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単一エッジの参照による移動ロボット位置の実時間推定について

Real-time Estimation of Mobile Robot's Position by Referring an Edge

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Abstract

This paper presents a novel method for estimating the position and orientation of a mobile robot using only sonar range data in an indoor environment. The mobile robot senses the environment with two sonar sensors as it moves, and utilizes the specular characteristics to recognize an edge. By referring to the location of the edge, the robot localizes itself rapidly. The data obtained by sensors at time $t-1$ can be used at time t, and are utilized to get the current position of a mobile robot. The presented algorithms are especially suitable for processing the sonar scan data obtained by ultrasonic sensors with wide beam spread. The validity of the proposed method has been proved by experiments and its performance is also investigated.

1. Introduction

Determining absolute position and orientation of a mobile robot is necessary for long distance navigation in an indoor environment. Because of the cumulative errors in dead reckoning system, the localization is usually performed by referring to the external features. Sonar sensor provides direct range information at low cost and fast processing time, so it has been widely applied to sense these external features. In general, two types of landmarks: "artificial" and "natural" ones, are used for a mobile robot to locate itself. A typical position system, consisting of two passive cylindrical beacons with different diameters, was proposed [1) 2)]. Their method can be used for estimation of the position and orientation of a mobile robot using the sonar scan data obtained by a single rotating sonar sensor. Although artificial landmarks have been proved to be successful in localization field, it is more suitable for a mobile robot to utilize the features that are naturally in the environment.

In the previous study [3)], we proposed an effective mobile robot localization method using a single rotating sonar sensor and two passive geometric elements such as walls, corners and edges that are inherent in the environment. The method does not require additional artificial beacons and offers the advantage of simplicity and low-cost. But it requires at least one pair of geometric elements. Besides that, the robot must stop moving to rotate for finding the geometric elements. It is therefore somewhat inconvenient for a autonomous mobile robot to navigate.

In this paper, we propose a new localization method in which two ultrasonic sensors and one geometric element are used. A mobile robot produced by Nomad Co. has been used to perform this algorithm. According to the ideas of sonar model and target models [4)], assuming the mobile robot moves in a corridor, the response data obtained by sonar sensors will vary with environment. When the robot meets an edge, the response data of nearest sensor in the moving direction will change violently because of specular reflection. At this time, we say that the edge was recognized by the sonar sensor. The robot position is defined as *"recognized point"* and the response data of *sensor* is called as *"critical reading"*. If the coordinate of the edge is known in prior, the current position and orientation of the robot (x_r, y_r, α) can be obtained by utilizing a triangulation algorithm. The underlying principle of the algorithm is that the response data obtained by $sensor_1$ and $sensor_2$ at time $t-1$ can be utilized at time t, as long as the cumulative movement vector is recorded. Positioning accuracy, depending on the geometry of the robot and the landmark, is typically within a few centimeters.

2. Sonar System

In usual indoor environment, the amplitude and speed of sonar wave do not change appreciably with distance comparable to the typical wavelength because the propagation medium of air is fairly homogeneous. Therefore, the sonar beam may be modeled as straight rays, which are the lines perpendicular to the surfaces of constant phase. A model of the sonar sensor range appears in Fig.1. The arc is centered by bisecting it with the central axis of the beam. The radius of the arc corresponds to the range measure R and the width corresponds to twice the beam angle θ_k.

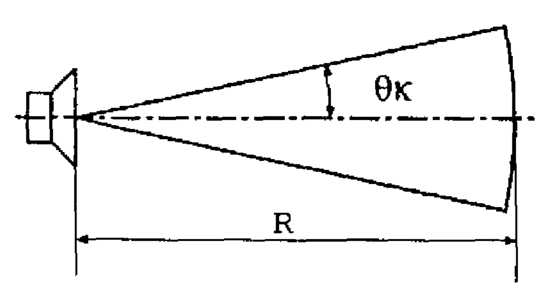

Fig.1 The model of a sonar

In this study sixteen sonar sensors mounted around the mobile robot are used to detect obstacles. The sensors ($sonar_i$; $i = 1, 2, \ldots, 16$) are numbered counterclockwise, consecutively beginning with the front of the robot, the reading of sixteen sonar sensors expressed as us_i; $i = 1, 2, ..., 16$.

The Polaroid transducer 6500 sensor is used both as a transmitter and as a receiver. We confine our discussion to the time-of-flight (TOF) method which measures the distance to an object from the time-of-flight. The distance that can be measured by this transducer is from 6 *inches* to 225 *inches* (about 15 cm ~ 1067 cm), with a typical absolute accuracy of ± 1 % over the entire range [8].

3. Edge Recognition

In this method, two sonar sensors, close to the moving direction, are used to recognize an edge while the mobile robot moves (see Fig.2).

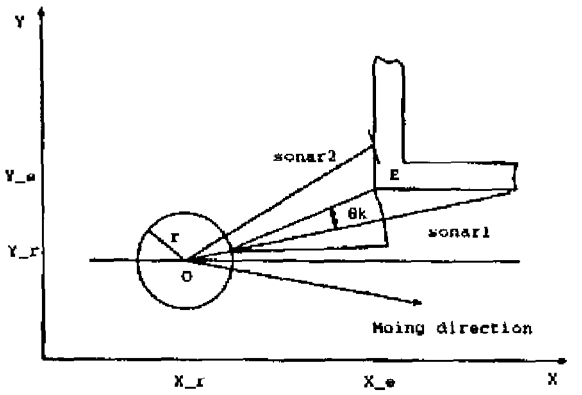

Fig.2 The principle of edge recognition

The sensors named as $sonar_1$ and $sonar_2$ have an interval angle of 22.5^o. The response data obtained by two sensors are expressed as us_1 and us_2, respectively.

The sonar system can detect an object as long as it overlaps and the object is within detectable distance. The detect-ability of an object by sonar further depends on the incident angle of the sensor relative to the normal of the object surface. When the incident angle is larger than a critical value, the object is no longer detectable because the sonar wave is not reflected back to the sensor. As the robot moves towards the edge, the value of response data reduces. When the $sonar_1$ beam is on the outskirts of the edge, the $sonar_1$ axis will hit the other side of the edge, the incident angle will change violently, and the response data will obey the changes. However the $sonar_2$ axis keeps touching in normally and does not have any violent change (as shown in Fig.3). Thus, the edge can be recognized by these two sensors.

To recognize an edge, a single measurement does not provide adequate information regarding the position of a mobile robot, but two consecutive readings taken at different positions can provide an estimation of an edge position. The reading obtained at time $t-1$ can be used at time t, and the data are expressed as us_1^t, us_2^t, $us_1^{t-1}$and us_2^{t-1} in time sequence. These data are then computed and stored when the edge is recognized. The edge is recognized by the following rules:

1. $us_2^{t-1} > us_1^{t-1}$ *and* $us_2^t < us_1^t$,
2. $us_2^t < us_2^{t-1}$ *and* $us_1^t > us_1^{t-1}+\delta$,

where, δ is a constant referring to the edge shape and can be determined experimentally.

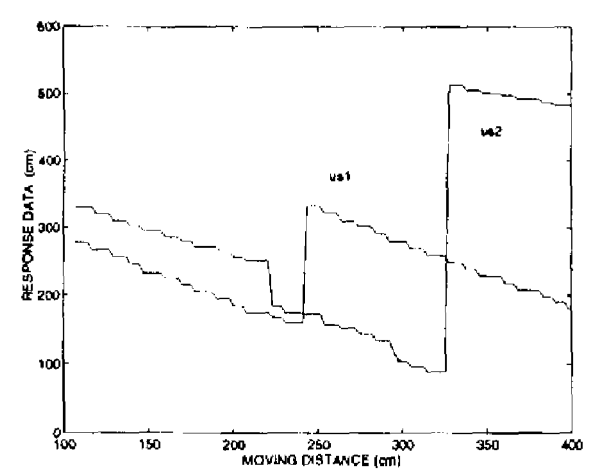

Fig.3 Two response data from an edge

When the edge is recognized at time t, the position of the robot at time $t-1$ is called *recognized point*, the response reading us_1 is called *critical reading* and the angle θ_k is called *critical angle*.

4. Location of Robot

We consider the case that the robot moves at an orientation α with X-axis (see Fig.4). Based on the sonar model of section 2, the value of d_1 and θ_e can be obtained from the triangle OSE,

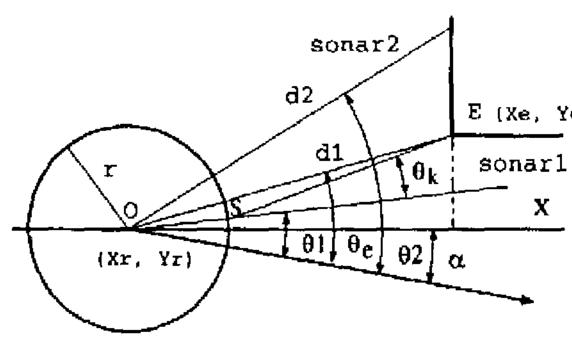

Fig.4 The environment of workspace

$$d_1 = \sqrt{r^2 + us_1^2 + 2rus_1 \cos\theta_k}, \quad (1)$$

$$\theta_e = \theta_1 + \arccos\frac{d_1^2 + r^2 - us_1^2}{2rd_1}, \quad (2)$$

where d_1 is the distance from the center of the robot to the feature point of the edge; r is the mobile robot radius; θ_e is the angle between d_1 and the direction in which the robot moves; θ_1, the angle between *sonar*$_1$ axis and the direction in which the robot moves, equals 22.5°.

In general, for localizing a mobile robot, the key point is to get the value of θ_k. From equations (1) and (2) we have that, if the parameter θ_k is known, the value of d_1 and θ_e can be obtained when the *critical reading* us_1 is obtained from *sonar*$_1$. Unfortunately, θ_k is not provided by the sonar system directly, besides, it is not a constant and it changes depending on the different measurements[8]. So, we present another way to seek for the value of θ_e instead of θ_k. Considering that the values of d_2 and d_1 have the same projection in the direction of X-axis, we have that

$$d_2 \cos(\theta_2 - \alpha) = d_1 \cos(\theta_e - \alpha), \quad (3)$$

where d_2 is a datum associated with the reading of *sonar*$_2$ ($d_2 = r + us_2$), α is the orientation of the robot moving. We assume θ_2, the angle between *sonar*$_2$ axis and the direction in which the robot moves, equals 45°, according to the physical analysis. The value of θ_2 will be proved by simulation experiments shown later.

In equations (1) ~ (3), there are four parameters, α, θ_e, θ_k and d_1, which are unknown. It is clearly that we cannot determine those four parameters from (1) ~ (3). So, we first assume that the robot moves in the direction of X-axis ($\alpha = 0$). Then, combining the equations (2) and (3), finally we obtain the following equation,

$$d_2 \cos\theta_2 = d_1 \cos[\theta_1 + \arccos\frac{d_1^2 + r^2 - us_1^2}{2rd_1}]. \quad (4)$$

Theoretically, it is possible to obtain the value of d_1 from the Eq.(4). Since the Eq.(4) is a nonlinear algebraic equation, we use a sequential search to find the proper value of d_1 ($us_1 < d_1 < us_1 + r$), and obtain the value of θ_e from Eq.(2). If the coordinate of edge (x_e, y_e) is known in advance, the position and orientation of robot at time $t-1$ can be obtained easily as

$$\begin{cases} x_r^{t-1} = x_e - d_1 \cos\theta_e, \\ y_r^{t-1} = y_e - d_1 \sin\theta_e, \\ \alpha = 0. \end{cases} \quad (5)$$

Later, the value of θ_e will be shown to be nearly constant by simulation experiments in the case when $\alpha = 0$. Based on these results, we anticipate that even in the case when $\alpha \neq 0$, the value of θ_e may be nearly constant. That also will be shown by simulation experiment presented later. Now, if θ_e is regarded as a constant, d_1 can be found readily.

So, in the case when $\alpha \neq 0$, the robot location at time $t-1$ can be obtained as follows

$$\begin{cases} x_r^{t-1} = x_e - d_1 \cos(\theta_e - \alpha), \\ y_r^{t-1} = y_e - d_1 \sin(\theta_e - \alpha), \\ \alpha = \arctan \frac{d_1 \cos\theta_e - d_2 \cos\theta_2}{d_1 \sin\theta_e - d_2 \sin\theta_2}. \end{cases} \quad (6)$$

The current location of the robot can be estimated now from Eq.(6) as

$$\begin{cases} x_r^t = x_r^{t-1} + v\delta t \cos\alpha, \\ y_r^t = y_r^{t-1} + v\delta t \sin\alpha. \end{cases} \quad (7)$$

where δt is a time step between time t and time $t-1$, and v is the speed of the robot.

5. Simulation

Concerning the validity of the proposed method, we note that the recognized point can not be judged accurately as the robot moves continuously. This problem is considered in a simulation environment with a simulator which is developed by the Nomadic software Co. This simulator models the real robot's basic motion and the sensor systems. It provides an elaborate graphic interface and simulation capabilities. The simulated robot responds to the same set of commands as the real robot has. We can run the simulator as a separate process on a workstation.

In order to simulate the localization accurately, the parameters in the setup file should be set the same as those for the real sonars. Here, the interval between two firings, named as firing rate, is set to 0.004 sec; the minimum and maximum distance are set to the range of real Polaroid 6500 ranging; the angular range of main lobe of the sonar named as half-cone is set to 12.5°; the maximum angular difference between the sonar axis and the normal of the surface for the sensor to return a value named as critical is set to 60°; the absolute random error factor, expressed as a percentage of real value, is set to 0.01 as the real sonar's.

Firstly, in the simulator, the robot is ordered to move from the start towards to an edge, and kept in the direction that parallels the X-axis ($\alpha = 0$). An edge is located at the position (548, 60). When the robot recognizes the edge, it stops and records the response data us_1, us_2 and the coordinate of recognized point. It calculates parameters such as d_1, θ_k and θ_e based on the Eq.(1) $\sim$ Eq.(4), and then localizes itself. We let the robot do the same performance repeatedly from the starting point (0,y), and change the vertical coordinate y from 10 cm to 100 cm at a constant step, as the absolute value of y increases, the relative position between robot and the edge varies, the coordinate of the recognized point also varies.

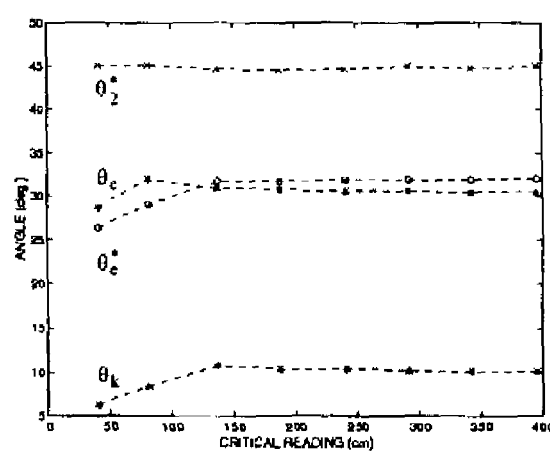

Fig.5 The angles of measurement

In addition we define θ_e^*, the angles between d_1 and X-axis, and θ_2^*, the angles between d_2 and X-axis. In the case of $\alpha = 0$, we have that $\theta_e^* = \theta_e$, $\theta_2^* = \theta_2$, respectively. These parameters can also be obtained by the dead-reckoning system

$$\begin{cases} \theta_e^* = \arctan \frac{y_e - y_r}{x_e - x_r}, \\ \theta_2^* = \arccos \frac{x_e - x_r}{us_2 + r}. \end{cases} \quad (8)$$

where the (x_e, y_e) and (x_r, y_r) are coordinates of the edge and the robot position, respectively. As the starting point varies, the relation position between the robot and the edge changes, so that the *critical reading* us_1 alters. The values of θ_k, θ_e, θ_e^* and θ_2^* are shown in Fig.5.

From the simulation results the value of θ_2^* is approximately 45^o. This is consistent with the physical angle of $sonar_2$ axis. The value of θ_k is within 12.5^o, which also consists with the theoretical model of sonar. The value of θ_e obtained by sensor measurement and the value of θ_e^* obtained by dead-reckoning system are approximately equal and constant when the *critical reading* is larger than 100 *cm*. This is because that, in the triangle OSE, when the value of us_1 is far larger than r ($us_1 >> r$), the angle between the d_1 and the $sonar_1$ axis is no more increase, practically.

In the simulation environment, there is neither noise nor invalid range readings. Also, there is no wheel slip. Thus the environment is regarded as an ideal environment, and the estimation of dead-reckoning is regarded as the real value of robot position. The estimations of recognized point obtained from sonar and from dead-reckoning system are shown in Fig.6. The errors between two estimations are caused due to the randomness factor of the sensed distance for sonar is taken into account by the simulator

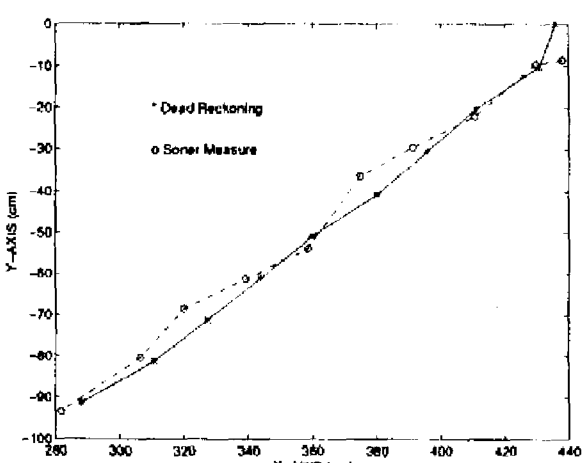

Fig.6 The principle of edge recognition

Secondly, the robot moves with an orientation angle α and starts from point (0,y). The simulation was performed with changing the orientation angle α and the vertical coordinate y. α is altered from 0^o to 20^o at a step about 2^o, at each step, the absolute value of y is varied from 10 *cm* to 100 *cm* at a constant step. Then, the relative position between robot and the edge are changed. The robot recognizes the edge under each condition and obtains the parameters needed for localization. The results are shown in Fig.7. During the simulation, θ_2^* and θ_e^* obey the changes of α. In Fig.7, their are expressed as θ_{2i}^*, θ_{ei}^* and α_i, respectively.

From the simulation results, we know that while α_i alters, the sum of the θ_{ei}^* and α_i keeps at a constant value θ_e. Also, the sum of θ_{2i}^* and α_i keeps at a constant value θ_2. The same value data of α_i, in the Fig.7, comes from the measurements as the robot moves from the different starting points. These parameters satisfy the following relation approximately

$$\begin{cases} \alpha_i + \theta_{ei}^* = \theta_e, \\ \alpha_i + \theta_{2i}^* = \theta_2. \end{cases} \tag{9}$$

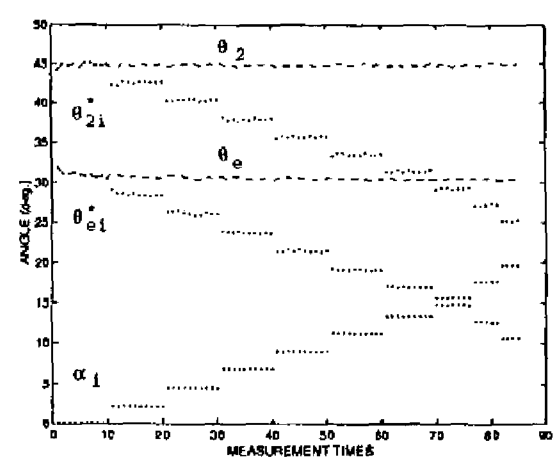

Fig.7 Different orientation measurements

Practically the value of angle θ_e does not vary with the orientation angle of the robot and the starting point of the robot.

Finally, the robot is ordered to move toward an edge with different orientations. As the robot recognizes the edge, it localizes itself by referencing to the location of the edge, then,using this estimation it updates its current value of dead-reckoning. Under the guidance of dead-reckoning system, the robot reaches the designed location.

The coordinates of edge and the goal are given in advance. The robot localizes itself utilizing the proposed method. This simulation was performed three times at various orientation angles ($\alpha = 0^o$, $\alpha = 4.5^o$, $\alpha = 11.2^o$). All of the estimations were successful. When the robot reaches the goal point, the errors between the reached point and absolute coordinate, are shown in Fig.8. The maximum error here is within ten centimeters. Therefore, the proposed algorithm has been proved to be valid by simulation.

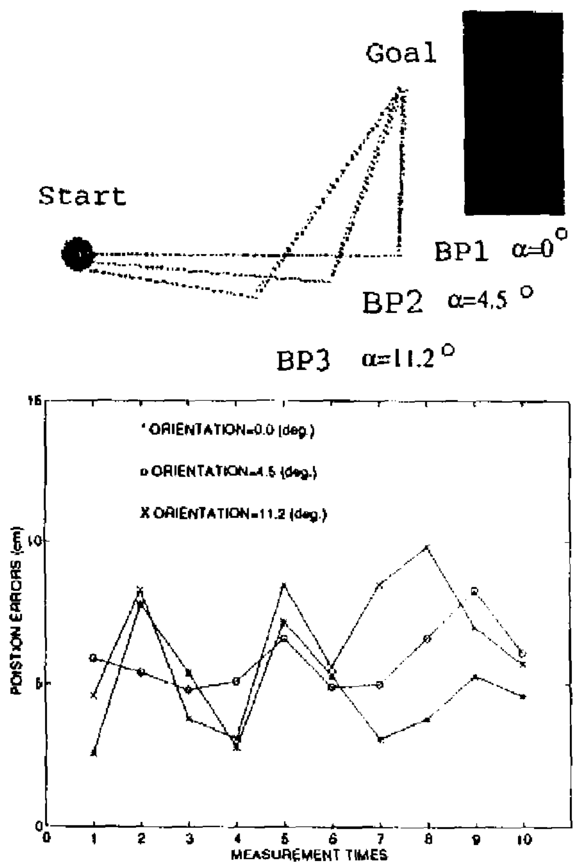

Fig.8 The principle of edge recognition

By the proposed method, the robot can localize itself smoothly. But what is the orientation range is a problem to be considered. Now let the robot navigate with an orientation α, where α is increased from 0 to 18^o with clockwise and counter-clockwise, respectively. Let us estimate the robot's position and orientation using Eq.(6). It is fined that when the value of α is bigger than 15^o, the errors increase violently (see Fig.9). Therefore, we can say that the range of localization is within about $\pm 15^o$. This is because that the maximum angle between the sonar axis and the normal of the surface is 60^o. The physical angle of $sonar_2$ axis is 45^o, so that the orientation of robot can not exceed 15^o. Otherwise, if the incident angle is larger than the *critical angle*, the $sonar_2$ will obtain unreasonable data.

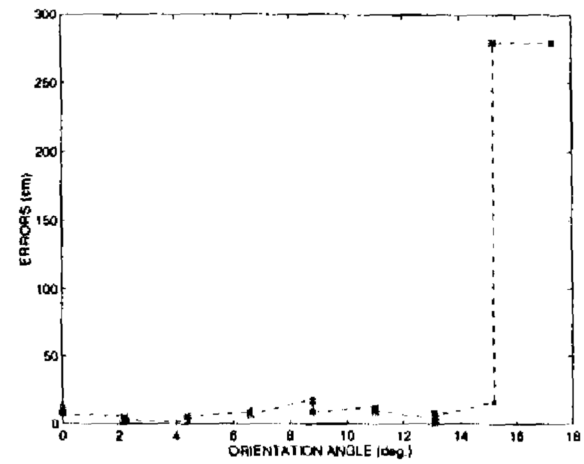

Fig.9 The range of the recognization

6. Experiments

The algorithm described above has been tested not only by simulation but also in a real environment. Since the robot moves continuously in the real environment, it is inconvenient for us to measure the parameters, such as coordinate of *recognized point* in time. The robot recognizes the edge at time t but the parameters are acquired at time t-1. Therefore, we can't directly judge whether the estimation is successful or not only by simple measurement.

As a typical example, the edge recognition experiment was performed first. The robot moves at a speed of 76.2 cm/sec from the starting point A, B, C and D (the coordinates are shown in table 1), towards the edge with different orientations. When the robot distinguishes the edge, it stops and localizes itself. We measure the real robot's position, and compare the estimation location with the real one. The results are shown in table 1.

Table 1 : Recognizing an edge

	SP	α	EP	RC	Er
A	(412, 87)	0.94°	(167, 91)	(178, 101)	14.8
B	(412, 52)	1.44°	(113, 60)	(127, 71)	17.8
C	(412,40)	3.46°	(98, 59)	(120, 61)	22.1
D	(412, 46)	6°	(160 72)	(178, 79)	19.3

SP: Starting Point (cm); EP: Estimating Point(cm); RC: Real Coordinate(cm); Er: Errors (cm).

There are some errors in the artificial measurement, main of them are caused by inertia. That is, the robot does not "know" when and where it will recognize an edge, it keeps a moving by inertia when it is required to stop. Really, the measure point includes the overlap distance which is difficult to estimate. Although we consider the distance of $\Delta s = v[t-(t-1)]$ in the above measurement, the experiment above may not be accurate because we are not able to estimate the movement caused by inertia. However, these experiments can be considered valid to prove that the robot can in fact recognize the edge successfully.

Second, the robot is ordered to move without stopping until it reaches the goal point. As a real environment, a lobby environment was used as the mobile robot's workspace, as shown in Fig.10. The edge's position with respect to the world coordinate frame was known in prior.

The E_2 edge's feature point was chosen as the world coordinate frame X-Y 's origin. The robot moves straight from the starting point. Utilizing the $sonar_5$, the robot recognizes the edge E_1, it turns and then, moves towards the another edge E_2 by the guidance of dead-reckoning. Assuming that the robot may lose its way near the edge E_2, the edge E_2 was used as a landmark, whose position with respect to the world coordinate frame was known in beforehand. The robot could estimate its location using the proposed algorithm while it moves towards the edge, then, update the dead-reckoning with the value estimated and reaches the goal by the guidance of dead-reckoning system. Here, the goal's coordinate is known in advance. For the navigation, from recognized point to the goal point, the path is planned as Eq.(10). The speed of the robot will be continuous decreased as the robot close to the goal. Finally, the robot stops at the goal point smoothly and without inertia.

$$\begin{cases} orientation = \arctan \frac{y_g - y_r}{x_g - x_r} \\ length = \sqrt{(y_g - y_r)^2 + (x_g - x_r)^2} \end{cases} \qquad (10)$$

where the (x_g, y_g), (x_r, y_r) are goal and recognized point coordinate, respectively.

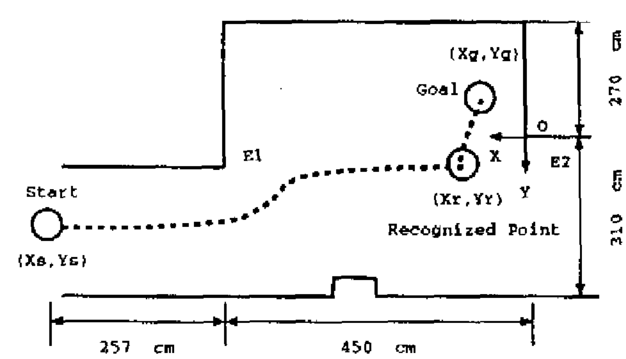

Fig.10 The environment of experiment

In the experiment, the goal coordinate was (100, -100) in the world frame, the robot stopped at the position (113, -104). If the error of short navigation in the dead-reckoning system is neglected, the error of reaching the goal will be regarded as the error of the estimation. Here, the absolute estimation error is about 14 cm.

This experiment was also performed only using the dead-reckoning system. When the robot recognized the edge, the localization is dependent upon the current estimation of dead-reckoning. Finally the robot reached at position (125, -130). The absolute estimation error is about 39 *cm*.

7. Discussions and Conclusions

A mobile robot localization method has been developed by using only the sonar response data. With this method the specular feature is used to recognize an edge as a landmark. By referring to the location of the edge, the robot's position is estimated conveniently.

Using this algorithm, the position and orientation of the mobile robot can be determined rapidly, and easily. The validity as well as the performance of the proposed methods were shown through the experiments in which a mobile robot is located in both the simulation and a real environment.

The main purpose of this study is to reduce the errors existing in the dead-reckoning estimate. It can be not only economically implemented but it can be also used to locate robot quickly. Moreover, it is not necessary for the mobile robot to stop moving while detecting a geometric element. With this method, accurate navigation is possible throughout a large area, although error sensitivity is a function of the point of observation.

Further efforts are needed to improve the accuracy of the proposed method, for example, using Kalman filter to cover the errors of localization. It is, however, believed that the method is of a potential value in practice, such as moving patients in hospitals or delivering luggage in office buildings.

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