APCS: Autonomous Position Correction System Using Ultrasonic Sensing for Indoor Mobile Robot Navigation

Takashi YAMAMOTO Shoichi MAEYAMA Akihisa OHYA Shin'ichi YUTA

Intelligent Robot Laboratory University of Tsukuba 305-8573 JAPAN
E-mail: takashi@roboken.esys.tsukuba.ac.jp

Abstract

We are developing APCS which is Autonomous Position Correction System that can autonomously cancel the error of the position based on the detection of flat walls by ultrasonic sensing. When it detects landmarks in the environment map, this system corrects the position of odometry using Maximum Likelihood Estimation (MLE). The characteristic 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 of the flat wall detection and matching to the environment map in detail. We will show the experimental results of matching process using a robot in a real environment. As the result of the experiment, we could confirm that this system is feasible 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].

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 [4]. On the other hand, using method 2, the sensing should be done continuously. Therefor the total sensing cost is not efficient. However, the planning of sensing points isn't needed, so it is easier to make this position correction system distributed and autonomous [5]. 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 can perceive landmarks. This means the system is given no information about the planned path apriori. Therefore, the system must decide autonomously when or where the position should be corrected using landmarks during robot's traveling. As a solution of this problem, there is a way to start the process of

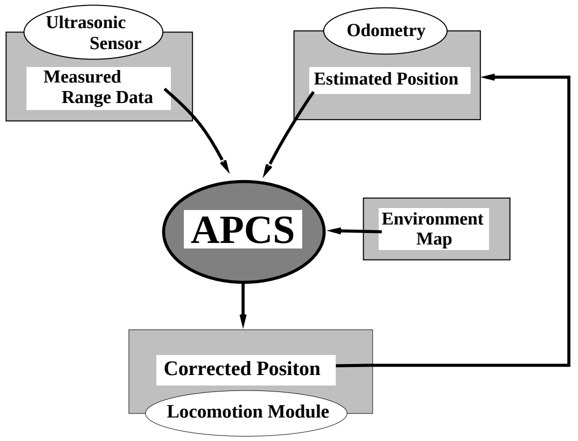

Figure 1: Flow of data in APCS. Input data are estimated position and measured range data. APCS outputs the corrected position by using an environmental map.

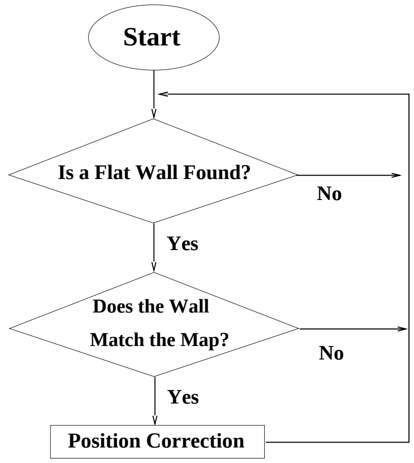

Figure 2: Procedure of APCS. When a flat wall is found, the system matches the obtained data with the environmental map. If there is a matched wall found, the robot's position is corrected based on the MLE method.

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.

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 automatic 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, it is possible to avoid the position correction using a wrong landmark information.

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 apriori. 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.

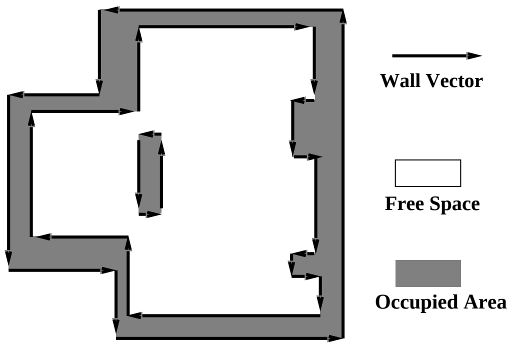

Figure 3: An example of an environmental map. The map consists of vectors expressing wall surfaces. The left side concerning the vector's orientation is defined as occupied area and the right side is a free space.

4 Process for Position Correction

4.1 Expression of environmental map

The environmental map consists of vectors expressing wall surfaces which will be used as landmarks. Each vector has its orientation and we define that the left hand side concerning the vector's orientation is occupied by an object and the right side is a free space. An example of the map is shown in Figure 3.

4.2 Extraction of flat wall

The following method will be used to verify whether a series of ultrasonic range data is generated by one flat wall or not.

4.2.1 Calculation of ERP (Estimated Reflection Point)

As shown in Figure 4, let us consider that a couple of range data r_1, r_2 are obtained by an ultrasonic sensor which is located on the left side of the robot 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. We call these points "ERP (Estimated Reflection Point)". Now, we name two ERP, 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 as shown in the following

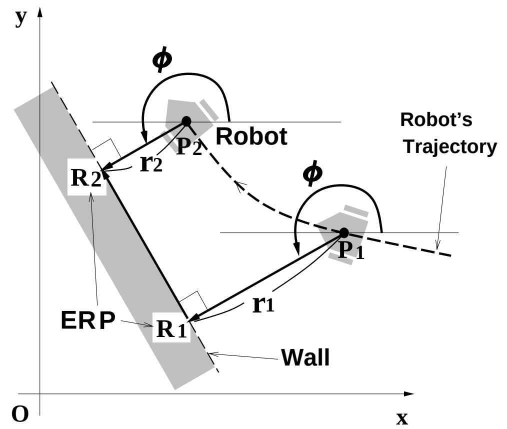

Figure 4: Configuration for the calculation of ERP r_1, r_2 are measured range data from robot's position P_1, P_2, respectively. When these range data originate from the same flat wall, ERP R_1, R_2 are on the intersections of the flat wall and two perpendicular lines through P_1, P_2.

equation.

$$\overrightarrow{\mathrm{P_1R1}} \cdot \overrightarrow{\mathrm{R_1R_2}} = 0 \tag{1}$$

The angle ϕ denotes the direction of the ultrasonic reflection and 0 degree is set on the direction of x-axis of the 2D coordinate system of the environment and the anti-clockwise direction is set to plus. Using components of the vectors $\overrightarrow{\mathrm{P_1R_1}}$ and $\overrightarrow{\mathrm{R_1R_2}}$ are expressed as follows:

$$\overrightarrow{\mathrm{P_1R_1}} = \begin{pmatrix} r_1 \cos\phi \\ r_1 \sin\phi \end{pmatrix} \tag{2}$$

$$\overrightarrow{\mathrm{R_1R_2}} = \begin{pmatrix} x_2 + r_2 \cos\phi \\ y_2 + r_2 \sin\phi \end{pmatrix} - \begin{pmatrix} x_1 + r_1 \cos\phi \\ y_1 + r_2 \sin\phi \end{pmatrix} \tag{3}$$

By substituting equations (2) and (3) for equation (1), ϕ is calculated as follows.

$$\phi = \frac{\pi}{2} - \alpha \pm \arccos\left(\frac{-(r_2 - r_1)}{\sqrt{(y_2 - x_2)^2 + (x_2 - x_1)^2}}\right) \tag{4}$$

Where, α is the angle that satisfies the following relations.

$$\sin\alpha = \frac{x_2 - x_1}{\sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2}} \tag{5}$$

$$\cos\alpha = \frac{y_2 - y_1}{\sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2}} \tag{6}$$

After the calculation of the value ϕ as mentioned above, we can determine the position of two ERP R_1

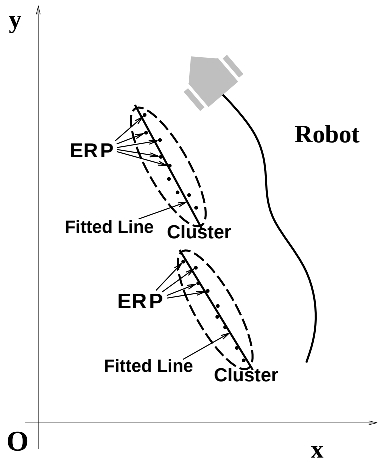

Figure 5: Detection of the flat walls. The calculated ERP are grouped by the discontinuity and fitted into lines. The variance of the fitted line is used for the verification.

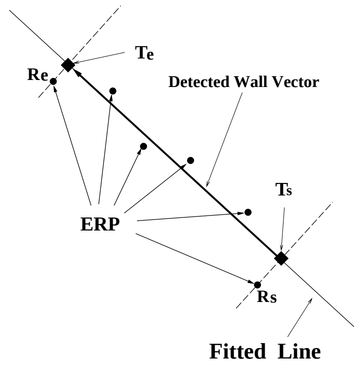

Figure 6: Extraction of end points of a fitted line. Two end ERP are denoted by R_s and R_e, also two end points of the fitted line by T_s and T_e. The end point is defined as the intersection of the fitted line and a line which meets the fitted line perpendicularly through an end ERP.

and R_2 corresponding to a couple of ultrasonic range data.

4.2.2 Detection of flat walls

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 5). If the distance between two ERP is short enough, these ERP are considered to belong to the same flat wall and are grouped in the same cluster. If the distance is longer than a threshold length, namely when a discontinuity is found, these ERP 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 flat wall detected.

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. This point is also an important feature to realize APCS. If there are some ultrasonic sensors equipped to the different directions, the flat wall detection process for each direction could be run in parallel. Then, the robot can extract flat walls effectively in the environment and can use them as landmarks.

4.2.3 Calculation of end points

In order to detect a line (wall) segment, both end points of the fitted line should be extracted. The end points are defined as the intersection of the fitted line and a line which meets the fitted line perpendicularly through an end ERP in the cluster (see Figure 6).

Two end ERP are denoted by R_s and R_e, also two end points of the fitted line by T_s and T_e. Then the detected line segment will be given an orientation to make it have a vector form like the environmental data has. Since we defined an occupied area on the left side of the vector and a free space on the right side, the vector becomes $\overrightarrow{\mathrm{T_s T_e}}$ in the example of Figure 6.

4.3 Selection of Landmark

In order to know which wall is detected, the detected vector should be matched to the wall data in the environmental map. The matching process will be done as follows.

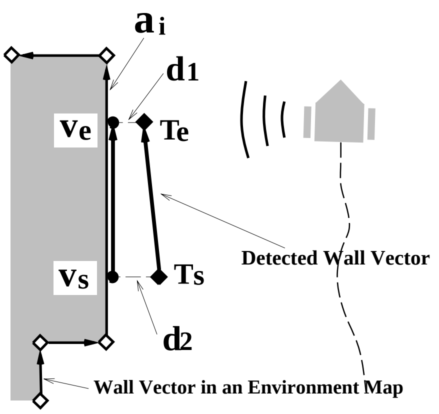

Figure 7: Configuration for the maching process in the landmark selection. The detected vector $\overrightarrow{\mathrm{T_sT_e}}$ is projected onto a vector a_i in the environmental map and the projected vector is denoted by $\overrightarrow{\mathrm{V_sV_e}}$.

For the preparation for the matching process, (see Figure 7) the detected vector $\overrightarrow{\mathrm{T_sT_e}}$ is projected onto a vector a_i in the environmental map and the projected vector is denoted by $\overrightarrow{\mathrm{V_sV_e}}$. The distances d1 and d2 between two end points of the vector $\overrightarrow{\mathrm{T_sT_e}}$ and two end points of the projected vector $\overrightarrow{\mathrm{V_sV_e}}$ 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 $\overrightarrow{\mathrm{a_i}}$.
- The distances d1 and d2 are small enough.

This process is repeated for all vectors in the environment vector map. 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.

4.4 Correction of the Position

We have already developed the position and its uncertainty estimation technique based on MLE [6]. Here, we use the same technique for the position estimation of APCS. In our system, not only position

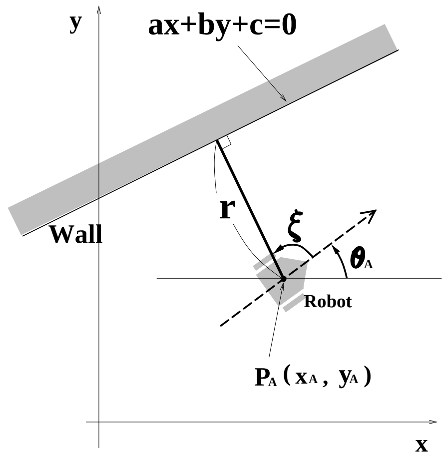

Figure 8: Relation between the robot's position and the landmark in the environment.

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:

$$P_A = \begin{pmatrix} x_A \\ y_A \\ \theta_A \end{pmatrix} \tag{7}$$

$$\Sigma_{P_A} = \begin{pmatrix} {\sigma_{x_A}}^2 & \sigma_{x_A y_A} & \sigma_{x_A \theta_A} \\ \sigma_{x_A y_A} & {\sigma_{y_A}}^2 & \sigma_{y_A \theta_A} \\ \sigma_{x_A \theta_A} & \sigma_{y_A \theta_A} & {\sigma_{\theta_A}}^2 \end{pmatrix} \tag{8}$$

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 8. 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 by our method. 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.

$$b\cos(\theta_A + \xi) - a\sin(\theta_A + \xi) = 0 \tag{9}$$

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

$$(ax_A + by_A + c)^2 - r^2(a^2 + b^2) = 0 \tag{10}$$

From the above constraint equations (9) and (10), P_A and Σ_{P_A} is corrected based on the formula derived from [6].

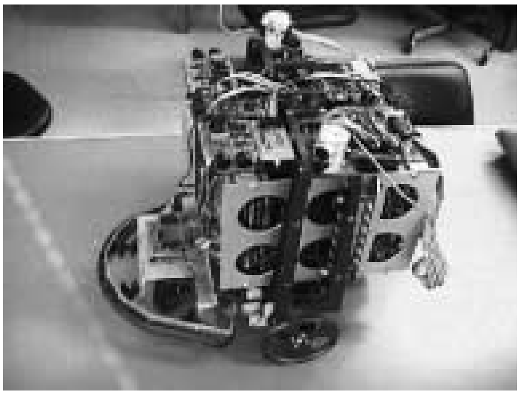

Figure 9: The mobile robot “Yamabico”

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

$$\hat{P}_f = \hat{P}_A + \Sigma_f J_{P_A}^T \Sigma_{su}^{-1} \hat{P}_{su} \tag{11}$$

$$\Sigma_f = \{\Sigma_{P_A}^{-1} + J_{P_A}{}^T \Sigma_{su}^{-1} J_{P_A}\}^{-1} \tag{12}$$

where

$$J_{P_A}^T \Sigma_{su}^{-1} \hat{P}_{su}$$

$$= \begin{pmatrix} \frac{a(c+ax_A+by_A)((a^2+b^2)r^2-c-ax_A-by_A)\sigma_r^2}{2(a^2+b^2)^2} \\ \frac{b(c+ax_A+by_A)((a^2+b^2)r^2-c-ax_A-by_A)\sigma_r^2}{2(a^2+b^2)^2} \\ \frac{a\sin(\xi+\theta_A)-b\cos(\xi+\theta_A)}{(-a\cos(\xi+\theta_A)-b\sin(\xi+\theta_A))\sigma_\xi} \end{pmatrix} \tag{13}$$

$$J_{P_A}^T \Sigma_{su}^{-1} J_{P_A}$$

$$= \begin{pmatrix} \frac{a^2\ (c+ax_A+by_A)^2\sigma_r^2}{(a^2+b^2)^2} & \frac{ab(c+ax_A+by_A)^2\sigma_r^2}{(a^2+b^2)^2} & 0 \\ \frac{ab(c+ax_A+by_A)^2\sigma_r^2}{(a^2+b^2)^2} & \frac{b^2\ (c+ax_A+by_A)^2\sigma_r^2}{(a^2+b^2)^2} & 0 \\ 0 & 0 & \frac{1}{\sigma_\xi} \end{pmatrix} \tag{14}$$

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

5 Implementation

We used a mobile robot “Yamabico” shown in Figure 9. Ultrasonic sensors are equipped on the front, back, left and right side of the “yamabico”. The directivity of the ultrasonic sensor is ± 15 °∼20 °and the possible sensing range is about 30cm∼500cm. Those transducers are MA40B8S/R made by MURATA Factory. Figure 10 shows the APCS implemented on the robot ”Yamabico”. “rd_us_data( )” is the process to get the range data from ultrasonic sensor and post the data on the State Information Panel (SIP). “thread_apcs(LEFT/RIGHT)” is the process to detect flat walls on the left/right side and match the detected flat walls with the environment map. Then, it sends the information of the detected wall segment and the matched wall segment in the environment to the Position Estimation Module (POEM III). POEM III manages the estimated robot position and its variances by referring to the odometry data. It also calculates the new robot position and its variance when it gets the position information from the external sensors. The calculated new robot position is sent to the locomotion controller, and then robot can correct its trajectory.

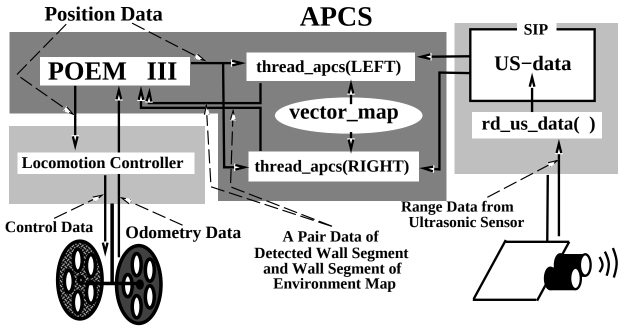

Figure 10: System configulation of APCS

6 Experiment of Landmarks Detection, Map Matching and Position Correction

The experimental data of the ultrasonic sensor is acquired by the robot in the real environment as shown in Figure 11. The arrow ‘A’ means the locus and the direction of the robot. The wall ‘B’ is not given in the environment map of the robot. The velocity of the robot was 30cm/s. The data of ultrasonic sensors were taken every 3cm. In this experiment only left side is used.

Figure 12 is the plotted ERP and the robot’s position by the method of section 4.2.1. Here, □ means the trajectory of the robot and ◆ are the ERP. ◇ means flat walls of the environment map that the robot has. The arrow ‘A’ means the direction of the robot. ‘B’ is ERP from the wall ‘B’ in Figure 11.

Figure 11: The experimental environment. The arrow 'A' mean the locus and the direction of the robot. We established a wall 'B' on purpose in the environment to experiment a wall which is not given to the environment map of the robot.

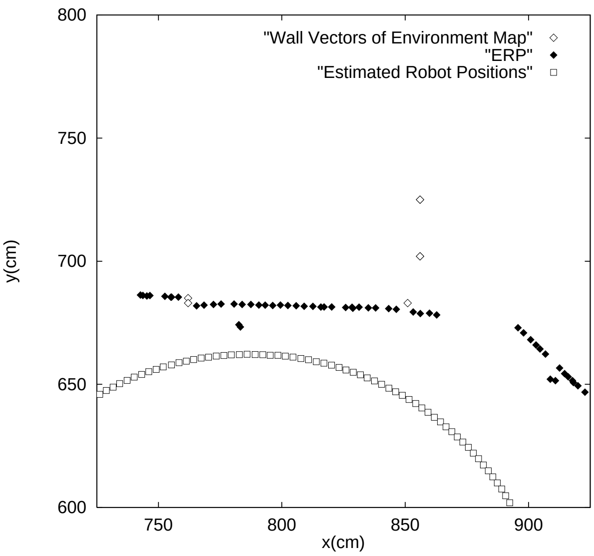

Figure 12: The robot's trajectory and ERP. The arrow 'A' means the direction of the robot. 'B' is ERP from the wall 'B' in Figure 11.

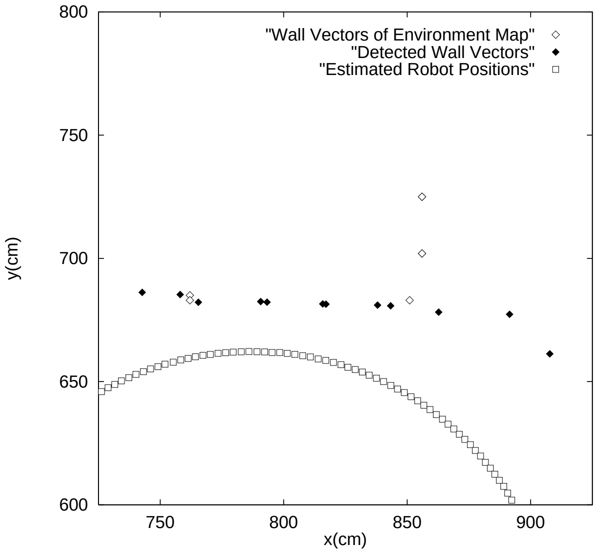

Figure 13: The detected result of wall vectors.

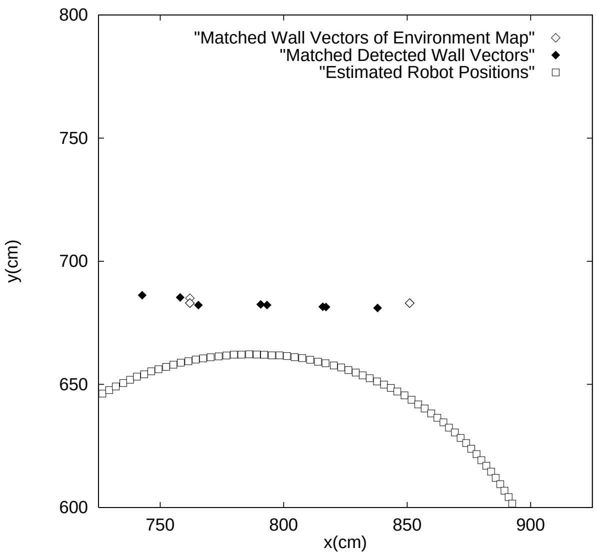

Figure 14: Matching results of the detected wall vectors and environmental map

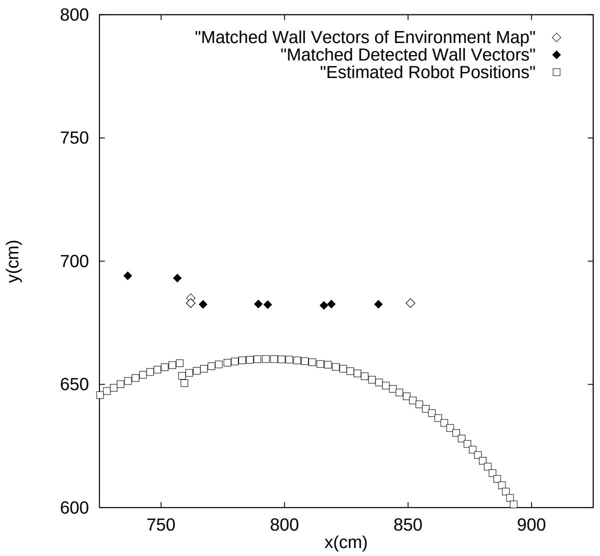

Figure 15: Estimated position has been changed after position correction.

Next, detected wall vectors by ultrasonic sensor are shown in Figure 13. Here, □ means the trajectory of the robot and ◆ are the detected wall vectors. ◇ means wall vectors of environment map that the robot has. We set the threshold $100cm^2$ to divide ERP to the groups at the process of section 4.2.2. About the size of the group, we ignored the small ERP groups less than 4 points and we also set the maximum number of points to 8 for each group. Thus, a long flat wall is divided to 5 detected wall vectors as shown in Figure 13. You can see an unexpected wall vector 'B' is detected.

Furthermore, Figure 14 shows the matching result by the method proposed in section 4.3. Here, We set the threshold $\pm$ 0.5deg to check the orientations of vectors in the process of the section 5. The threshold of map matching was set $d1^2 + d2^2 = 200cm^2$. d1 and d2 are the values shown in Figure 7. The wall' B' is not found in the environment map, thus it was rejected.

Figure 15 shows another example of the experiment including the process of position correction. You can see that the estimated robot position has changed. The robot's position can be corrected by the method shown in section 6 after processing these calculation.

7 Conclusions

In this paper, we examined the problems for realizing the autonomous position correction system APCS, and showed an algorithm to solve them. The problems are as follows: When/where should the robot correct its position? How can the detected landmark match the map information? What kind of landmark should be used? 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 planning 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.

References

[1] J.J. Leonard and H.F. Durrant-Whyte: "Mobile Robot Localization by Tracking Geometric Beacons", IEEE International Conference on Robotics and Automation, pp.2011-2016 (1990).

[2] K. Komoriya and E. Oyama and K. Tani: "Planning of Landmark Measurement for the Navigation of a Mobile Robot", IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.1476-1481 (1992).

[3] Y. Watanabe and S. Yuta: "Position Estimation of Mobile Robots with Internal and External Sensors Using Uncertainty Evolution Technique", 1990 IEEE International Conference on Robotics and Automation, pp.2011-2016 (1990).

[4] K. Nagatani and S. Yuta: "An Autonomous Mobile Robot "YAMABICO"-The path and sensing point planning and navigation in real indoor environment", 1993 IEEE Robotics and Automation Conference Video Proceedings, (1993).

[5] T. Nishizawa, A. Ohya and S. Yuta: "An Implementation of On-board Position Estimation for a Mobile Robot", IEEE International Conference on Robotics and Automation, pp.2524-2529 (1995).

[6] S. Maeyama, A. Ohya and S. Yuta: "Non-stop outdoor navigation of a mobile robot - Retroactive positioning data fusion with a time consuming sensor system-", IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.130-135 (1995).