# Vision Based Navigation System of Air Conditioning Equipment Inspection Robot

## - Position / Orientation Control by Landmark Recognition with Plus and Minus Primitives -

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## ABSTRACT

A template matching is a popular method for visual recognition. It costs much time to detect target objects. We have applied a Fuzzy and Neural Network algorithm to solve this problem. However, the problem to mistake recognizing the target object is not solved. Hence, in this paper, we propose a robust visual recognition algorithm for the autonomous robot navigation. The proposing algorithm employs a fuzzy template matching with the target object as well as the similar objects in the environment. As a result, the robot verifies the tentative recognition by comparing the likelihood of plus elements (target objects) with that of minus elements (similar objects). To integrate this algorithm into the robot navigation system, we propose a hierarchical control architecture. The validity of the proposing navigation system is shown with experimental results.

## 1. INTRODUCTION

Several kinds of robots take an active part in a lot of fields, such as manufacturing, space, amusement and medical fields etc. The main reason of encouraging the robotization is that robots are substituted for human to work continuously or to do hard or dangerous tasks. Construction field is one of such fields. There are many research works on robots for construction fields. However, it is difficult to realize the autonomous robot. Because environment is very complicated. Hence, the robust navigation system is needed for the autonomous mobile robot to accomplish tasks automatically and efficiently.

Therefore, we have studied on the autonomous mobile robot (fig.1) [1][2][15][16]. For the robot navigation, we need to install several sensors on the robot. There are many sensors such as internal sensors and external sensors. Hence, in order for robots to recognize self position and orientation, there have been many attempts to adopt the several external sensors, for example ultra sonic sensor [3], laser range finder [4], [5] and CCD camera [6]. Many research works on autonomous mobile robots based on vision recognition are made [7]~[9]. We adopt a CCD camera for the robot to calculate the relative location between the robot and the landmark, based on vision recognition. As the landmark, this robot adopts an anemo (air conditioning equipment, air diffuser in fig. 4) which is located in the system-line on the ceiling and is equipped in the ordinary office buildings. One of the major approaches is template matching which is a method to detect the target object in the image by the CCD camera. We have proposed the Fuzzy Template Matching (FTM) whose template consists of fuzzy set [2].

However, the problem to mistake recognizing the target object is not solved. The main reason comes from the similarity between the target object and the other object around it. The recognition algorithm employs the binarization of the original image, and the environment conditions such as brightness and color affect this process so much. Hence, the important feature of the image is removed through this process, and the NN fails to distinguish the target object from the similar objects. Generally, working environment of the robot is very complicated and robust visual recognition algorithm is required.

In the previous approach, we used only the template of the target landmark for recognition. On the other hand, if we use templates of the other similar structural elements together, we can make the robot verifying the recognition result. Here we define the "primitive" as the basic element of which the template is composed. We use the term "plus primitive" as the primitive which composes target landmark template. We use the term " Minus Primitive (MP) "as the primitive which composes the template of the minus structural elements. The robot verifies the recognition result by comparing the likelihood of plus elements (target template) with that of minus elements (similar objects).

The robot moves autonomously comparing recognition results with the prepared map information. Once the robot makes a mistake of recognition and moves to the wrong direction, the robot cannot identify the self position and orientation. To solve this problem, we propose a hierarchical control architecture. We navigate an autonomous mobile robot with this control algorithm which has error recovery characteristics. The validity of the proposing navigation system is shown with experimental results.

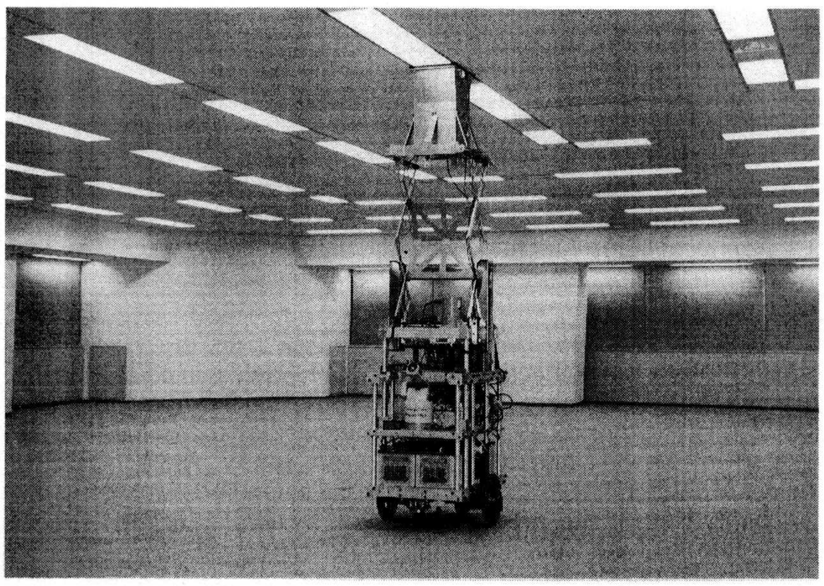


Fig. 1 Air Conditioning Equipment Inspection Robot

## 2. Hierarchical Control Architecture

When we navigate the autonomous mobile robot, the theme is the way to make up the control architecture. There have been proposed many kinds of control architectures which adopted a hierarchical system approach and a behavior based approach. For example, NASREM which adopts an idea of the hierarchical system approach is proposed by Albus et al. [10] as a model of Real - Time Control System for robots. Subsumption architecture which adopts an idea of the behavior based approach is proposed by Brooks [11] as imitating the insect's autonomous system.

### 2. 1 HALAS (Hierarchical Adaptive and Learning Architecture System)

In this paper, we propose the autonomous mobile robot architecture HALAS ( Hierarchical Adaptive and Learning Architecture System ) as the control system in fig. 2 and fig. 3.

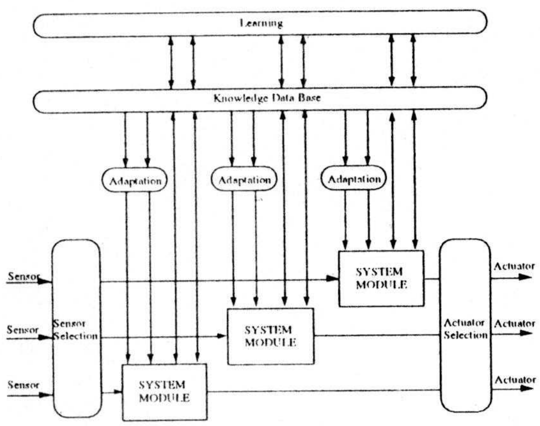



Fig. 2 HALAS
(Hierarchical Adaptive and Learning Architecture System)

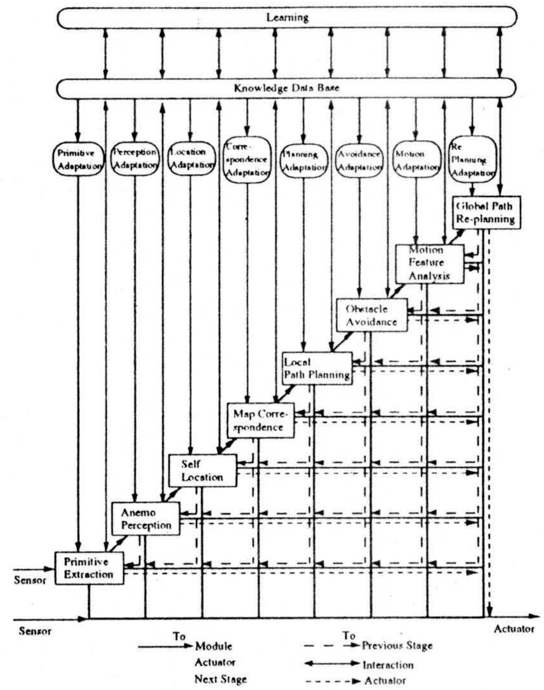



Fig. 3 System module

Figure 2 shows the whole structure of the HALAS which indicates the relationship between system modules from sensory input to actuator output. Figure 3 shows system module in the HALAS, and indicates the relationship between the adaptive function and the learning function of the system modules. Here, in the initial state, the robot has environmental map and initial global path plan that is considered in advance.

We describe the information flow inside this architecture as follows. Sensor selection part selects the sensory information which is needed for the submodules. Each submodule form hierarchical structure shown in fig. 3. Submodule performs tasks based on these sensory inputs or another submodule output as follows.

**Primitive Extraction:** Preprocess of image, and Extraction of primitives

**Anemo Perception:** Combine primitives to form the landmark. Check the correlation between the extracted landmarks.

**Selflocation:** Recognize position and orientation of the robot from the image, and compare the result with that by the deadreckoning.

**Map Correspondence:** Compare the result with the CAD data, and display the selflocation and the failure point.

**Obstacle Avoidance:** Detect the obstacles and avoid them.

**Local Path Planning**: Correct path planning locally.

**Motion Feature Analysis:** Analyze the robot's behavior characteristics.

**Global Path Re-planning:** Minimize the global path.

Submodules have adaptive function respectively to make an adjustment of the system parameters employing the knowledge data base (K.D.B). The K.D.B. stocks knowledge and adds the acquired knowledge. Learning function interacts all submodules closely and has a function to rewrite the K.D.B. Actuator selection part selects the actuator based on the output of system modules.

## 2. 2 Air Conditioning Equipment Inspection Robot

In this paper, we consider to apply this system to the air conditioning equipment inspection robot. The inspection is usually carried out before the completion of the building. We experiment in the flat floor with a carpet tile finish and no furniture as experimental fields. The robot is equipped two CPUs and two CCD cameras. The system of the robot consists of the vision control unit, vehicle control unit and lifting control unit. Now, we show the system configuration from primitive extraction to map correspondence in fig. 3. Once the sensory input enters the HALAS, primitives are extracted, and the landmarks are detected based on the extraction result with the proposing method. As a result, the robot can identify self position and orientation with vision recognition result. The robot is navigated based on this result. We consider CCD cameras as sensory inputs for navigation. Another sensory input can be considered in the HALAS.

## 3 FTM with MP

Fuzzy template matching is a method to make a model based on the characteristic of the landmark in the image. In the previous research works we only used plus template (anemo template) in the FTM. For robust recognition, we propose an advanced recognition algorithm in the following section.

### 3. 1 Definition of Minus Primitive

As an environment is formed by complex patterns, the robot makes a mistake to recognizing landmarks. One of the methods to solve this kind of problem is to represent a complex pattern by its simpler subpatterns . However, if each subpattern is very complex, we may represent each subpattern by even simpler ones [12]~[14]. The simplest subpattern is called "pattern primitive".

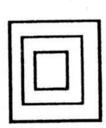
In case of searching a square anemo, the anemo is treated as a pattern, and square elements are treated as a subpattern. Moreover, a side which composes the square is treated as a pattern primitive.

In this paper, the structural element which we treat as the landmark is called plus primitive, and we define the other structural elements as minus primitive (MP). The MP is obstructive elements to recognize the anemo.

The robot has information of the objects in advance that may cause a mistake to recognize the landmark. The MP are constructed based on these information. The anemo template is composed by the plus primitive, the MP template is composed by the MP. We make the MP template in the same way as we have reported before[2].

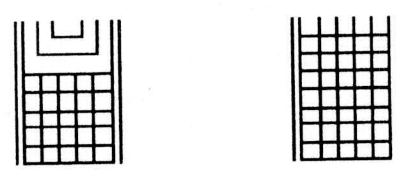
### 3. 2 Category of Minus Primitive

In the ordinal office building, there are systemlines on the ceiling. In our experimental environment, the anemo is located on the systemline. Structural object except the anemo is the MP. They are located on the systemline, too. Those are the louver, fluorescent lamp, speaker, emergency light, and fire alarm (fig.5). We can express these structural elements with grid, parallel lines and circle. These elements correspond to subpattern in the previous definition. These subpatterns can be divided with primitive again, and they are expressed with a line segment, an arc of circle and free line.



Square Type

Fig. 4 Anemo(Air Diffuser)



Systemline　Louver

Fig. 5 Minus Primitive

### 3.3 Expression of Recognition Condition

To navigate the autonomous mobile robot, we select the anemo as the landmark. Then we choose the anemo as the plus primitive.

We begin with considering how to express the recognition condition. If the operator can watch the monitor, he can find that the robot detects the landmark or not. However, the robot can't conclude whether it is correct or not.

To verify the recognition result, we evaluate and compare the grade of membership function in the FTM. We represent recognition condition by the transitions of the grade of membership function. We decide the grade of membership function as follows.

$$Grade(i,j)=1-|train\_data(i,j)-recog\_data(i,j)| \quad (1)$$

Grade(i, j): The grade of the membership function on the position (i, j).
i: x axis or y axis in the image.
j: the number of membership function.
train_data(i, j): the grade of membership function when the template coincides with the landmark of the training data.
recog_data(i, j): the grade of membership function while the robot search the landmark.

### 3.4 Comparison of Recognition Condition

In the preprocessed image (binary) , some minus elements arise similar conditions as an anemo. Therefore we introduce the MP. However, if the robot detects the anemo and the MP separately, it cost much time to search the landmark. Hence, we take a procedure as follows. In the beginning, the robot detects the anemo in the image. If search of the anemo is finished, the robot applies the MP template to the matching point and compares recognition condition of the anemo with that of the MP.

## 4 Sensing Strategy

### 4.1 Main Camera Sensing

Main CCD camera is loaded in front of the robot. The robot detects the landmark forward 3m with it. In the previous work, we navigate the robot with FTM of the plus primitive only. When the robot detects the anemo, the robot decides that the matching position equals to the anemo position. According to this recognition result, the robot calculates self position and orientation, and moves directly under the target anemo. However, if the robot happens to mistake a recognition of the anemo, the robot may be navigated to the wrong position. As a result, the robot loses the landmark position and can not identify self location. Then, we propose a control algorithm to move based on the result of main camera sensing with the MP.

Distinction conditions in fig. 6 are classified as follows.

**1) Finish of search:** If the search of the anemo finish in the preprocessed image, the robot next confirms the recognition result with the MP. Otherwise, the robot calibrates the camera control unit (pan and tilt), and continues to search the anemo in new preprocessed image.

**2) Comparison of grade:** Compare with the value of GA and that of GP (GA is the grade of the anemo template, and GP is that of the MP template), the robot distinguishes whether matching subject is the target anemo or the MP. If GA is greater than GP, the robot detects the anemo. According to this perception result, the robot calculates self position and orientation, and moves directly under the anemo.

**3) Search again:** In 2), GP is greater than GA, moreover the number of searching the anemo is less than 4 times. Then the robot extracts the center line of the systemline, and changes next searching point to that of the systemline. If the previous searching is finished for the upper part of the image, next point is set the lower part of it. Otherwise, next point is set for the upper part of it.

**4) Interruption of search:** In 2), GP is greater than GA, moreover the number of searching the anemo is already greater than 3 times. Then, the robot decides that there is not the anemo as the landmark in the image, and stay there.

### 4.2 Small Camera Sensing

Small camera sensing has a difference with main camera sensing. Because small camera is loaded for calibrate self position and orientation in the center of air volume measurement unit. As this robot has a final aim to measure air volume, we decide that the convergence conditions for measurement is set as follows.

$$\text{Position error} \quad L \leqq 20\text{mm}$$

$$\text{Orientation error} \quad \theta \leqq 3^\circ$$

To satisfy the convergence condition, we propose control algorithm to modify the robot

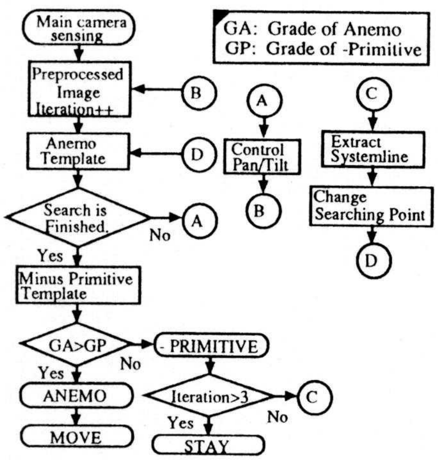



Fig. 6 Flowchart of Main Camera Sensing

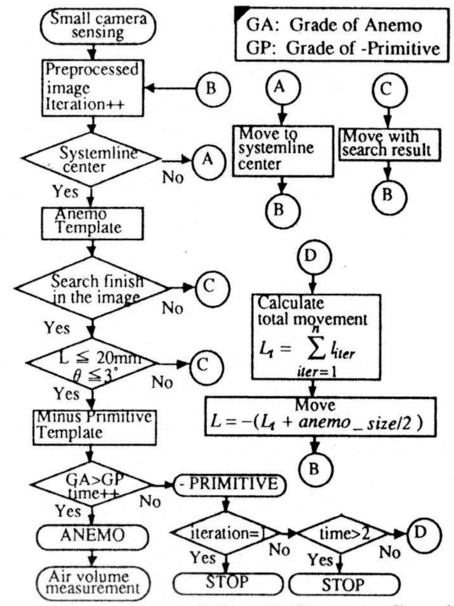



Fig. 7 Flowchart of Small Camera Sensing

position and orientation error based on the result of small camera sensing with the MP in fig.7.

Distinction conditions in fig. 7 are classified as follows.

1) **Extraction of systemline:** The robot makes a histogram with the preprocessed image, and moves the center line of the systemline. If there is large gap between the center of the robot and that of systemline, the robot moves to that of systemline in the beginning.

2) **Finish of search:** If searching the anemo is finished, the robot verifies the previous convergence condition. Otherwise, the robot moves based on the recognition result, and continues search of the landmark taking new image.

3) **Convergence condition:** If the matching position is in the area within convergence condition for air volume measurement, the robot applies the MP template to the image. Otherwise, the robot modifies the self position and orientation based on recognition result, and continues to search the landmark in the new image.

4) **Comparison of grade:** According to compare GA and GP, the robot distinguishes whether matching subject is the target anemo or the MP. If GA is greater than GP, the robot inspects air conditioning equipment.

5) **Intractable condition:** In 4), GP is greater than GA. Moreover, this is the first time to detect the anemo by small camera sensing. Then the robot must be located directly under the MP. Therefore the robot is interrupted to work.

6) **Search again:** In 4), GP is greater than GA, moreover in case of that the number of checking MP template is less than 3 times. The robot calculates the quantity of total movement in small camera sensing. If total movements are positive, the robot moves backward L (defined in fig. 7). Otherwise, the robot moves forward L.

7) **Intractable condition:** In 4), if the number of checking MP template is more than 3 times, the robot can not search the anemo as a result of it. Therefore the robot interrupts to work.

## 5 Experimental Results

### 5. 1 Reliability of Main Camera Sensing

We applied the proposed algorithm to the control method aiming at confirming the position and orientation accuracy for autonomous mobile robot. When we select the anemo as the landmark in the experimental environment, the sensing distance of main camera is about 3 m in most cases. The relative position of between the robot and the landmark is shown in fig. 8.

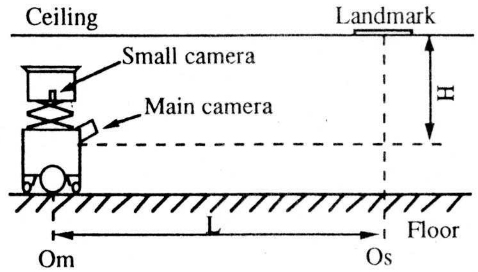
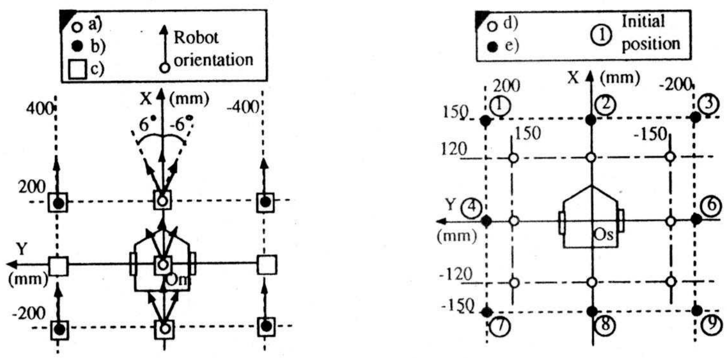


Fig. 8 Locations of Robot and Landmark



(a) Main Camera (b) Small Camera
Fig. 9 Initial Position of Sensing

When the robot is located on the sensing point of main camera directly under the systemline, the center of the robot is shown the reference point Om in fig. 8. We put the robot around Om to carry out mobile experiments. Then we select the following 3 cases as the initial position of the robot as shown in fig. 9 (a).

a) The reference point Om and points in front and behind 200 mm away from it are selected as measurement points. On these points, the orientation of the robot is right in front, and is changed right and left 6 degree against it.

b) The center of the robot is changed right and left 400 mm away from the following points which are in front and behind 200 mm away from the reference point Om. The robot is located on parallel along the systemline.

c) Each orientation of the robot is located on parallel along the systemline. The reference point Om and two points in front and behind 200 mm away from it are adopted as measurement points. Still more, points are located right and left 400 mm from these three points as measurement points.

On the previous points, we navigate the robot to recognize the landmark, and to control its position and orientation based on the algorithm of main camera sensing as shown in fig. 6. Table 1 summarizes the comparison of the recognition result FTM only with FTM and the the MP. This table indicates that the robot can recover the error of recognition through the robot uses FTM with the MP to detect the landmark. As a result, the rate of vision recognition is improved by considering the MP.

Table 2 and Table 3 indicate the reliability of the sensing. The accuracy of the position and orientation are measured as mean value of the position error and orientation error between desired point Os and actual robot location after sensing and motion.

Table 2 (a) shows that the results include error in case of that the robot detects the landmark with FTM only, and moves based on the recognition result. On the other hand, table 2 (b) shows the results with FTM and the MP in the same way. On the contrary, table 3 (a) and (b) indicate the position and orientation reliability measured in the condition that the robot stays on the Om with calculating selflocation, where deadreckoning error is not included. As we consider the error of the recognition in table 3 (a), the results are worse than that of table 3 (b). That is to say, table 4 is based on robot's standard. Table 3 (b) is based on operator's or observer's standard. Especially in table 3 (a), since the robot fails to measure correctly, the recognition results are divergent in some cases. On the other hand, as we don't consider these results, we get table 3 (b) better results than table 3 (a).

Table 1 Recognition Result

| | Success | Failure |
|---|---|---|
| Fuzzy Template Matching | 82% | 18% |
| FTM + MP (Recovery rate) | 93% (62%) | 7% |

Table 2 Position/Orientation Accuracy
(Include deadreckoning error)

(a) FTM

| | Position Error (mm) | Orientation Error (deg) |
|---|---|---|
| Forward (200,0) | 83.1 | 1.20 |
| Center (0,0) | 64.8 | 0.57 |
| Backward (-200,0) | 106.1 | 1.21 |
| Average | 84.7 | 1.05 |

(b) MP

| | Position Error (mm) | Orientation Error (deg) |
|---|---|---|
| Minus Primitive (by Error Recovery) | 103.4 | 1.01 |

Table 3 Position / Orientation Accuracy
(without deadreckoning error)

(a)Include mistake of recognition

| | Position Error (mm) | Orientation Error (deg) |
|---|---|---|
| FTM | 115.4 (except divergence) | 0.87 (except divergence) |
| FTM + MP | 100.4 | 0.72 |

(b)Exclude mistake of recognition

| | Position Error (mm) | Orientation Error (deg) |
|---|---|---|
| FTM | 50.7 (except divergence) | 0.64 (except divergence) |
| FTM + MP | 50.9 | 0.67 |

## 5. 2 Reliability of Small Camera Sensing

Contrary to the main camera sensing, small camera sensing is needed severe accuracy to measure air volume. We set up measurement points as follows in fig. 9(b). Robot located on the following mesh except the small camera sensing reference point Os in fig. 9(b).

d) Inside: (X * Y): (120 , 150) - (-120, -150)
e) Outside: (X * Y) : (150 , 200) - (-150, -200)

Robot located on parallel along the system-line in both d) and e).

Outside points are large gap between Os and the center of the robot. We assume some cases that the robot moves to the wrong direction in some reasons, for example slipping, overrunning or another disturbance rather than the robot cannot navigate accurately by main camera sensing. Figure10 and 11 show the example of mobile trajectory with small camera sensing algorithm as shown in fig. 8. Both figures are selected e) as initial points of the robot. Figure 10 is a case of navigating the robot with FTM, and shows that the recognition results are till divergence. On the other hand, Figure 11 indicates the trajectory with FTM and the MP navigation. To compare with fig. 10, we can find that the robot can recover errors.

Table 4 is summarized based on the mean values of mobile trajectories such as fig. 10 and fig. 11. If the robot start on the point d), both FTM and FTM+MP are result in settling within about 22 mm. On the other hand, if we navigate the robot on the point e), FTM+MP is settling down the position on which the robot can measure air volume. On the contrary, if the robot is located without the MP on the system-line as an initial condition, the robot mistakes a recognition of the landmark as anemo template matches the MP. In this case, position error is about 350 mm and orientation error is about 0.5 degree. As a result, the robot losses self position and orientation. To make matters worth, if the robot is located on far right and far left system-line as an initial condition, the robot continues to detect the landmark, and soon move to the wrong direction as shown in fig. 10.

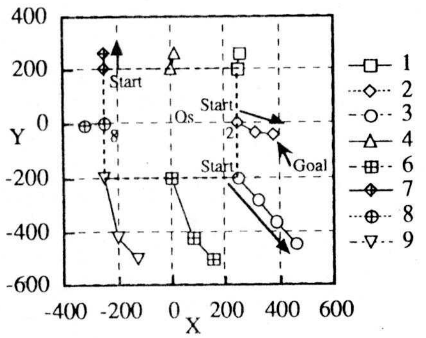



Fig. 10 Trajectories of Robot with FTM

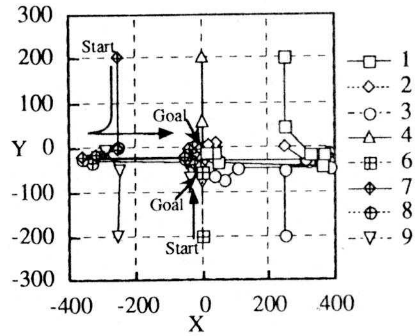



Fig. 11 Trajectories of Robot with FTM and MP

Table 4 Position / Orientation Accuracy (Include deadreckoning error)

| | Position Error (mm) | Orientation Error (deg) |
|---|---|---|
| b-1) FTM | 22.8 | 0.51 |
| b-1)FTM + MP | 22.0 | 0.33 |
| b-2) FTM | on the systemline : mistake to recognize<br>surrounding the systemline : divergence | |
| b-2)FTM + MP | 28.4 | 0.47 |

## 5. 3 Results of Air Volume Measurement

We experiment to confirm the effectiveness of the navigation system in actual office room. Air volume of air diffusers have already adjusted in the experimental field. The robot is navigated to confirm the air volume with two methods 1) with FTM 2) with FTM and MP. Mobile trajectories are shown in fig. 12 and 13. Table 5 is the results of air volume measurement. According to these results, we confirm air volume adjusted within 210 ~ 230 $m^3/h$.

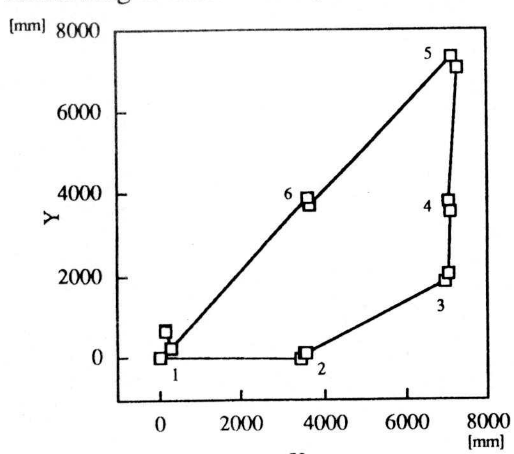



Fig.12 Trajectory of Robot with FTM

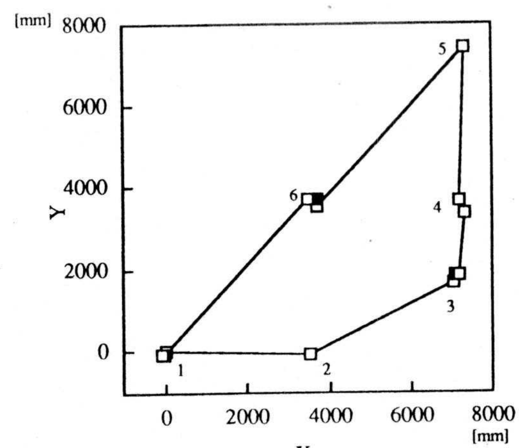



Fig.13 Trajectorys of Robot with FTM and MP

Table 5 Results of Air Volume Measurement

| No. | Air Volume($m^3$/h) | No. | Air Volume($m^3$/h) |
|---|---|---|---|
| 1 | 217.2 | 4 | 213.0 |
| 2 | 215.6 | 5 | 217.8 |
| 3 | 215.2 | 6 | 216.8 |

## 6. Conclusions

In this paper, firstly, we proposed a hierarchical adaptive and learning architecture system (HALAS). Next, we proposed the visual recognition method considering the MP in the algorithm. The vision recognition rate is improved in the experiments.

We applied this system architecture and visual recognition algorithm to navigate the robot that is used for autonomous inspection. The robot used both main camera and small camera to recognize the target object on the ceiling. The robot is navigated precisely compared with the previous experimental results. We can confirm the effectiveness of using the MP and system architecture (HALAS). It is shown that the proposing system has error recovery property from the experiments in actual office room.

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