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赤外線と超音波センサの融合による移動ロボットの精密軌道推定

Precision Trajectory Estimation of a Mobile Robot with Infrared and Sonar

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Abstract

In this paper, a method for estimating long distance navigation of a mobile robot, by fusing dead reckoning and the landmark detection sensor which consist of sonar and infrared, is proposed. A corridor with interval convex edges is applied as the mobile robot's moving space, and the convex edges are accepted as good landmarks for robot's position estimation. The robot detects the convex edges using combining sensor system, and navigates in this corridor by using the information from the combining sensor. The experimental result has shown that the method is effective for estimating of long distance navigation of the mobile robot.

1. Introduction

A lot of the work in the field of mobile robot navigation has been conducted so far only in laboratory environments[1]. The question is how these systems will scale up when faced with more complex environments covering longer distance[2]. Some methods for navigating in this case have been proposed, one of them is called "wall following"[3]. But assuming an environment, such as a big hall, where there is no wall to follow but only pillars which have a shape of convex edge, the robot has to regard these convex edges as landmarks for its navigating.

In this paper, a mobile robot with a combining sensor system (sonar and infrared) is used in a real environment, which is called "long distance navigation". We are interested in the long distance navigation of an autonomous mobile robot, such as a corridor in the building. In the corridor environment, a convex edge is a special type of landmark that can be reliably observed by combining sensor measurements. Moreover, the convex edges are stable, and natural environment features so that they are useful landmarks for robot navigation.

This paper is divided into three parts: the first part is about a way of detecting convex edges using combining sensor system mounted on a mobile robot body; the second part describes a method for robot navigating in corridor by fusion of dead reckoning and convex edge detection sensor; the last is discussion on experimental results of navigation with a mobile robot.

2. Modeling the Sensors

Generally speaking, the robot can always determine its current position and orientation by dead reckoning. However, it is impossible to navigate long distance because the errors of position by dead reckoning are accumulating gradually. Therefore, to navigate for a long distance, the robot must be able to modify its own estimated position by external sensors. Two types of sensors, sonar and infrared are usually used to obtain external information for mobile robot. In order to determine the best way to fuse information from combining sensors, we need a characterization of the strengths and weaknesses of each other.

2.1 Sonar features

In this study, the sonar range finder is capable of measuring distance to an object with a resolution of 2.54 *cm* through a range of 15.24 *cm* to 647.7 *cm*. This is accomplished by measuring the time of flight between a transmitted pulse and a returned echo and multiplying by the speed of sound. the sonar sensor has a large beam width, a specular reflections on smooth surfaces, and is influenced by temperature and humidity, it can be used to measure the distance from a convex edge, but the obtained result has poor angular resolution due to its feature above[4]. The main features of sonar sensor are

firing rate = 0.004 sec
minimum distance = 6.0 inches
maximum distance = 255.0 inches
half cone = 12.5 deg
critical = 60.0 deg

The sonar used here has a typical absolute accuracy of 1 percent over the entire range.

2.2 Infrared features

In contrast, infrared sensor emits a plus of near-infrared light and then uses a parabolic dish and a near-infrared detector to sense any returned energy, over a very narrow area. Unlike sonar, the time of flight of light plus can not be easily measured. The sensor merely indicates whether any returned plus was detected. So the infrared sensor is not able to measure distance accurately, but has good angular resolution in detecting the feature point of convex edge. The measurement of infrared sensor is influenced by some factors, such as geometry, lighting, color and surface[7]. Therefore, the data of measurement can not be used as the distance information. The main features of infrared sensor are

calibration = 0 20 ... 300 320

dependency = 0

half cone = 10.0 deg

incident = 0.05

The environment in which the robot is working is white painted wall. The infrared respect feature is shown as Fig.1.

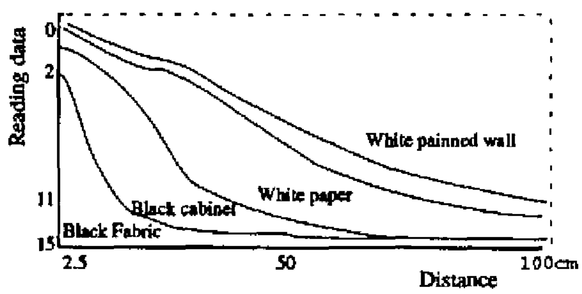

Fig.1. The response data from the different environment

2.3 Convex edges recognition

It is important how a convex edge can be detected by combining sonar. Let's denote feature of convex edge as the POE (Peak Of Edge). According to the feature of Time of Flight system, the POE can be detected in the rang of AOB(see the Fig.2).

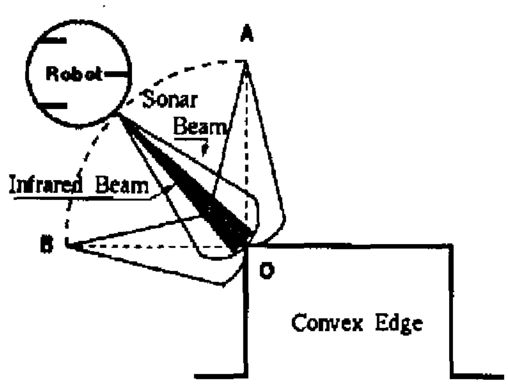

Fig.2. Fusing of sonar and infrared detecting rang

Consequently, if the robot is not within this range, the real convex edge become very hard to locate. In this range, though the robot can get the distance information from POE to itself, it is difficult to determine robot's position even if the location of POE is a prior known number. The robot's position can not been obtained directly. However, the robot is expected to be located on the circumference of a circle which has radius r and a location center O. Then if the robot's location on the circumference is fixed, the orientation of the robot become unique.

Here as an example, the robot is positioned in front of a convex edge and rotated with an angle, the response data from two sensors are shown in Fig.3. It is found that the information of convex edge can be got from the sonar for distance and from the infrared for the direction, respectively.

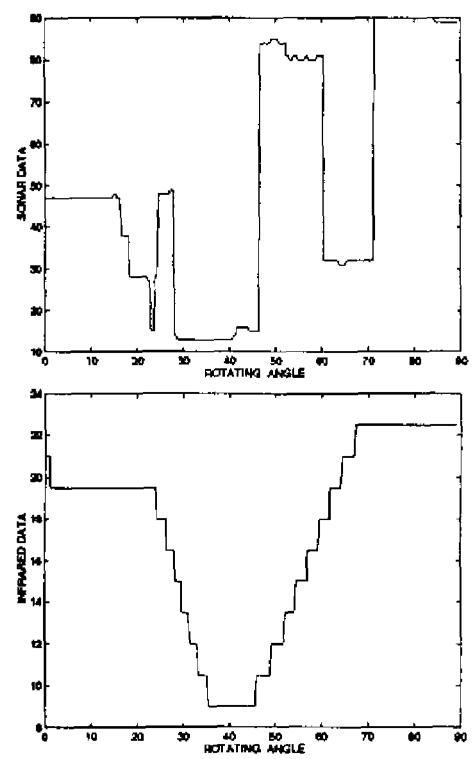

Fig.3. Sensor's response data from a convex edge

Then, it comes that how the sensors distinguish the convex edge from the others objects. The experiment has been done to prove that sonar can not tell apart an edge from a pole. When the pole (with an diameter 5 cm) and edge are set in same place, the response data from the sonar are so similar that it is difficult to tell them (see Fig,4). Quite the contrary, the infrared sensor can easily distinguish them by different response data (see Fig.5).

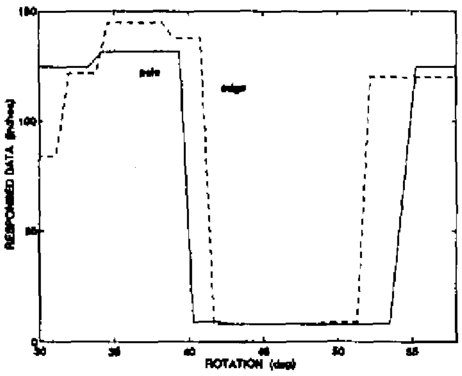

Fig.4 Sonar's response data

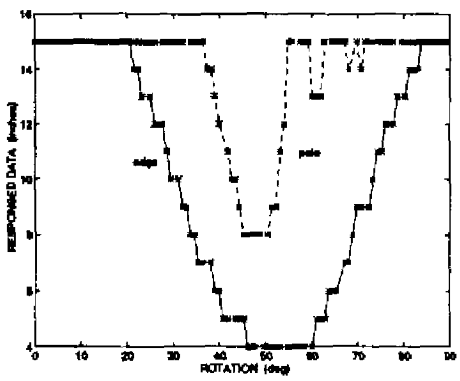

Fig.5 Infrared's response data

2.4 Combining data from sonars and infrared

By using both sensors, the robot is able to estimate its position more accurately by itself[4]. Comparing two response data of sensors shown in Fig.3, the infrared's one has a good angular resolution and stable minimum, so infrared's direction is selected as the combined sensor's direction.

A series of experiments have been performed in order to find a way to compensate the recognizing method based on the combining sensors. Firstly, the minimum of sonar measurement is regarded as the distance from robot to *POE* according to the feature of Time of Flight system. Secondly, the direction in which the infrared sensor gets the minimum is regarded as the direction of the POE. Infact, the data of direction is not unique because of sensor's beam width. Considering the experimental characteristics, the mean value of direction data is regarded as valid direction.

3. The Estimation of Trajectory

As shown in Fig.6, the mobile robot is assumed to move at all time on the horizontal X, Y-plane, the ground-plane. The robot's position and oretation are specific by the coordinates (x, y, θ), where x, y are the world-frame coordinates of the robot body's center, and θ is the robot's orientation relative to the world X-axis. The robot-centered frame $X'O'Y'$ is defined to have its origin on the ground plane directly under the robot center, with the X'-axis pointing to the front of the robot, Y'-axis to the right. r is the distance from robot to the POE of convex edge and α is the angle between r and X'-axis.

At the starting point, the robot's location in the world frame is defined to be $x = 0, y = 0, \theta = 0$, and the world frame coincides with the robot frame.

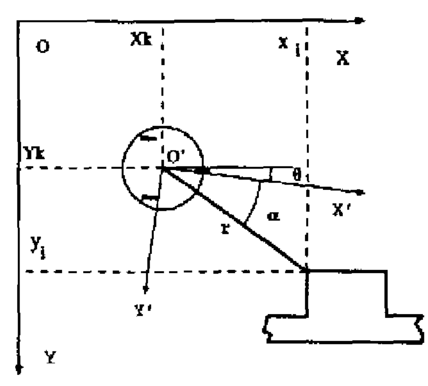

Fig.6. Configuration of convex edge and robot

3.1 System modeling

The system is modeled as a discrete time system, the position and orientation of the mobile robot at time step k is denoted by the state vector; $\mathbf{x}(k) = [x(k) \quad y(k) \quad \theta(k)]^T$ comprising a Cartesian location and a orientation defined with respect to a global coordinate frame. During a period ΔT, the system modeling is updated as

$$\begin{pmatrix} x(k+1) \\ y(k+1) \\ \theta(k+1) \end{pmatrix} = \begin{pmatrix} x(k) \\ y(k) \\ \theta(k) \end{pmatrix} + \begin{pmatrix} \Delta T v(k)\cos(\theta(k)+\alpha(k)) \\ \Delta T v(k)\sin(\theta(k)+\alpha(k)) \\ \alpha(k) \end{pmatrix}. \tag{1}$$

The robot's state $\mathbf{x}(k)$ changes with time in response to a control input $\mathbf{u}(k)$ and a noise disturbance $\mathbf{w}(k)$. The state translation equation can be briefly expressed in general

$$\mathbf{x}(k+1) = \mathbf{f}\,[\mathbf{x}(k) \quad \mathbf{u}(k)] + \mathbf{w}(k), \tag{2}$$

where, $\mathbf{x}(k)$ is the state of the system at time step k, $\mathbf{u}(k) = [\,v(k) \quad \alpha(k)\,]^{\mathrm{T}}$, represents external input to the system, here, $\alpha(k)$ and $v(k)$ are the steering angle and the velocity of the driving wheel. $\mathbf{w}(k)$ is an additive zero-mean process noise and is defined by the covariance matrix $\mathbf{Q}(k)$. $\mathbf{f}$ is the state transition matrix, which relates the state at time step k to the step $k+1$, and includes such parameters as driving function $\mathbf{u}(k)$.

3.2 Estimation error using the dead reckoning

For Eq.(2), there are errors in estimating the state of the robot at each time step. The errors arise from the fact that the dead reckoning measurements from the wheels are imperfect and wheels slippage. Let $\hat{\mathbf{x}}(k)$ is the estimated value of $\mathbf{x}(k)$, $\Delta\hat{\mathbf{x}}(k)$ is the errors of $\hat{\mathbf{x}}(k)$, $\hat{\mathbf{u}}(k)$ is the measured value of $\mathbf{u}(k)$, and $\Delta\hat{\mathbf{u}}(k)$ is the errors of the $\hat{\mathbf{u}}(k)$. Then

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{f}\,[\hat{\mathbf{x}}(k)+\Delta\hat{\mathbf{x}}(k) \quad \hat{\mathbf{u}}(k)+\Delta\hat{\mathbf{u}}(k)] + \mathbf{w}(k) \\ &\cong \mathbf{f}\,[\hat{\mathbf{x}}(k) \quad \hat{\mathbf{u}}(k)] + \mathbf{J}_1(k)\Delta\hat{\mathbf{x}}(k) \\ &\quad +\mathbf{J}_2(k)\Delta\hat{\mathbf{u}}(k) + \mathbf{w}(k) \\ &= \hat{\mathbf{x}}(k+1) + \Delta\hat{\mathbf{x}}(k+1), \end{aligned} \tag{3}$$

the errors in dead reckoning increase as

$$\Delta\hat{\mathbf{x}}(k+1) = \mathbf{J}_1(k)\Delta\hat{\mathbf{x}}(k) + \mathbf{J}_2(k)\Delta\hat{\mathbf{u}}(k) + \mathbf{w}(k), \tag{4}$$

where,

$$\mathbf{J}_1(k) = \frac{\partial \mathbf{f}}{\partial \mathbf{x}}(\hat{\mathbf{x}}(k), \hat{\mathbf{u}}(k)),$$
$$\mathbf{J}_2(k) = \frac{\partial \mathbf{f}}{\partial \mathbf{u}}(\hat{\mathbf{x}}(k), \hat{\mathbf{u}}(k)).$$

By the concept of the error ellipsoid[6], we can know about degree of the estimation accuracy.

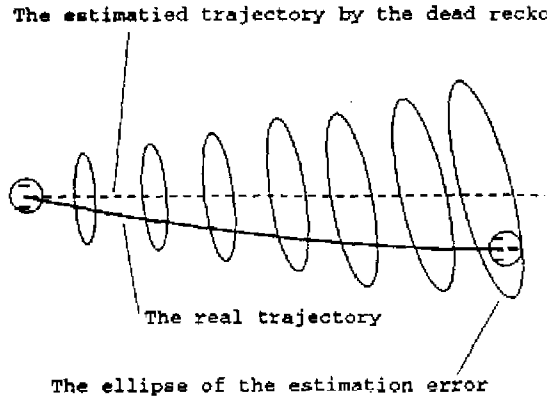

Fig.7. Estimation error using the dead reckoning

Figure.7 shows the simulated trajectory of robot and estimated one by the dead reckoning and error ellipsoid on XY plane. The result shows the estimation uncertainty of the dead reckoning system increases as robot moves. So that it is impossible for a robot to navigate for long distance if it only relies on a dead reckoning system.

3.3 Estimation using sonar sensors

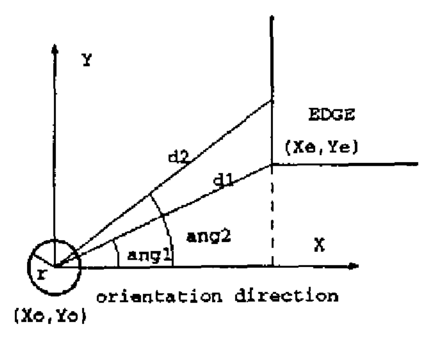

Fig.8. The orientation of robot and X-axis are overlap

A method with which the robot's position estimated from dead reckoning is found. The position estimated can be corrected by the measurements made by combining sensor.

Firstly, let's consider the case that the robot is moving in X direction (see Fig.8), the combining sensor pick out an edge in front of it, the relationship between the edge and robot is,

$$\begin{cases} (d_2 + r)\cos ang_2 = x_e - x_o \\ (d_1 + r)\cos ang_1 = x_e - x_o. \end{cases} \quad (5)$$

in which, ang_2=45 deg., ang_1=29.89 deg.

These parameters do not change with the orientation of robot.

Secondly, let's consider the robot moves straightly at different orientation which is shown in Fig9.

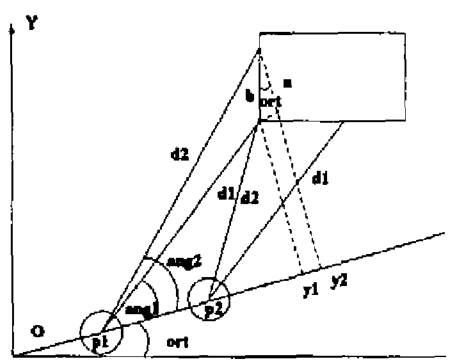

Fig.9. The robot moving with an angle

The Geometric relationship is gived as

$$\begin{cases} a = d_2\sin(ang_2) - d_1\sin(ang_1) \\ b = \sqrt{d_1^2 + d_2^2 - 2d_1d_2\cos(ang_2 - ang_1)} \\ ort = \arccos(a/b). \end{cases} \quad (6)$$

By these equations it is convenient to estimate the position of robot current point(if the coordinates of edge is known before head).

A simulation was been done as shown in Fig.10. The robot moves along direct lines in different orientation to obtain the data for Eq(7). the result is shown as Fig.11.which is marked with *.

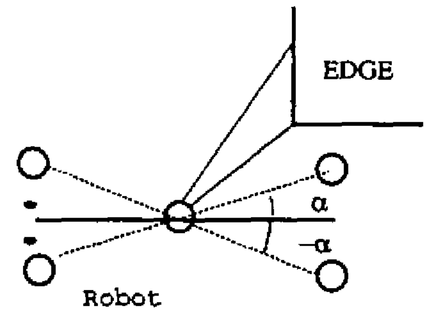

Fig.10. Simulation on different orientation

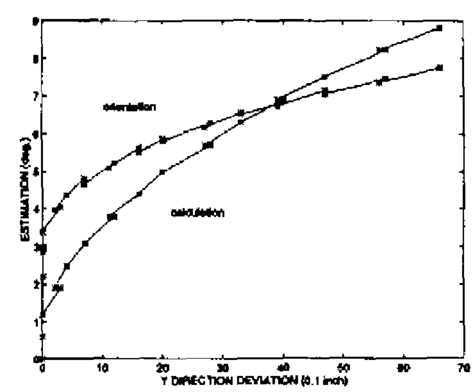

Fig.11. Orientation and estimation (ort ≥ 0)

Then, using the compensation equation

$$y = k_1 * x + k_2 \quad (7)$$

in which,

$ort \geq 0$, k_1=165.713, k_2=-43.8051

$ort \leq 0$, k_1=198.746, k_2=3464.72

The compensated result can be gotten accurately (shown in Fig.12).

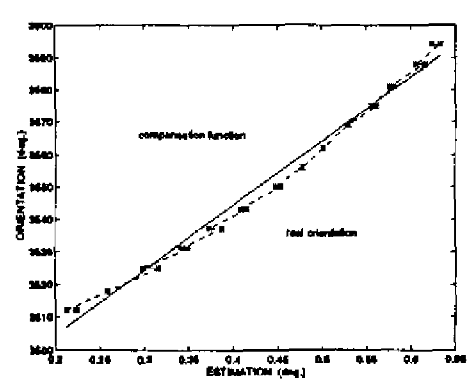

Fig.12. Compensation line ($ort \geq 0$) and ($ort \leq 0$)

3.4 Estimation using infrared sensors

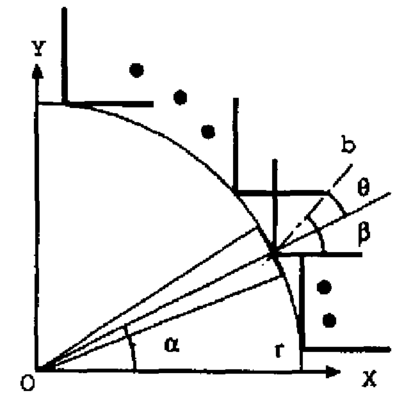

Fig.13. The edge's orientation and sensor's direction

As shown in Fig.13, the edge's feature point (POE) was set on the circumference of a circle, which has radius r. The sensor beam center line a is located at an angle α, and the convex edge's orientation b at an angle β. Here, β is kept at 45 *deg.*, the relationship θ (α-β)is changed with α. When POE changes position every 5 *deg.*, the deviation of direction by infrared measurement is showed in Fig.14.

It is clear that there are big differences between the real position and the measurement, especially in the measurement of direction. So that a method of compensating angle measurement is necessary. An angle deviation between measurement and real position is shown in Fig.14.

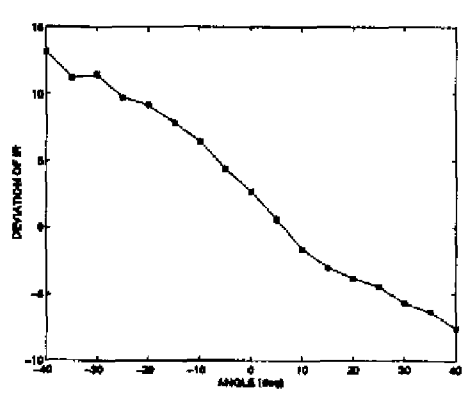

Fig.14. Infrared response on direction

A simple equation was found to compensate the covariance. This relationship is described as

$$Y = 16.0288 - 0.0782176x - 0.00486723x^2. \quad (8)$$

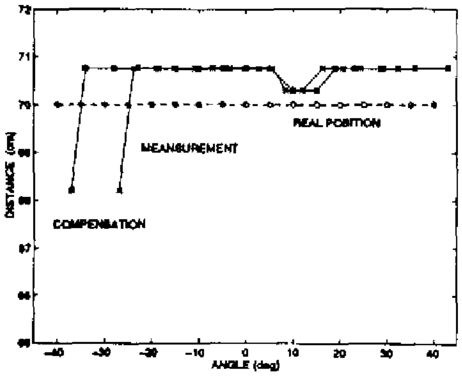

Fig.15. compensation of angle

Now, fusing two sensors estimation information, we can get the new compensation line as shown in Fig.15. It is more suitable and accurate for a mobile robot to navugation in long distance.

Notice that it is convenient to use this method for recognizing a convex edge in a real-time system.

4. Navigation Experiment

4.1 The Mobile robot

The robot used in this study is a commercial Nomad 200 mobile robot. The Nomad 200 is a wheeled cylindrical robot with a zero-turning radius and has three independent motors. The first motor moves the three wheels of the robot together. The second one steers the wheels together. The third motor rotates the turret of the robot. The robot has 16 infrared sensors (range up to 91.44 *cm*) and 16 sonar sensors (range up to 10.6 *m*) that provide instance to the nearest obstacles the robot can perceive, and 20 tactile sensors that detect collisions. The infrared and sonar are evenly placed around the perimeter of the turret and the tactile sensors cover all the perimeter of the robot below the turret. Finally, the robot has a dead reckoning system that keeps track of the robot's position and orientation.

4.2 Procedure

The experiment is performed in a corridor with some convex edges, which are along to the corridor with suitable intervals 8 *meters* (see Fig.13). When the robot moves, it can know the moment for detecting the convex edge, the place is called sensing zones whose locations are known in advance as a map information. The robot moves along the planned path according to the dead reckoning from start to a sensing zone(for example A sensing zone), it rotates the sensors an angle to get the information of sensors as it moves.

The navigation course is divided into following steps:

1) The planning path from current point to next sensing zone is a straight path. Navigating the robot between these two points is performed based on dead reckoning;

2) Detecting a landmark by combining sensor, the robot obtains the position and the direction information of a convex edge as a landmark from an environmental map, and calculates the expected distance and direction of the convex edge from the robot. Using these parameters, the convex edge detection sensor tries to face the convex edge and measure the distance and direction.

3) After detecting a convex edge, the robot fuses the measured values and the dead reckoning information to correct its estimated position by the proposed method. When gotten estimated position, the robot update the dead reckoning by this information, then, regards next sensing point as subgoal to make a new path plan.

Let the sensed convex edge is located at (x_i, y_i), the relation between the robot's and convex edge is illustrated in Fig.9. r is the distance and α is the angle of the detected sensor with respect to the robot front, the relation can be shown as

$$\begin{cases} r = \sqrt{(x(k)-x_i)^2 + (y(k)-y_i)^2} \\ \theta = \tan^{-1} \frac{y(k)-y_i}{x(k)-x_i} - \alpha. \end{cases} \quad (9)$$

By combining two estimations, dead reckoning and external sensor, the robot position becomes more accurate than either of estimations, individually.

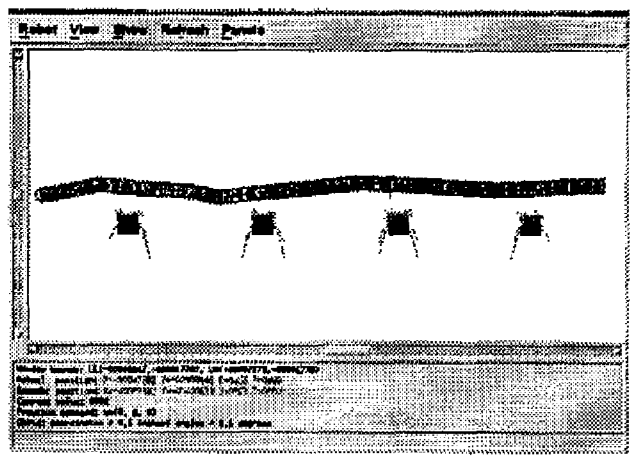

Fig.16. Navigation using recognizing point

5. Conclusions

In this paper, we have described a model of combining sensor which include sonar and infrared. Then, correction of robot position by the observation of landmarks based on the information of combining sensors. In addition, a mobile robot was controlled to follow a rout of over $100m$ in length. This system used convex edges as landmarks and combined sensor based on self-guide. The result shows that natural landmarks such as convex edges are useful to correct the robot position by the proposed method.

In our future work, a half-automatic system should be considered to make environment map guide robot navigation without priori map which will make it possible to achieve a longer distance navigation than by an autonomous mobile robot.

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