An Implementation of Landmark-based Position Estimation Function as an Autonomous and Distributed System for a Mobile Robot

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Abstract

We developed APCS (Autonomous Position Correction System) that can autonomously cancel the error of the estimated robot position from odometry by detecting flat walls using ultrasonic sensing. When it detects flat walls in the environment, this system corrects the estimated position using Maximum Likelihood Estimation (MLE). The feature of this system is that it can correct the position not being concerned with the behavior of the robot because the system autonomously decides the trigger of the position correction. In this paper, we will show the algorithm and implementation of APCS, and some experimental results to confirm feasibility of the system in a disordered environment.

1 Introduction

We adopt the strategy for mobile robot navigation in which the robot is given a numerical path such as line segments or arcs to the destination in the 2D coordinate system. In our case, the position of the robot should be *continuously* estimated. When the robot is traveling on an indoor floor, the odometry system is very useful to estimate the position. However, odometry has an inevitable cumulative error in proportion to traveling distance. To overcome this problem, there is a solution to observe its surrounding and detect landmarks for position error correction with its external sensors[1][2][3][4].

In such a case, there are 2 methods to detect those landmarks as described below.

1. The robot corrects the position at the sensing points of landmarks planned in advance of navigation.
2. The robot corrects the position when the landmarks in the environment are detected by chance.

There is a merit that total sensing cost is efficient using method 1. Because the robot observes only at the planned sensing points of landmarks[5]. On the other hand, using method 2, the sensing should be done continuously. Therefore the total sensing cost is not efficient. However, method 2 doesn't need the planning of sensing points, so it is easier to make this position correction system distributed and autonomous[6]. The most suited method is also depending on the environment. In case of a few landmarks which can be used for position correction, method 1 should be used. Method 2 can be applied in an environment which has many landmarks.

In this study, the position correction system is developed by using method 2 and ultrasonic sensors.

2 Problems to realize APCS

Here, we consider the essential functions of APCS. As shown in Figure 1, input of the system are the estimated position data from the odometry and the measured range data from the ultrasonic sensor which are given at every moment. With these data and the environmental map which is given to the system in advance, APCS outputs the corrected robot's position.

First, there is a problem when/where the mobile robot should correct its position. Our objective is to develop an autonomous position correction system which uses method 2 mentioned in the previous section, namely, the robot corrects the position occasionally when it could perceive landmarks. This means the system is given no information about the planned path a priori. Therefore, the system must decide autonomously when or where the position should be corrected using landmarks during robot's traveling. As

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a solution of this problem, there is a way to start the process of position correction when the robot seems to detect a landmark by the sensor which is continuously working. Another way is to start the procedure of the sensing and position correction when the robot approaches the place where it is assumed that the robot can detect a landmark. The latter way is more suitable if the sensing cost is high. But in case like this study, the former could be a good solution, since we use the ultrasonic sensor which can work constantly with less cost.

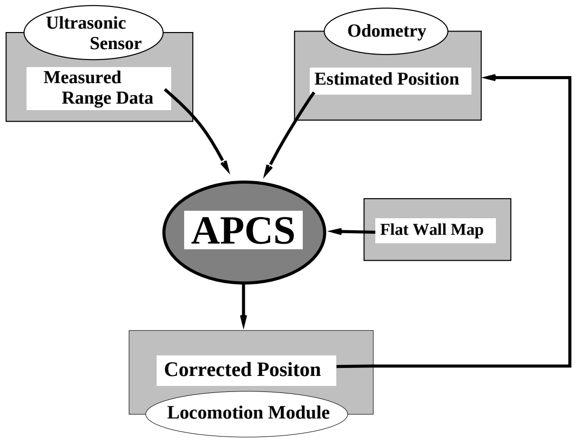

Figure 1: Flow of data in APCS. Input data are estimated robot's position and measured range data. APCS outputs the corrected position by using an environmental map information.

Second, the system must recognize by itself which landmark in the environmental map was sensed, because it is not planned in advance which landmark will be used. This problem could be solved by matching the detected landmark with a landmark in the map.

Next, which kind of landmark should be used is a problem. It is fatal to use the wrong information obtained from a mismatched landmark in the position correction process. Therefore, the landmark information for the position correction must be well verified. On the other hand, the range data from the ultrasonic sensor data only means that some object may exist around the robot, and there is a possibility the data is generated by an unknown obstacle which is not described in the environmental map. Then, in this research, we don't use each range data individually. The position correction will be done after several sensor data are integrated and verified by checking whether these data really come from the landmark or not.

3 Procedure of APCS

Here, we propose the following algorithm for the autonomous position correction of the mobile robot as the solution of the problems mentioned in the previous section. At first, we use flat walls as landmarks, which can be easily and often found in the environment. If several consecutive sensor data can be recognized to be generated by the same flat wall through careful verification, then the robot corrects its position using those data. Therefore, the position correction using a wrong landmark information can be avoided.

Figure 2 shows the procedure of APCS. The robot keeps observing the data from the ultrasonic sensor. When it can be recognized that a series of sensor data is generated by a flat wall, the system compares these data with a wall in the environmental map that was given to the robot a priori. If there is a matched wall found in the map, the wall is considered to be the actually measured one, and the robot's position is corrected based on the MLE (Maximum Likelihood Estimation) method using the information about that wall. If no matched wall is found in the map, or two or more matched walls are found, the position correction will not be done for safety reason.

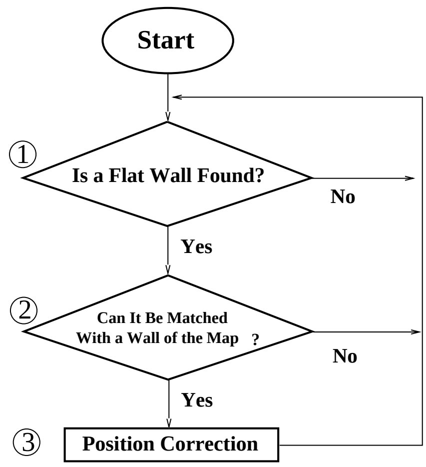

Figure 2: Procedure of APCS. When a flat wall is found, the system matches the obtained data with the environmental map. If there is the matched wall, the robot's position will be corrected.

4 Process for Position Correction

4.1 Extraction of flat wall

The following method will be used to verify whether a series of ultrasonic range data is generated by one

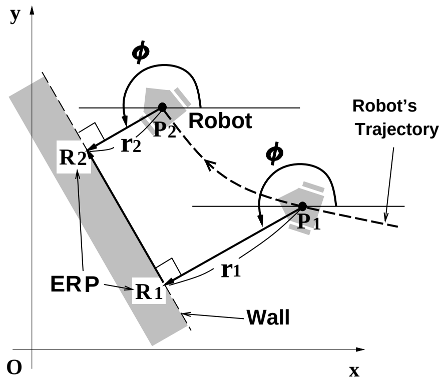

Figure 3: Configuration for the calculation of ERP (Estimated Reflection Point). r_1, r_2 are measured range data from robot's position P_1, P_2, respectively. When these range data originate from the same flat wall, ERP R_1, R_2 are on the intersections of the flat wall and two perpendicular lines through P_1, P_2.

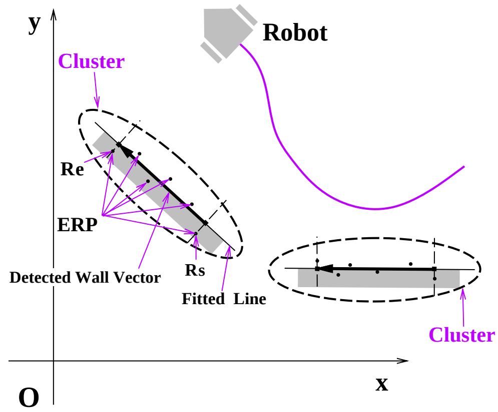

Figure 4: Detection of the flat wall and extraction of DWV (Detected Wall Vector). The calculated ERPs are grouped by the discontinuity and fitted into lines. DWV is extracted referring to two end ERP points, R_s, R_e.

flat wall or not.

As shown in Figure 3, let us consider that a couple of range data r_1, r_2 are obtained by an ultrasonic sensor when the robot was located on $P_1(x_1, y_1)$, $P_2(x_2, y_2)$, respectively. If these range data originate from the same flat wall, the reflection points on the wall should be on the intersections of the flat wall and two perpendicular lines through P_1, P_2, because the ultrasonic wave is reflected specularly at the flat wall surface[7]. We call these points "ERP (Estimated Reflection Point)". Now, we name two ERPs, R_1 and R_2. The vectors $\overrightarrow{\mathrm{P_1R_1}}$ and $\overrightarrow{\mathrm{R_1R_2}}$ meet perpendicularly, then the inner product of these vectors should be 0. The angle ϕ denoting the direction of the ultrasonic reflection can be calculated using this geometrical constraint. Then we can determine the position of two ERPs R_1 and R_2 referring to this ϕ.

While the robot is traveling, a new range data is measured by the ultrasonic sensor whenever the robot proceeds a certain length. The above mentioned process for the calculation of ERP is repeated when a pair of new range data is obtained. In order to detect a flat wall, position continuity of ERP is checked and they are grouped (see Figure 4). If the distance between two ERPs is short enough, these ERPs are considered to belong to the same wall and are grouped in the same cluster. If the distance is longer than a threshold length, namely when a discontinuity is found, these ERPs are clustered to the different groups. This grouping process continues until a discontinuity is found. If the number of ERP in the cluster exceeds a defined maximum number, the grouping process also stops in order to use obtained data properly.

Then, the number of ERP in the cluster is counted and if it is over a threshold the verification process will be done. To verify weather all ERP in the cluster originate from the same flat wall or not, an approximate line is fitted using the least squares method. The degree of fitness to the line is evaluated using the value of variance. When the variance is less than some threshold, it is considered that there is a detected flat wall. After the verification, a vector is extracted referring to two end ERP points, R_s, R_e. We call this vector as DWV (Detected Wall Vector).

In this method for flat wall detection, the shape of the robot's trajectory doesn't have to be a line. It could be an arbitrary curve.

4.2 Selection of Landmark

The environmental map consists of vectors expressing wall surfaces which will be used as landmarks. We call each vector WVEM (Wall Vector in Environment Map). The DWV should be matched to the WVEM to know which flat wall is detected. The matching process will be done as follows. For the preparation for the matching process, the detected vector $\overrightarrow{\mathrm{T_sT_e}}$ is projected onto one of vectors a_i of WVEM and the projected vector is denoted by $\overrightarrow{\mathrm{V_sV_e}}$ (see Figure 5). The distances d1 and d2 between two end points of the vector $\overrightarrow{\mathrm{T_sT_e}}$ and two end points of the projected vec-

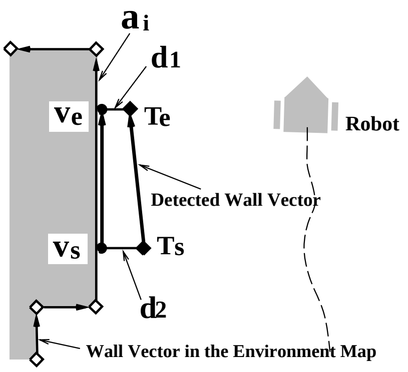

Figure 5: Configuration for the matching process in the landmark selection. The detected vector $\overrightarrow{\mathrm{T_sT_e}}$ is projected onto a vector a_i in the environmental map.

tor $\overrightarrow{\mathrm{V_sV_e}}$ are calculated. The detected vector matches a vector in the environmental map when the following conditions are satisfied:

- The orientation of the vectors are almost the same.
- The vector $\overrightarrow{\mathrm{V_sV_e}}$ is included in the vector a_i.
- The distances d1 and d2 are short enough.

This process is repeated for all vectors of WVEM. If no matched vector is found in the environmental map or two or more vectors are found, it is considered that the matching process is failed. When a matched vector is found, the system performs the position correction of the robot.

4.3 Correction of the Position

We have already developed the position and its uncertainty estimation technique based on MLE[8]. Here, we use the same technique for the position estimation of APCS. In our system, not only position P_A but also the error covariances Σ_{P_A} are always estimated, and occasionally corrected by using landmarks. P_A and Σ_{P_A} are expressed as follows:

$$P_A = \begin{pmatrix} x_A \\ y_A \\ \theta_A \end{pmatrix} \tag{1}$$

$$\Sigma_{P_A} = \begin{pmatrix} {\sigma_{x_A}}^2 & \sigma_{x_A y_A} & \sigma_{x_A \theta_A} \\ \sigma_{x_A y_A} & {\sigma_{y_A}}^2 & \sigma_{y_A \theta_A} \\ \sigma_{x_A \theta_A} & \sigma_{y_A \theta_A} & {\sigma_{\theta_A}}^2 \end{pmatrix} \tag{2}$$

Here, we explain the method for the position correction using the detected flat wall mentioned above section. The illustration of the relation between the robot's position and the landmark is shown in Figure 6. The robot could get the information about not only the distance r between the robot's position and the landmark but also the angle ξ which shows the direction of the landmark from the robot's orientation. Therefore, if we express the position of the flat wall as a line $ax + by + c = 0$ in the x-y coordinate, the direction of this line is perpendicular to the normal line of the flat wall that was detected by using ultrasonic sensor, so the following constraint can be made.

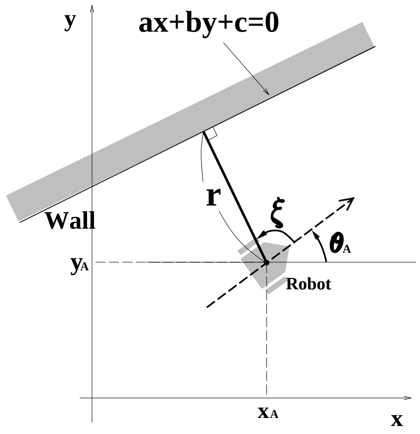

Figure 6: Relation between the robot's position and the landmark in the environment.

$$b\cos(\theta_A + \xi) - a\sin(\theta_A + \xi) = 0 \tag{3}$$

The distance from the robot to the landmark is r. Therefore,

$$(ax_A + by_A + c)^2 - r^2(a^2 + b^2) = 0 \tag{4}$$

From the above constraint equations (3) and (4), P_A and Σ_{P_A} is corrected based on the formula derived from [8].

The results of the calculation to get the corrected position are as follows:

$$\hat{P}_f = \hat{P}_A + \Sigma_f J_{P_A}^T \Sigma_{su}^{-1} \hat{P}_{su} \tag{5}$$

$$\Sigma_f = \{\Sigma_{P_A}^{-1} + {J_{P_A}}^T \Sigma_{su}^{-1} J_{P_A}\}^{-1} \tag{6}$$

where

$$J_{P_A}^T \Sigma_{su}^{-1} \hat{P}_{su} = \begin{bmatrix} \frac{a^2}{a^2+b^2}\frac{1}{\sigma_r^2} & \frac{ab}{a^2+b^2}\frac{1}{\sigma_r^2} & 0 \\ \frac{ab}{a^2+b^2}\frac{1}{\sigma_r^2} & \frac{b^2}{a^2+b^2}\frac{1}{\sigma_r^2} & 0 \\ 0 & 0 & \frac{1}{\sigma_\xi^2} \end{bmatrix} \tag{7}$$

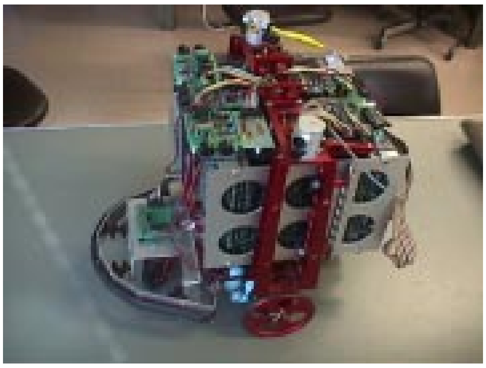

Figure 7: The mobile robot “Yamabico”.

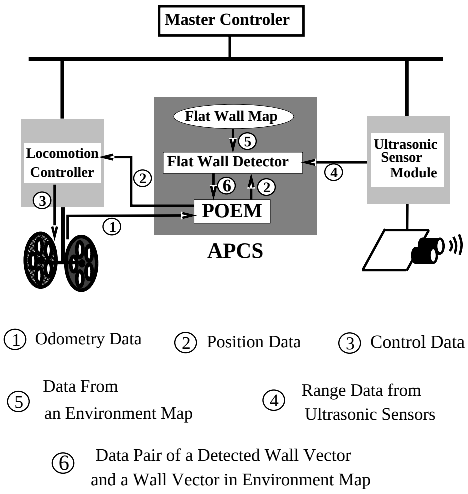

Figure 8: System configuration of APCS.

$$J_{P_A}^T \Sigma_{su}^{-1} J_{P_A}$$
$$= \begin{bmatrix} -\frac{a\{(ax_A+by_B+c)^2-r^2(a^2+b^2)\}}{2(a^2+b^2)(ax_A+by_B+c)}\frac{1}{\sigma_r^2} \\ -\frac{b\{(ax_A+by_B+c)^2-r^2(a^2+b^2)\}}{2(a^2+b^2)(ax_A+by_B+c)}\frac{1}{\sigma_r^2} \\ -\frac{b\cos(\theta_A+\xi)-a\sin(\theta_A+\xi)}{-b\sin(\theta_A+\xi)-a\cos(\theta_A+\xi)}\frac{1}{\sigma_\xi^2} \end{bmatrix} \quad (8)$$

$\hat{P}_A$ is the estimated value of P_A before correction. $\hat{P}_f$ is P_A after correction. Σ_f is Σ_{P_A} after correction. σ_r and σ_ξ mean the variance of r and ξ, respectively.

5 Implementation

We used a mobile robot “Yamabico” shown in Figure 7. Ultrasonic sensors are equipped on the front, back, left and right side of the “Yamabico”. The directivity of the ultrasonic sensor is ± 15 to 20 degrees and the measurable sensing range is about 30cm to 500cm.

Figure 9: The environment of Experiment 1.

We use piezoelectric transducers (MA40B8S/R by Murata Manufacturing Co., Ltd.). Figure 8 shows the system configuration of APCS implemented on the robot. APCS refers range data from ultrasonic sensor module and odometry data. After calculating the new position then APCS transfers the position data to locomotion controller. APCS has a flat wall map of environment and consists of Flat Wall Detector and POEM(POsition Estimation Module). POEM manages the estimated robot position and its error variance[8]. When Flat Wall Detector passes a data pair of DVW (Detected Wall Vector) and WVEM (Wall Vector in Environment Map), then POEM calculate the new robot position using the method of a previous section.

6 Experiment of Landmark Detection, Map Matching and Position Correction

6.1 Experiment 1

APCS detects flat wall landmarks automatically, and check whether these landmarks match to the flat walls in the Environment Map. In this section, we confirm this automatic landmark perception process of APCS.

6.1.1 The condition of Experiment 1

With this experiment, we set up the environment with some objects in front of a wall as shown in the Figure 9. We put umbrellas, umbrella stands, wastebaskets in front of the wall. APCS has information about the wall behind the objects but it doesn't have

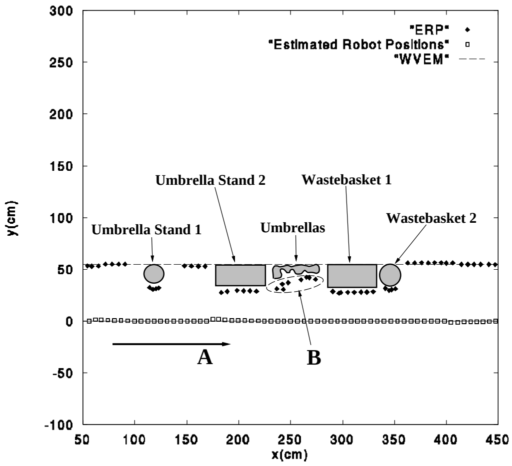

Figure 10: The result of calculated ERPs.

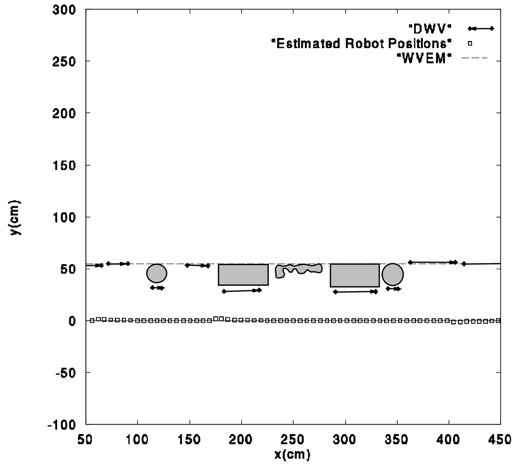

Figure 11: DWVs (Detected Wall Vectors).

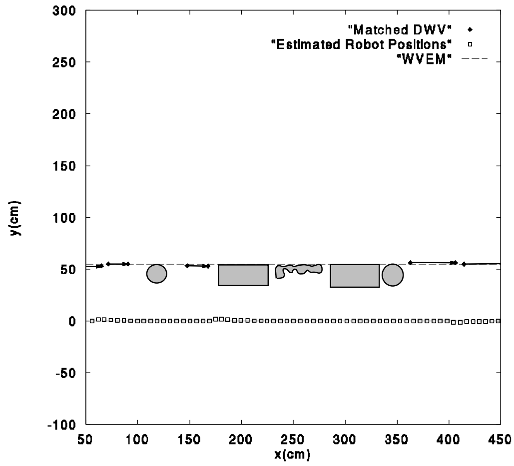

Figure 12: DWVs matched with WVEMs (Wall Vectors in Environment Map).

any data about the objects in this experiment. APCS must not perceive those obstacles but perceive only the wall landmark.

The robot went straight for 500cm at a speed of 10cm/s. APCS used the range data from the ultrasonic sensor every time when the robot moved 6cm.

We set up the value of the thresholds as follows.

1. The thresholds for detecting a flat wall:
   - The threshold of the distance to divide the groups of ERPs is 6cm.
   - The maximum number of ERPs which is accumulated by APCS to make one group is 8.
   - The minimum number of ERPs in one group for approximating a line is 4.
   - If the ERPs' standard deviation of approximation to a line is less than 1cm, APCS realizes that it detects a flat wall.
2. The thresholds for the matching process:
   - If the difference of the direction of DWV and WVEM is less than 30 degrees, the APCS assumes that the direction are the same.
   - If the value of $d1^2 + d2^2$ is less than $(10\text{cm})^2$, then APCS regards DWV and WVEM as being close enough.

Furthermore, we define the measure error variance as follows:

- The error variance of the detected range data between an ultrasonic sensor and a flat wall is $(1\text{cm})^2$.
- The error variance of the calculated direction of a flat wall is $(10 \text{ degrees})^2$.

6.1.2 The experimental result

Figure 10 shows the result of calculated ERPs. The robot traveled along the x-axis in the direction of arrow A. The robot passes in front of the objects in the order : Umbrella Stand 1, Umbrella Stand 2, Umbrellas, Wastebasket 1, Wastebasket 2. There are some ERPs forming a straight line and some ERPs are scattered as group B shows. Figure 11 shows the DWVs from the groups of ERPs of Figure 10. You can see the group B from Figure 10 has disappeared in Figure 11. Figure 12 shows DWVs which are matched with the WVEMs. As a result, DWVs which was given by the

Figure 13: The environment of Experiment 2.

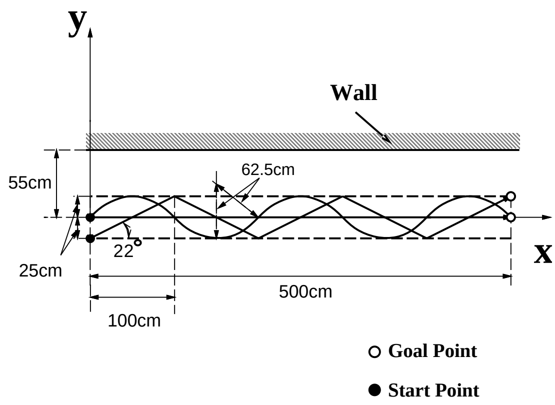

Figure 14: 3 traveling courses in Experiment 2.

flat walls of umbrella stands and wastebaskets are removed. Hence DWVs are rightly matched off against a WVEM of the wall finally.

6.2 Experiment 2

The purpose of Experiment 2 is the confirmation that APCS is independent of traveling routes. APCS doesn't need sensing plans. Therefore, APCS is independent from the other systems of the robot, especially from the master controller which has the route plan. In this experiment, we confirm that APCS can estimate the position using landmarks without making any change, even if the robot runs three different routes.

6.2.1 The condition of Experiment 2

Figure 13 shows the environment of Experiment 2. We set up 3 routes of the robot as shown in Figure 14, a straight course, a zigzag course and a curve line course. We took off all objects to make a comparison of the results when the robot travels 3 different courses.

The robot traveled at a speed of 10cm/s. We used all the same thresholds as in Experiment 1 for this experiment.

6.2.2 The experimental results

Figure 15 shows the result after following a straight course. Shown are the estimated robot positions, a WVEM, DWVs which is matched off against the WVEM, and ellipses which mean the standard deviation before the position correction and after the position correction. The ellipses are drawn enlarged with a scale of 6 : 1. The robot traveled along the x-axis

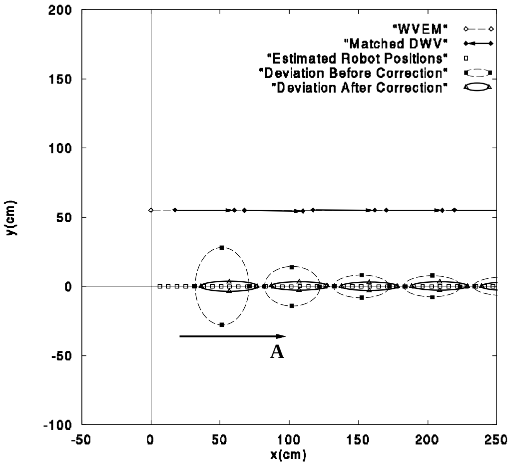

Figure 15: The experimental result after traveling a straight course.

in the direction of arrow A. It can be seen the ellipses became smaller when APCS detects some flat wall landmarks.

Figure 16 shows the experimental result after traveling a zigzag course using the same APCS without any changes. The robot traveled in the direction of arrow A. APCS doesn't have sensing plans, so we could confirm that APCS is available even if the traveling course has been changed.

Figure 17 shows the experimental result after traveling a curve line course using the same APCS of the straight course and the zigzag course. You can see APCS could detect the flat wall landmarks automatically and calculates the new estimated robot positions at some places. However, the flat wall could not be detected sometimes. We suspect that this is caused by

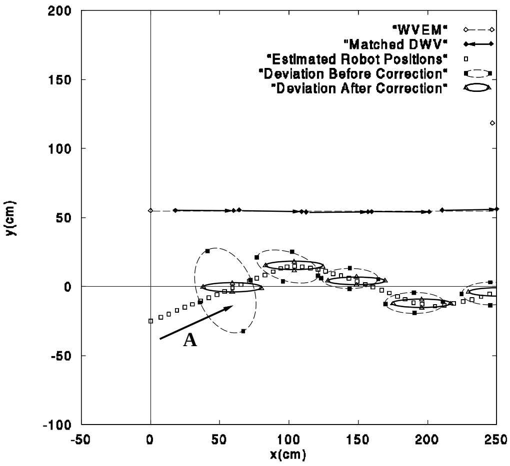

Figure 16: The result after traveling a zigzag course.

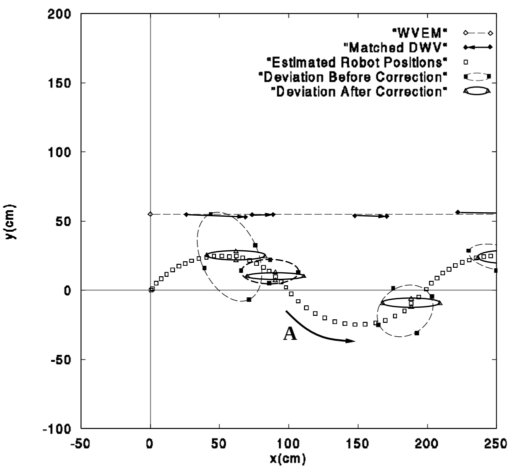

Figure 17: The result after traveling a curve line course.

the problem of ultrasonic sensors' directivity.

7 Conclusions

In this paper, we examined the problems for realizing the APCS (Autonomous Position Correction System), and showed an algorithm to solve them. In the proposed system, flat walls are used as landmarks, the matching process is based on comparison of the wall position, and the position is corrected when the robot finds a flat wall by the ultrasonic sensor. APCS manages the position correction autonomously and it is easier to make this system distributed because no plan of sensing points is needed. It will be easy to develop behavior programs for the robot with APCS, because APCS works independently of the robot's path. The next step of this study is to verify the usefulness of the system through experiments of mobile robot's long distance navigation.

Acknowledgments

The authors would like to thank very much Dr. Markus Rude of the University of Tsukuba for his useful suggestions for preparing this manuscript.

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