). The RCD's extracted from sonar scan data.

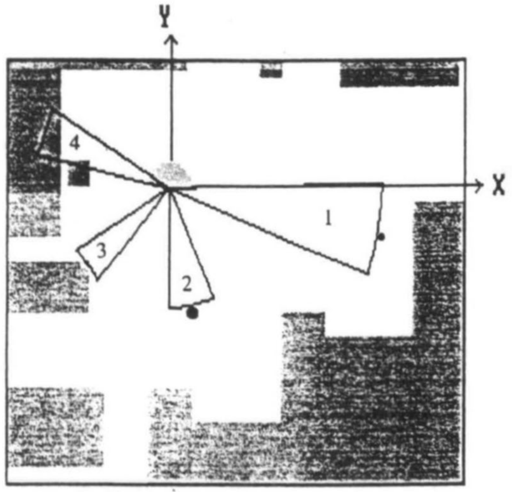

Fig. 8(c). The RCD's satisfying the angular extent condition.

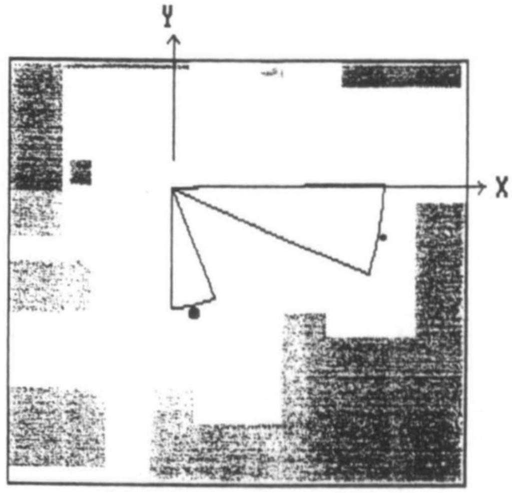

Fig. 8(d). The RCD's satisfying the symmetricity condition and a priori known information.

reduction step. In order to find the true information of the beacons from the three RCD's, a priori known information, i.e., the distance between two beacons, is employed. After choosing only two RCD's among the three, we calculate the distances between them. The estimated distance is compared with the known distance and then the pair with the smallest error within allowable error range set to 0.04 m is chosen as a true pair. The estimated distance errors represented by equation (7) are calculated by two geometric parameter sets listed in Table II. The distance errors calculated by the first and second, the first and fourth, and the second and fourth

Table II. The geometric parameter set and symmetrically measure

RCD No.	δ [m]	β [degree]	η [degree]	γ [m]
1	2.8542	−10.3	22.0	0.0027
2	1.4401	−78.3	24.0	0.0012
3	1.4612	−140.3	18.0	0.0074
4	1.8311	158.7	18.0	0.0021

RCD's are 0.031 m, 2.049 m and 0.257 m, respectively. Thus, the first and second RCD's in Figure 8(c) will be used for mobile robot localization, while the other will be removed as shown in Figure 8(d). Also, we can easily deduce that the first RCD in Figure 8(d) is formed by the small beacon since its angular extent η shown in Table II is smaller than that of the second. Therefore, since two geometric parameter sets and beacon diameters are determined, the position and heading angle can be calculated.

C. The experiments for estimation of position and heading angle

For the experiments of localization of mobile robot, three straight line paths shown in Figure 9(a) are used since its true position and heading angle can be easily measured with accuracy of 2 mm. The mobile robot stops at the positions marked as dark rectangles on the paths shown in Figure 9(a). Then, after completing scanning operation to acquire the sonar scan data, the mobile robot moves again in the direction of X-axis of world coordinate frame {W} along the planned path. Figure

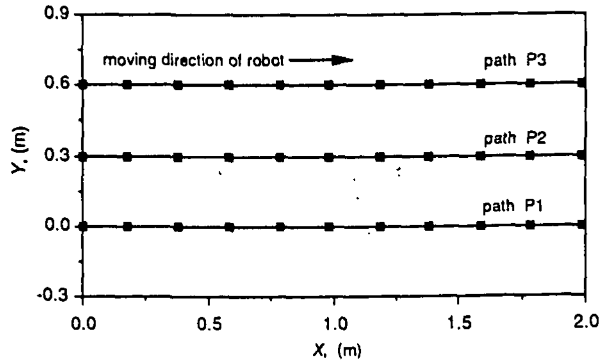

Fig. 9(a). Three straight line paths and mobile robot positions, marked as dark rectangles, where the estimation is performed.

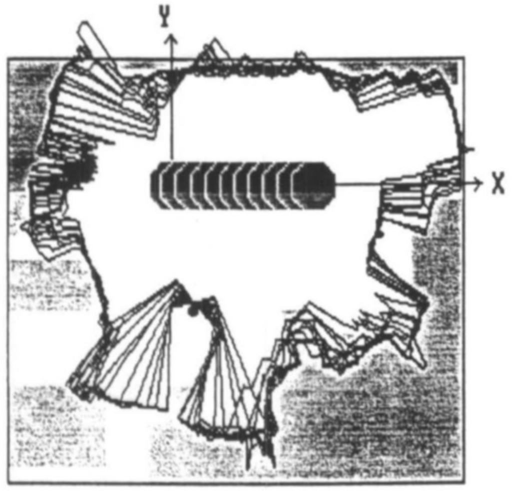

Fig. 9(b). The sonar scans obtained at the multiple points on the path P1.

9(b) shows the multiple sonar scan data obtained from the locations marked as dark rectangles on the path, P1.

Figure 10 shows the experimental results in the case when the mobile robot follows the paths P1. Here, the upper and lower figures in Figure 10 denote the position errors and the heading angle errors, respectively. The position error, E_{xy} and heading angle error, E_θ in equation (16) are the distance and angle differences between the true and estimated values, respectively. The mobile robot true position and heading angle are calculated by measuring the positions of the two wheels using tiles (30 cm × 30 cm) in floor. If we compare the estimation results of two methods, we can also see that the DR method must be used in the case when the wheel slippage does not occur and the mobile robot travels over

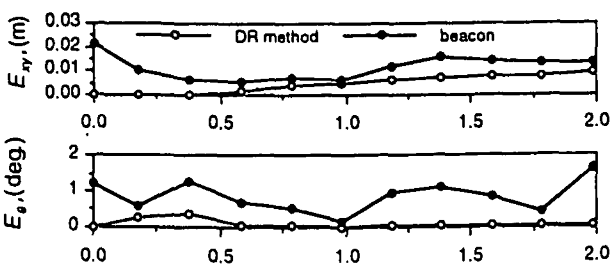

Fig. 10. The experimental results of the estimation of position and heading angle when the mobile robot follows the path P1.

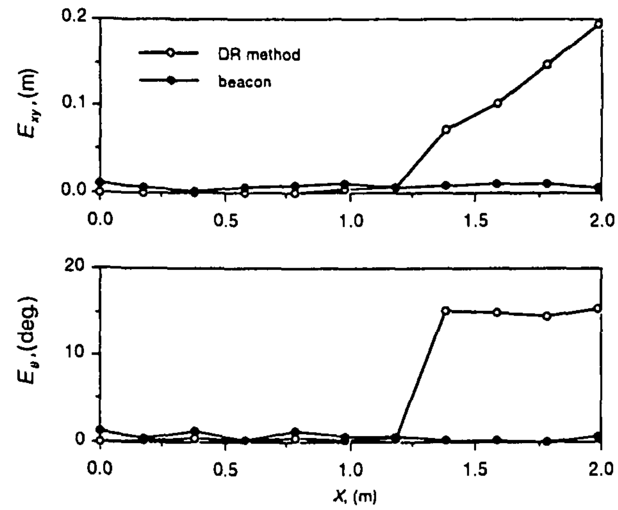

Fig. 11. The experimental results of the estimation of mobile robot position and heading angle when wheel slippage occurs.

a short distance. Errors of the DR method result from the unevenness of the floor whereas the errors of the proposed method result from inaccuracy of the measured range value δ and angle β. The inaccuracy of range value is associated with sensor noise and resolution of range finder. The resolution of range finder depends on the operating frequency of the counter measuring the round-trip TOF. The inaccuracy of the angle β is associated with incremental rotation angle of the pan-tilt device. The smaller the incremental rotation angle of pan-tilt device is, the more accurate should the parameter β be. However, if the incremental rotation angle is too small, it takes much time to obtain the sonar scan data. We performed the experiments in the case when the mobile robot follows the paths P1 and P2, respectively. From these experiments, we can see that the estimation errors are slightly different according to the mobile robot paths, but in all the cases of the paths the position and heading angle errors of the proposed method are bounded within 3.0 cm and 2.0 degrees, respectively.

Figure 11 shows the experimental results in the case when the wheel slippage occurs. In this experiment, the slippage between the left wheel of the robot and floor occurs near the coordinate point, (1.2 m, 0 m) on the path P1. We can see from Figure 11 that the proposed method can be effectively used to update the position and heading angle even in the case of wheel slippage.

VI. CONCLUSIONS

We have developed a mobile robot localization system which uses two cylindrical beacons and a single rotating ultrasonic sensor. Also, we presented a sensor calibration method to periodically compensate for the variation of environmental conditions. We have demonstrated the effectiveness of this method using a mobile robot, named LCAR, in our laboratory.

The proposed method can estimate the position and heading angle of a mobile robot using the sonar scan data obtained at a single mobile robot location. To realize this, two cylinders with different diameters, acting as passive beacons, were employed. To acquire the center positions of two beacons from the sonar scan data, a data processing algorithm was developed. This algorithm is especially suitable for processing the sonar scan data obtained by the ultrasonic sensor with wide beam spread. Using this algorithm, we could accurately obtain the geometric parameter sets of beacons and, consequently, determine the position and heading angle of the mobile robot.

The performance and validity of the proposed method were evaluated through a series of the experiments in actual indoor environment. To show the effectiveness of the proposed method, the experimental results of the proposed method were compared with those of the DR method in the case of wheel slippage. It is believed that the proposed method can be used as an alternative of mobile robot localization in environment where other methods can not be used.

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