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移動ロボットナビゲーションのためのソナー反射波によるエッジ検出

Distinguishing Edges by Sonar Reflections for Mobile Robot Navigation

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Abstract

This paper proposes a new method for estimating the position and orientation of a mobile robot in an indoor environment. The method is different from previous ones in which the simply shaped objects, such as edges selected from the environment are used as landmarks instead of artificial ones. The mobile robot moves from a starting point to its target point along a designed path relying on its own sensors. When it passes through the feature point in the environment, the mobile robot measures the distance to the feature point, estimates the position of itself and corrects its path. The presented algorithm is especially suitable for processing the sonar scan data obtained by ultrasonic sensors with wide beam spread. The validity of the proposed method was proved by simulation experiments, and it's performance was also investigated.

1. Introduction

For the navigation of a mobile robot, the determination of its absolute location is one of the essential tasks. To date several methods have been proposed to estimate the position of a mobile robot using ultrasonic sensors, and one of them is using two artificial beacons to reliably determine the mobile robot's current position and orientation(Cho *et al.*,1996)[1]. Although artificial landmarks were proved to be successful in localizing, for a mobile robot it would be more suitable to utilize the features that are inherent in the environments. Considering a navigation and localization problem in indoor environment, and assuming that the indoor environment is a two-dimensional floor plane in which some geometric positions of feature points like edges are known beforehand, then, the edges have to be recognized by the mobile robot first of all.

In order to recognize edges, a method was proposed by using a sensor that is vertical to the mobile robot's moving direction. When the vertical sensor checks out on an edge, it is said that the robot enters a localization zone. In this zone, as it moves the mobile robot rotates the sensors to search the features in the environment necessary to recognize the edges near by. It is needed to search out at least one pair containing edges. The result from searching is the distance from the feature point to the mobile robot itself. Using the two feature points, the robot location can be determined by the algorithm proposed by Cho *et al.*[5]. The above process are regarded as mobile robot's observation. After this the final estimation can be successfully obtained by matching the designed path with the observation value.

A mobile robot produced by Nomadic Co. was used in a simple environment, and the experiments were shown that the proposed method is feasible.

2. The System Description

2.1 Sonar Physical Model

Since most of indoor walls in the real world are smooth compared with the typical ultrasonic wavelength, the walls are assumed to behave as specularity surfaces to incident ultrasonic waves. Also in usual indoor environments, the amplitude and the speed of ultrasonic wave is supposed to not change appreciably in distance comparable to the typical wavelength because the ambient air, the propagation medium is fairly homogeneous. According to the above conditions the ultrasonic beam is modeled as straight rays, which is the line perpendicular to the surface of constant phase[2)3)]. A physical model presented by Roman Kuc describes the transducer reflection process from environments[7)] and is illustrated in Figure 1.

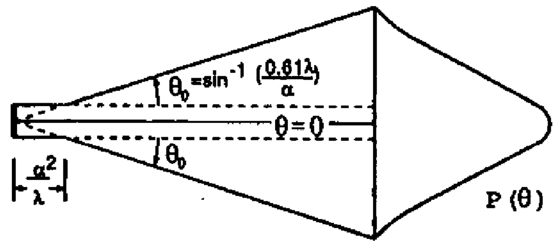

Figure 1 The beam pattern for the piston model of the Polaroid transducer

The beam pattern for the pressure amplitude $P(\theta)$ of the transmitting can be modeled by

$$P(r,\theta) = \frac{P_{max}}{r} exp\frac{-2\theta^2}{\theta_0^2} \quad (1)$$

where $\theta_0 = sin^{-1}(\frac{0.61\lambda}{a})$, and a is the transducer radius. When $r = \frac{a^2}{\lambda}$, $P(r,\theta) = P_{max}$. In this paper, $a = 1.88cm$, $\lambda = \frac{c}{f}$, for the Polaroid transducer $f = 49.4KHZ$, $\lambda = 6.76cm$, c is speed of ultrasonic beams, and taken as $331.4\sqrt{T/273}$ (m/sec). The speed varies slightly with humidity but greatly with temperature. In our mobile robot, sixteen sonar sensors mounted in the around of mobile robot are used to detect obstacles around the mobile robot. The Polaroid transducer 6500 sensor was used as both a transmitter and receiver. The distance that can be measured by this transducer is from 15.24 *cm* to 1066.8 *cm*, with a typical absolute accuracy of ± 1 percent over the entire range[8].

2.2 The Model of Geometric Edges

In the present study, an edge is defined as the intersection of two walls which are assumed to be vertical as observed from inside the convex space generated. In order to use it as one of the passive landmarks, it must have a feature point to determine its position accurately. Here the POE (Peak Of Edge) as shown in Figure 2a is chosen as the feature point. Therefore, when we say that an edge is distinguished that means the POE is recognized.

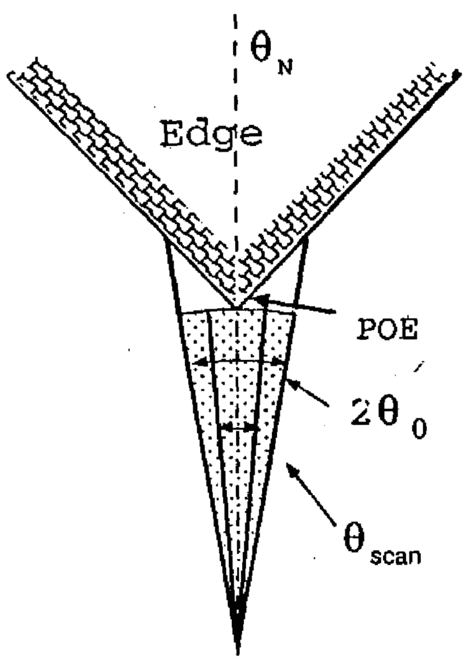

Figure 2a. Constraint on edge identification

According to Rom Kou's theory[3], the amplitude of the transmitted pulse decreases with range in the far zone since the diameter of the beam cross section increases with range and with divergence angle θ_o. As the sonar scans across an edge reflector, the echo amplitude follows the Gaussian Curve as shown in Figure 2b and is given by

$$\begin{cases} P_E(\theta, r) = \sigma_E \frac{P_f r_f^{1/2}}{r^{1/2}} e^{-4(\theta-\theta_N)^2/\theta_0{}^2} \\ r > r_f \end{cases} \quad (2)$$

where θ_N denotes the sensor orientation in the base frame that produces the echo with the maximum amplitude. σ_E is the scattering strength that depends on the sharpness of the edge and varies with the orientation of the edge. For a right edge, $\sigma_E = 0.035 \sim 0.10$. r is the distance and P_f is the amplitude at range r_f along the sensor of sight, $r_f = \frac{a^2}{\lambda}$.

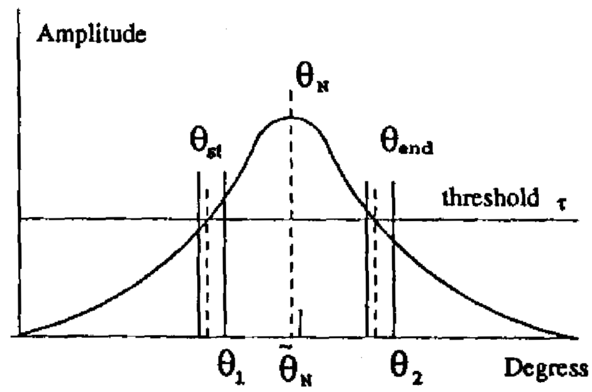

Figure 2b. Amplitude of the ehco versus the sonar orientation with discrete angles of rotation

From (2), when $\theta = \theta_N$ the $P_E(\theta, r)$ reaches its maximum value. The θ_N defined above has some important properties: a) the maximum echo amplitude from an edge occurs at $\theta = \theta_N$; b) due to symmetry of the sensor and the scanning procedure, the center of the scan arc occurs at $\theta = \theta_N$; c) the location of the object is along the direction $\theta = \theta_N$. From these important properties, an edge can be detected only when the sensor orientation θ lies in the $[\theta_{st}, \theta_{end}]$ and the POE can be distinguished only when the $\theta = \theta_N$. Then, some simulations can be carried out.

3. The Determination of Location of Edges

3.1 Preparation for processing Sonsar Scan Data (SSD)

In order to check the disturbances from the environment and improve accuracy of localization, we have to process the sensor data which are obtained from the ultrasonic sensor with wide beam spread. To find the edge feature point, the POE, the geometric parameters of SSD's can be extracted by using the following procedure: a) the data obtained from one sensor are grouped, and every consists of three data together; b) the average of the two closer data in one group is represented by d_i, the one is left is neglected.

An edge can be detected at time $i\Delta t$, if the above three range values obtained from SSD satisfy the following conditions:

$$\begin{cases} |d_i - d_{i-1}| \geq \delta \\ |d_{i+1} - d_i| < \delta \end{cases} \quad (3)$$

Here, δ denotes a measure of determining whether the three range values are produced by the edge or not. The parameter δ depends on the resolution of the range finder and the edges shapes and it is determined by a series of experiments.

In the same way, an edge can not be detected until next Δt, if SSD satisfy the following condition:

$$\begin{cases} |d_i - d_{i-1}| < \delta \\ |d_{i+1} - d_i| \geq \delta \end{cases} \quad (4)$$

If SSD satisfy the following condition:

$$\begin{cases} |d_i - d_{i-1}| < \delta \\ |d_{i+1} - d_i| < \delta \end{cases} \quad (5)$$

there is not an edge and if

$$\begin{cases} |d_i - d_{i-1}| > \delta \\ |d_{i+1} - d_i| > \delta \end{cases} \quad (6)$$

the measurement is thought to be a disturbance.

3.2 The location of edges

After processing SSD on the above conditions, the next step is to find the SSD's associated with the POE. The angular extent condition is used to test whether the SSD's are associated with the passive edges or not. The simulation of experiments was round out by making use of Nomadic CO.software. The two-dimensional indoor environment around an ultrasonic sensor is represent by a piecewise continuous distance function from the sensor to the surrounding edges. For example, Figure 3a shows a situation in which the mobile robot is located at the center, and the SSD are obtained by rotating the mobile robot a counterclockwise revolution. The distance to the edges within the detection range is shown as a function of the sensor orientation in Figure 3b. In this example, the POE's real positions are marked with a star * .

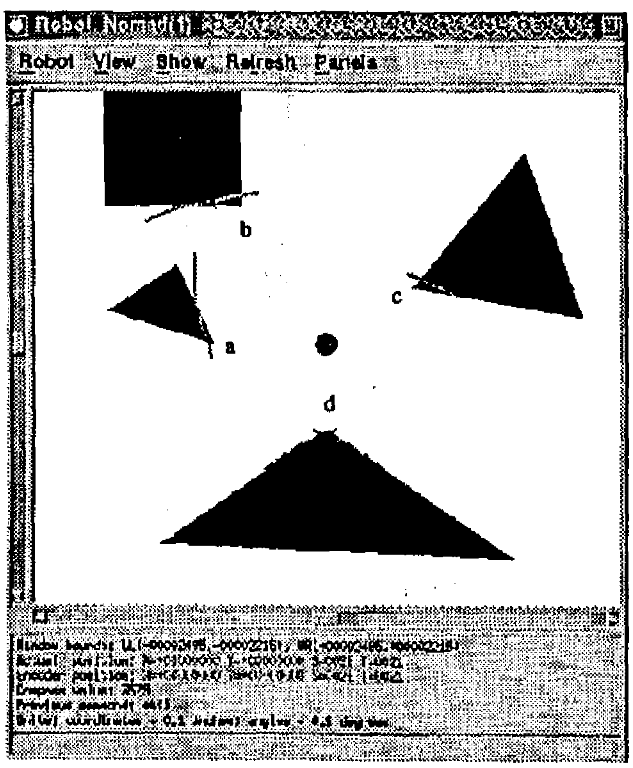

Figure 3a Environment model

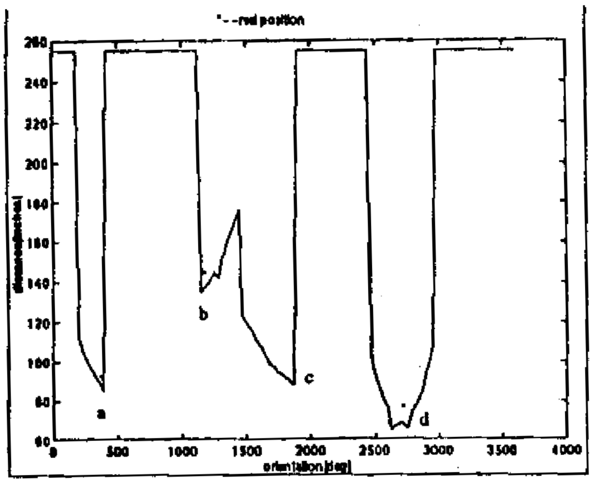

Figure 3b. Distance function from the ultrasonic to surrounding edges

Figure 4a shows the case in which the mobile robot moves through the geometrical shapes with edges along a straight line. The distance to the edges within the detection range is shown as a function of the moving distance in Figure 4b.

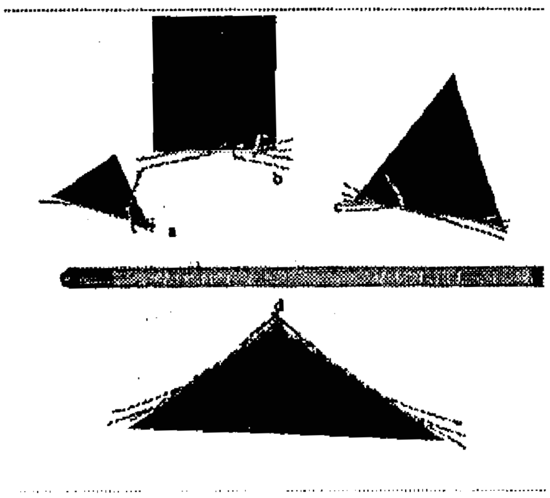

Figure 4a Environment model

From these two examples, it is shown that the mobile robot can recognize edges in its environment, whether it rotates at a point or moves along a straight line. Of course, the recognition process includes at some extent errors. However the errors can be compensated by modifying the parameter in the equation (2).

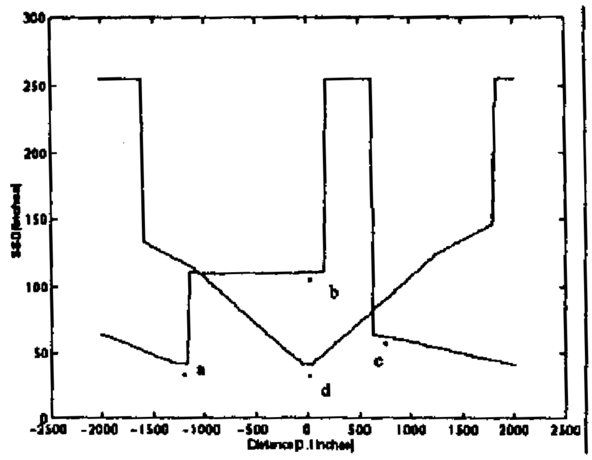

Figure 4b Distance function from the ultrasonic

Some more simulation tests were finished. In these tests, the 90^o angle is set and faced to mobile robot, the mobile robot is moving at different distance and different slant, and then other several angles were also tried. Figure 5a shows the results of simulations when mobile robot moves straightly from distance $15.75cm$ to $200.15cm$ far from the edge. Figure 5b shows the simulation results when robot moves slantingly at 15^o , 30^o ,45^o angle. Figure 5c shows the simulation results when edge is changed from 60^o to 150^o.

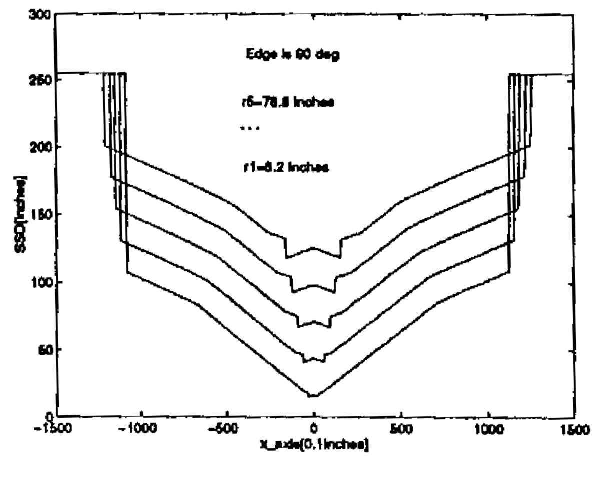

Figure 5a Different distance from edge

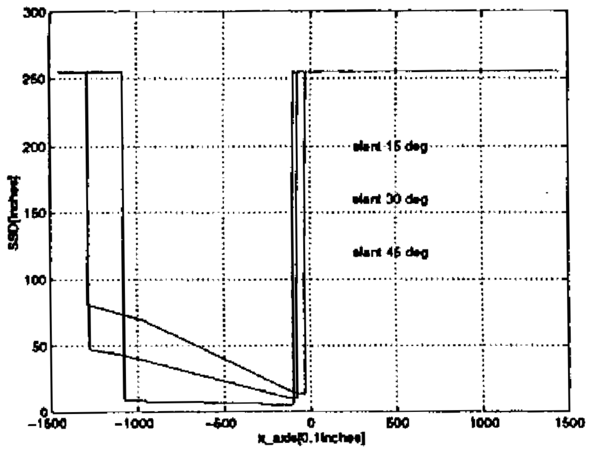

Figure 5b Different slanting

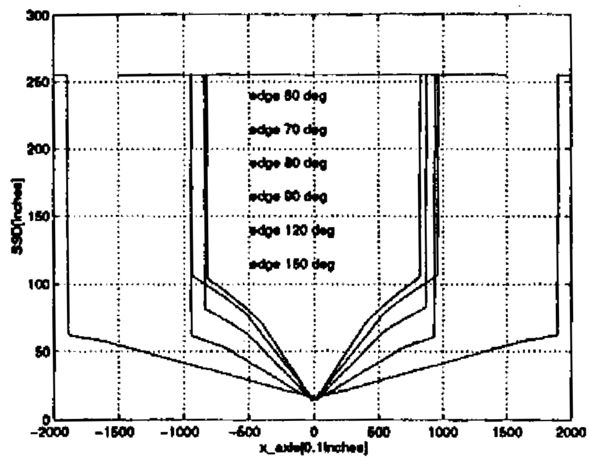

Figure 5c Different edges

From these simulations, it is found that the further the mobile robot is from the edge, the larger the recognizing errors; the more slant, the greater the error, and the POE can be measured effectively only when mobile robot moves perpendicular to the edge. Furthermore POE can be effectively recognized when the smallest angle is larger than 60°.

4. Mobile Robot Localization

As shown in Figure 6a, the coordinates of the two edges, $Edge_L(x_L, y_L)$, and $Edge_R$ (x_R, y_R), are given apriori, and the distance D_c between two POEs can calculate. The sensors mounted to the mobile robot obtain the SSD from two edges one by one. The measured distance between two POE, D_m, can be calculated from the geometric parameters of the triangle.

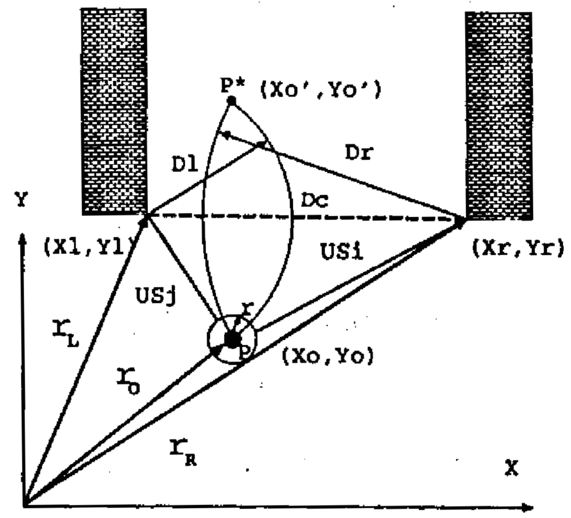

Figure 6a Analytic geometry solution

$$D_m = \sqrt{D_R^2 + D_L^2 - 2D_R D_L cos\phi_{ij}} \qquad (7)$$

D_R and D_L are SSD measured from the $Edge_L$ (x_L, y_L) and $Edge_R$ (x_R, y_R), and ϕ_{ij} is the angle between sonar us_i and us_j. Then, the mobile robot calculates the absolute estimation error between D_c and D_m by

$$Error = \Delta D = |D_c - D_m| \qquad (8)$$

The above estimation error ΔD is calculated for all of the combination of SSD's. Finally at least, there is a pair of measurements which is the smallest error and will be used for localization of a mobile robot. This analysis has been proved by simulations (see Figure 6b~6d). When ΔD is under a specification, the measure is thought to be correct and can be used as a parameter to find the position and orientation of the mobile robot.

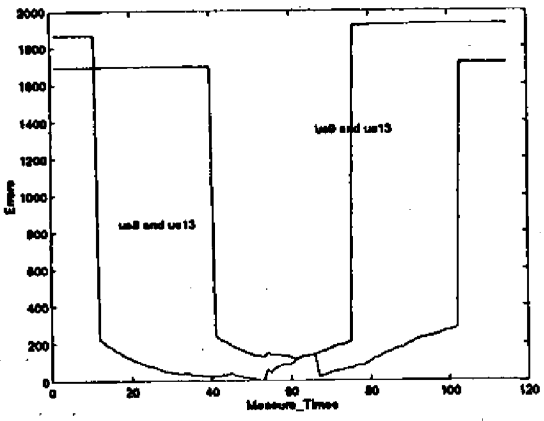

Figure 6b.

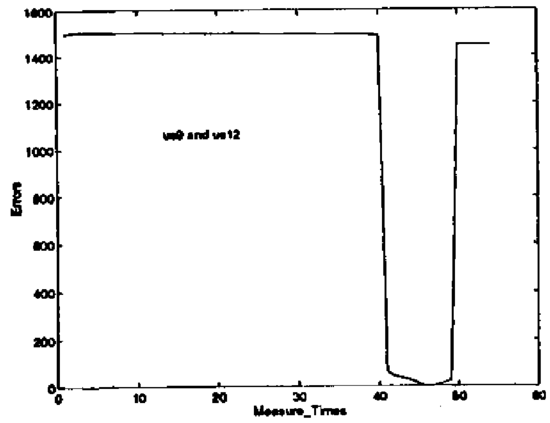

Figure 6c.

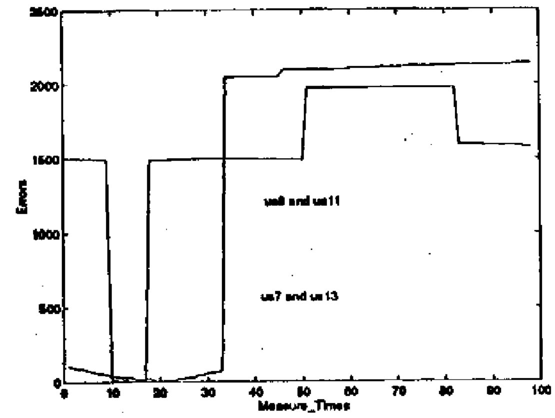

Figure 6d.

On the contrary, if ΔD is larger than an allowable error, we can not determine the position and orientation because we can not obtain accurate SSD from the ultrasonic sensor, and neither are the pair of sonar (us_i, us_j) face to the edges.

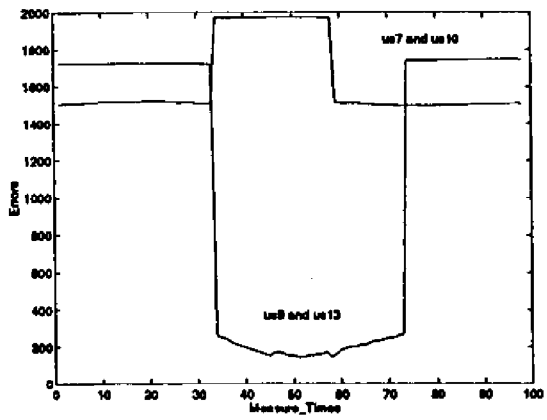

Figure 6e.

Let us consider that the mobile robot is located at an unknown point (x_O, y_O) with respect to the world coordinate frame fixed at point O. The D_R, D_L and Φ_{RL} can be obtained from a sets of SSD's. The mobile robot positions correspond to the intersection points of two circles which are the loci of possible positions corresponding to the measured angle ϕ_{ij} .

Analytic geometry may be used to solve for the common point's (x_O, y_O) and (x'_O, y'_O) of two circles. Here, $D_L = us_j + r$ and $D_R = us_i + r$ (r is the mobile robot radius). The intersection points of two circles are obtained by

$$\begin{cases} \overrightarrow{R_O} = \overrightarrow{R_L} + \overrightarrow{d_L} \\ \overrightarrow{R_O} = \overrightarrow{R_R} + \overrightarrow{d_R} \end{cases} \tag{9}$$

As shown in the Figure 6a, two feature positions, $P(x_o, y_o)$ and $P^*(x'_o, y'_o)$ are determined. One of them is the real position of mobile robot, which can be decided according to the dead-reckoning(x_d, y_d).

$$\begin{cases} \sqrt{(x_O - x_d)^2 + (y_O - y_d)^2} = \delta_1 \\ \sqrt{(x_O^{'} - x_d)^2 + (y_O^{'} - y_d)^2} = \delta_2 \end{cases} \quad (10)$$

In general,comparing the δ_1 and δ_2 , the smaller one is decided to the real position.

5. Experimental Results and Discussions

For experiments of localization of mobile robot, two edges are used in an indoor lobby with flat floor. The lobby is approximately 5.59m by 14.72m as shown in Figure 7a.

The mobile robot was initially located at the origin of the world coordinate frame O (0,0), and the goal position was given as G(5040,1200). In the experiments, two edges set at (3840,-240) and (4560, -720) were utilized to determine the absolute position and orientation of the mobile robot.

The mobile robot equipped with sonar-based navigation system moves from the starting position, towards the goal position while avoiding the obstacle. When the mobile robot detects an edge which we assume as a natural landmark, it moves in the specified localization zones. In general situations, the position and orientation of the mobile robot is unknown. By using the localization algorithm presented above, the mobile robot estimates its current location and orientation as it moves along the planned path. If the localization is successful, the mobile robot updates its posture and present position, correcting its path planning.

Figure 7a and 7b show simulation results without and with an obstacle on its way, respectively. The mobile robot can reach its goal successfully in either case.

6. Conclusions

A mobile robot localization system was developed by using two edges as a pair of landmarks. The proposed method can estimate the position and orientation of the mobile robot using the Sonar Scan Data (SSD) obtained by the ultrasonic sensor. First, the distance errors between the calculation and measurement was estimated to judge whether the measurement is right or not. Secondly, the triangle geometry was to used to estimate the mobile robot's current position and orientation. Using this algorithm, the geometric parameter sets of edges can be accurately obtained and consequently, the position and orientation of the mobile robot can be determined. It is believed that the proposed method is of a potential value in practical, such as moving something in hospital or delivering something in office building.

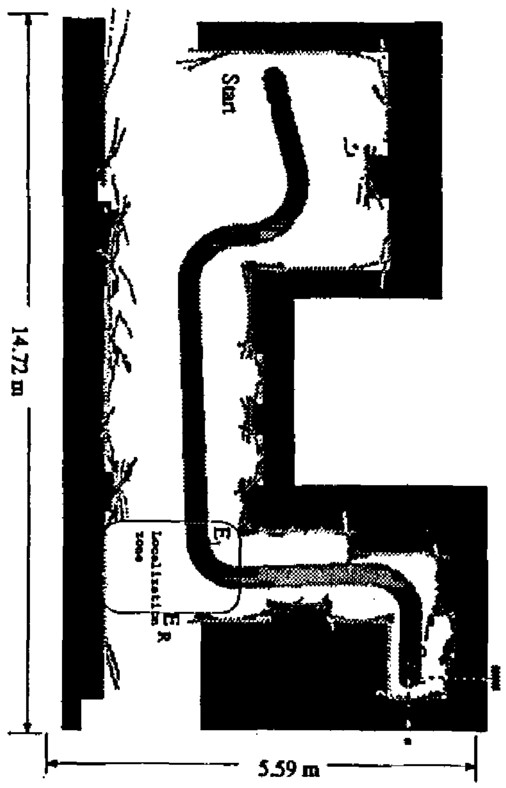

Figure 7a The environment for localization experiments with two edges system

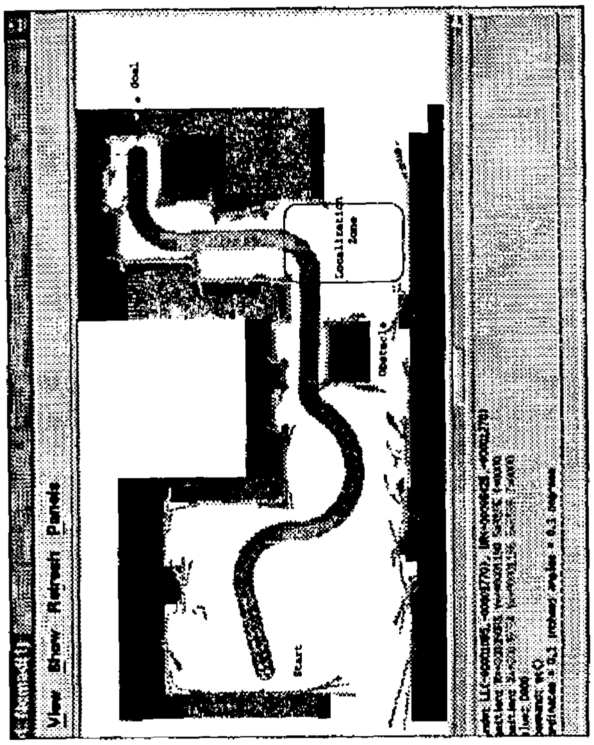

Figure 7b The environment with an obstacle on it's way

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