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Development of air conditioning equipment inspection robot with vision based navigation system

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Abstract

In order to maintain a comfortable office environment periodical inspection of the air conditioning equipment is very important. It is necessary to measure the air temperature and the volume of the controlled outlet air correctly from the ceiling air diffuser. The periodical inspection of a large number of ceiling air diffusers must be done efficiently and in a short time. Up to now this hard work has been done by humans. However, we have developed a robot which will take the place of the human and perform these inspections automatically. This autonomous mobile robot recognises the position of ceiling air diffusers from map information supplied to it. The robot measures the air temperature and air volume, and moves on to the next diffuser and so on. In this paper we present an outline of this autonomous mobile robot.

1. INTRODUCTION

When you look up the word "Air-conditioning" in the dictionary, it defines it as the system that controls the humidity and temperature of air in a room or building. Nowadays, it is hard to find a major building without an air conditioning system. Recently, the demand for air conditioning quality has become severe and the means to control individual zones with specific temperature, humidity and air-flow requirements an important consideration.

During building, the measurement of air velocity, volume and temperature are necessary in order to test the air conditioning system and ensure that it is in correct working order. However, there are countless ceiling air diffusers installed in a single building and there inspection and maintenance require much strenuous labour. On the basis of these present conditions, we have developed an AIR Conditioning Equipment Inspection robot (ACEI-robot) having vision based navigation system.

In this report, we present the outlined description of the basic functions and our achievement in the actual application of the ACEI-robot on a building construction site.

2. PROBLEMS, AIMS AND SYSTEM REQUIREMENTS

On the actual building construction site, measurements are currently carried out by three persons. One person (Mr. A) has the role of lifting and holding the hood, another (Mr. B) the task of measuring and another (Mr. C) the task of recording measurements . Mr. A first lifts the measurement hood to collect the air flow of the ceiling air diffuser. Then Mr. B climbs a ladder and puts the sensor inside the hood and measures the air velocity at several points. Mr. C takes records and calculates the air volume and the inspection check is thus completed for a single ceiling air diffuser. This process is carried out to endless repetition.

On basis of our investigation on the actual building construction site, we identified the following problems, aims and requirements for the system.

2.1 Problems

(l) Lots of manpower needed
(2)Unattractive blue-collar work
(3)Measurements must be performed quickly
(4)Unreliability of measurements
(5)Too much data to deal with manually

2.2. Aims

(l) Reduce manpower
(2)Improve efficiency
(3)Improvement accuracy of data
(4)Avoid heavy labour requirement

2.3. System Requirements

The following are the system requirements needed to solve the problems and meet the aims:

(1) Automatic ceiling air diffuser location.
(2) Straight movement towards and under the ceiling air diffuser
(3) Can be move freely without any codes
(4) Measurement must be done efficiently and accurately
(5) Printouts provided for the measurement results
(6) Path planning can be set freely
(7) It is safe for humans
(8) It does not damage the building fabric

3. THE SYSTEM

Following automatic functions are needed for the robot to take the place of existing personnel:

(l) Ceiling air diffuser recognition and measurement of the distance and calculation of the direction between the ceiling air diffuser and the robot.
(2) Autonomous mobility
(3) Lifting up of the end effector (sensor of air velocity and temperature)
(4) Measurement of air velocity and temperature
(5) Calculation of air volume and recording of data
(6) Storing of map information

Therefore, our ACEI-robot contains four modules. By combining each system it can perform the six functions stated above. The four system modules are:

(1) VISION SYSTEM	(2)VEHICLE SYSTEM
(3) SENSOR SYSTEM	(4) LIFT UP SYSTEM

An overview of ACEI-robot is shown in Fig. 1 and its specification is given in Table 1.

Table 1 SPECIFICATION

Shape and size(mm) of the diffuser.	Nominal square as 260 x 300
Working space.	50 to 60 diffusers
Inspection speed.	5mins/diffuser (inc. travelling)
Accuracy.	+ 10%
Travelling speed.(km/h)	Max. 2
Moving mechanism.	Autonomous mobile robot (wheel type)
Sizes (mm).	W=600 x L=1100 x H=1880 to 2800
Weight (kg).	350
Power supply.	Batteries of DC 12V, 24V, 48V

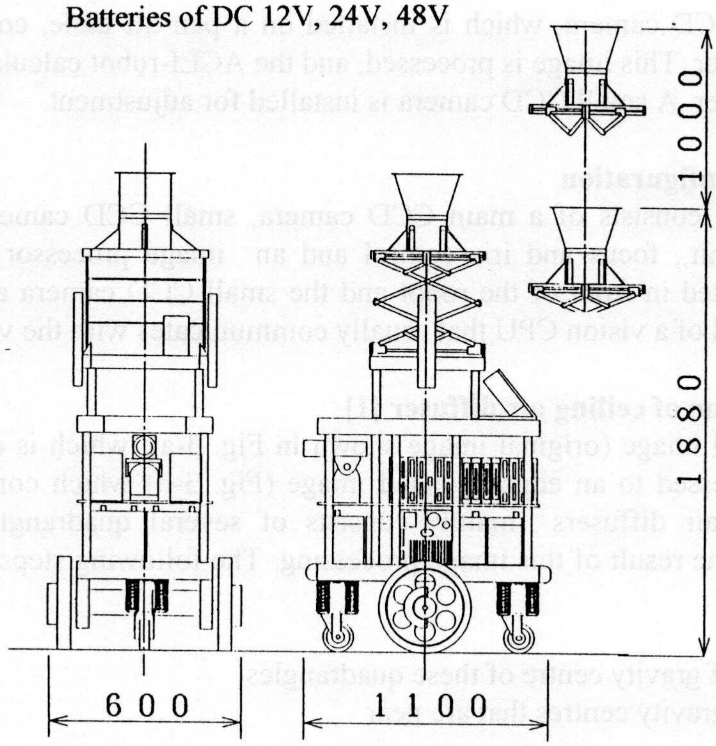
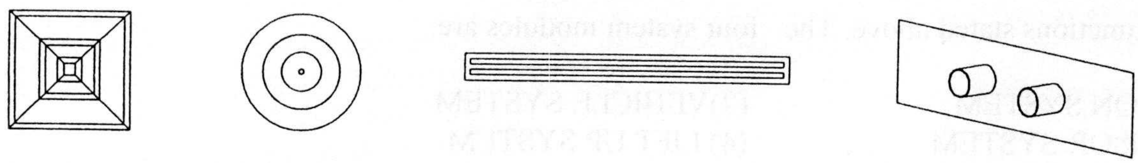


Fig. 1 ACEI-robot

In this paper we applied the ACEI-robot to a typical floor of an office building, because in most office buildings the same shapes of ceiling air diffusers are likely to be installed. Also typical floors are flat and heights of ceilings are mainly the same. When the measurements take place, the office is empty and free of obstructions (checking is done before bringing in the desks and chairs). There are many types of ceiling air diffusers (Fig. 2), however, the office building we used for our experiment had square ceiling air diffusers installed. So in this experiment we set our vision system to recognise the square ceiling air diffuser.



(a)Square type (b)Circle type (c)Line type (d)Nozzle type

Fig. 2 Various type of ceiling air diffuser

4. MODULES OF THE ACEI-ROBOT

The ACEI-robot consists of four modules; vision system, vehicle system, sensor system and lift up system.

4.1. Vision system

4.1.1. Outline

The main CCD camera, which is installed on a pan-tilt table, collects the image of a ceiling air diffuser. This image is processed, and the ACEI-robot calculates the distance to the ceiling air diffuser. A small CCD camera is installed for adjustment.

4.1.2. System configuration

This system consists of a main CCD camera, small CCD camera, pan-tilt table, lens zoom control unit,, focus and iris control and an image processor unit. The main CCD camera is mounted in front of the robot and the small CCD camera at the centre. They are under the control of a vision CPU that usually communicates with the vehicle CPU.

4.1.3. Recognition of ceiling air diffuser [1]

A grey level image (original image shown in Fig. 3-a), which is collected by the CCD camera, is processed to an edge detected image (Fig. 3-b) which consists of straight lines. Square ceiling air diffusers mainly consists of several quadrangles, so we gathering quadrangles as the result of this image processing. The following steps are taken to recognise the centre.

(a) calculation of gravity centre of these quadrangles
(b) grouping of gravity centres that are near

Then the group that has the most gravity centres is recognised as the centre of the ceiling air diffuser.

4.1.4. Principle of position measurement

It is very meaningful for the ACEI-robot to measure the position of the ceiling air diffuser accurately. Basic principles of position measurement are stated below:

(a) Direction to the ceiling air diffuser

Co-ordinates processed by ACEI-robot are expressed as Fig. 4. Co-ordinates (x, y, z) are the centre co-ordinates of the ceiling air diffuser. By these co-ordinates, the ceiling air diffuser position (x, y, z) is calculated as follows,

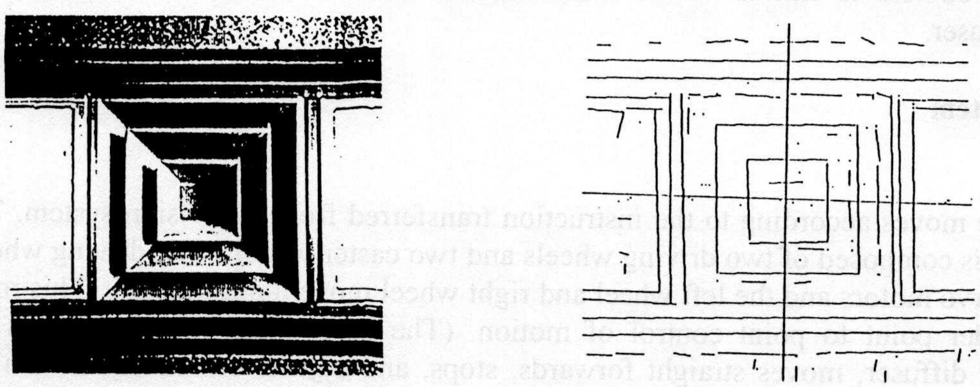
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos\phi_C & 0 & -\sin\phi_C \\ 0 & 1 & 0 \\ \sin\phi_C & 0 & \cos\phi_C \end{pmatrix} \begin{pmatrix} (y_g - DY/2) * SY/DY \\ (DX/2 - x_g) * SX/DX \\ f \end{pmatrix} \quad (1)$$

,where (x_g, y_g) are the centre of gravity of the ceiling air diffuser in image,
DX,DY the image resolution
SX,SY the CCD image pixel number,
f: the CCD focal length
θ_C the camera pan angle
ϕ_C the camera tilt angle
θ the direction of ceiling air_diffuser in the ACEI-robot co-ordinate system
ϕ the elevation angle of the ceiling air diffuser in the ACEI-robot co-ordinate system and ceiling air diffuser direction, as seen by ACEI-robot is calculated as follows:

$$\delta\theta = \arctan(y/x) \quad (2)$$

$$\theta = \theta_C + \delta\theta \quad (3)$$

$$\phi = \arctan(\sqrt{x^2 + y^2}/z) \quad (4)$$



(a) Original image (b) Image processing result

Fig. 3 Image processing result

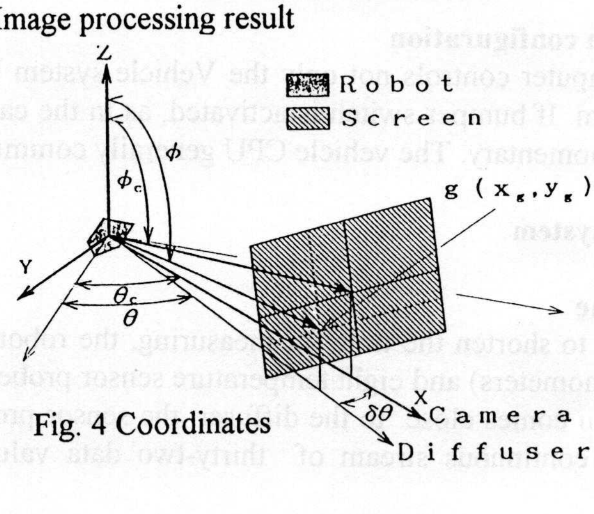


Fig. 4 Coordinates

b)Distance to ceiling air diffuser

When the height of the ceiling is known, the horizontal distance between the robot and the ceiling air diffuser can be calculated as shown in Fig. 5.

$$L = (H - H_C)\tan\phi \qquad (5)$$

H_c: Height of Camera

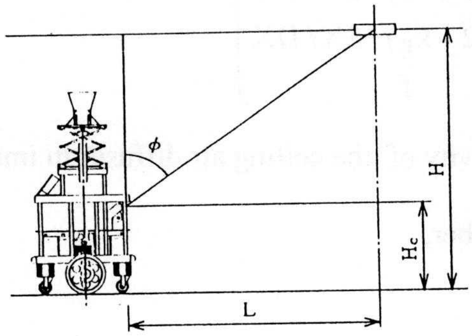


Fig. 5 Distance measurement

4.1.5. Position correction

As the robot moves to the ceiling air diffuser is basis on the data obtained from the CCD camera and the pan-tilt table, it is rare for the robot to reach the destination in one go. This is due partly to wheel slippage which can vary even for the same size wheel. This is adjusted by the small CCD camera that is installed in the upward facing sensor system. The function of the small CCD camera is similar to the main camera and it calculates the distance and direction of diffuser.

4.2. Vehicle system

4.2.1. Outline

The vehicle moves according to the instruction transferred from the Vision system. The Vehicle system is composed of two driving wheels and two caster wheels. The driving wheels have two DC servo motors and the left wheel and right wheel move independently. This robot is operated under point to point control of motion. (The robot spin turns and faces the direction of the diffuser, moves straight forwards, stops, and adjusts the direction with the spin turn).

4.2.2. System configuration

The computer controls not only the Vehicle system but also the Sensor system and the Lift up system. If bumper switch is activated, as in the case of an emergency, the robot can be stopped momentary. The vehicle CPU generally communicates with the vision CPU.

4.3. Sensor system

4.3.1. Outline

In order to shorten the time for measuring, the robot has twenty-four air velocity sensor probes (anemometers) and eight temperature sensor probes (thermometers) (Fig. 6). When the sensor system comes close to the diffuser, the sensor probes commence gathering data, thus providing a continuous stream of thirty-two data values. The air volume flow rate and average temperature is calculated from this.

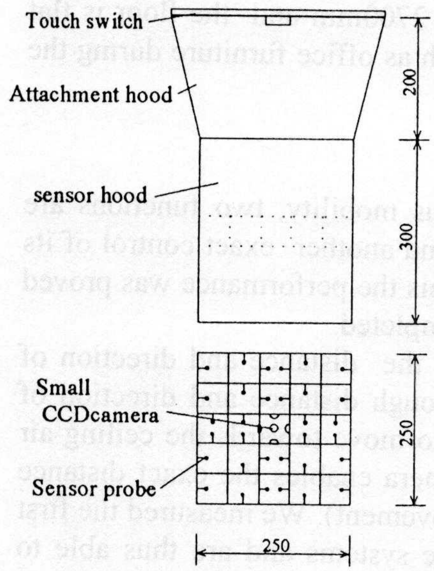


Fig. 6 Sensor system

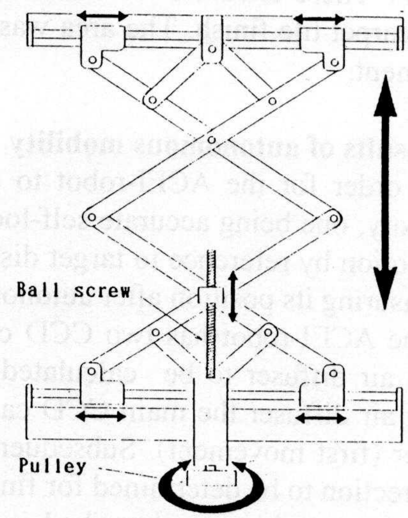


Fig. 7 Lift up system

4.3.2. System configuration

The hood part is composed of sensor hood (stable) and the attachment hood (size can be change to correspond to the diffuser size) . The sensor hood is divided into a 5x5 mesh with aluminium vanes with the CCD camera is installed in the centre. Velocity and temperature sensors are installed in rest of the 24 mesh cells. This aluminium vane acts also as a distributing plate.

4.4. Lift up system

4.4.1. Outline

The Lift up system lifts the Sensor system when measuring the air volume. While the robot is moving, the hood is 500mm below the ceiling in order to avoid any obstacle. As the module changes to the measurement mode, the hood is lifted until the distance between the ceiling and the hood is in the range of 70mm to 200mm. Then the photoelectric switch turns on, and the lift up speed slows down to avoid a shock when hitting the ceiling. As the hood touches the ceiling, the touch switch on the attachment hood is activated and the lift up operation is ended. This whole process takes about 30 seconds.

4.4.2. System configuration

The motor rotation is transferred to the pulley by a timing belt. The pulley is connected to a ball screw and as the pulley turns, a nut moves up and down. This up and down movement is enlarged by a link mechanism. (Fig. 7)

5. RESULTS OF CONSTRUCTION SITE EXPERIMENT

The robot has been applied to the 70 storey 'L Building' construction site in

YOKOHAMA city. This building is intended for use as offices and a hotel. The floor used for the experiment was for offices with an area of about 600m2 having 54 ceiling air diffusers. These diffusers are installed at the ceiling height of 2700mm and the floor is flat with a carpet tile finish. The area was free of obstructions such as office furniture during the experiment.

5.1. Results of autonomous mobility

In order for the ACEI-robot to achieve full autonomous mobility, two functions are obligatory, one being accurate self-locating measurement[2] and another exact control of its own motion by reference to target distance and direction. In this the performance was proved by measuring its position after autonomous movement was completed.

The ACEI-robot has two CCD cameras that both enable the distance and direction of ceiling air diffuser to be calculated. After calculating the rough distance and direction of ceiling air diffuser the main CCD camera enables the robot to move towards the ceiling air diffuser (first movement). Subsequently, the Small CCD camera enables the exact distance and direction to be determined for fine adjustment (second movement). We measured the first movement position as described in both camera co-ordinate systems and are thus able to determine the difference between our robot's location and the location of ceiling air diffuser.

In our experiment, we set up several trajectories that visit several ceiling air diffusers. For example, two experiment path patterns are shown in Fig. 8 and the results of pattern A are given in Table 2. The differences shown in Table 2 stands for the distance between the desired target (location of ceiling air diffuser) and the actual location of the robot. The sensor hood is larger than ceiling air diffuser by 20mm in length and width. Therefore the tolerance of autonomous mobility must be within 20mm in both the x and y directions.

From the result of our experiment, we proved the ACEI-robot's ability to approach the target roughly using the main CCD camera and use the small CCD to reach the target within the stated tolerance by means of successive corrections. The number of convergent times given in table 2 stands for the number of correction cycles necessary.

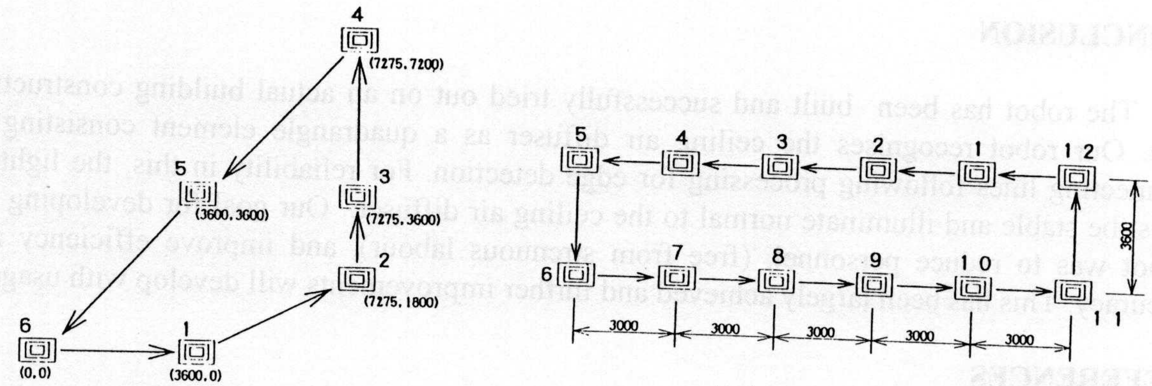
5.2. Results of air volume measurements

The result of air volume determined by the robot and manually are compared in table 3. It should be noted that the robot did complete these measurements without damaging the ceiling or the ceiling air diffuser.

The difference of the result between robot and human being is within an average of 10%, which proves that the robot's air volume measurement is accurate. Two and a half minute, including the movement from one diffuser to another, were taken by the robot which is half the time for humans. The time needed for the robot to measure one diffuser about one half that for humans.

5.3. Results of building site experiment

On actual building construction site, the robot's total recognition was eighty percent reliable. This is due to the change of diffuser shadows with sun light. In our experiment, the robot sometimes mistook a sprinkler head adjacent a ceiling air diffuser. This brought down the accuracy rate of the experiment. However, with perfect lighting conditions robots recognition was 100% reliable.



(a) Pattern A

(b) Pattern B

Fig. 8 Experimental path pattern

Table 2 Accuracy of autonomous movement experiment

Point No.	Target		First Movement			Second Movement			Convergent times
	X	Y	X	Y	Diff.	X	Y	Diff.	
1	3600	0	3731.2	15.0	131.2	3603.4	-11.7	12.2	1
2	7275	1800	7243.3	1788.8	33.6	7273.2	1795.4	5.0	1
3	7275	3600	7226.0	3557.9	64.6	7242.5	3569.0	45.0	2
4	7275	7200	7259.3	7269.8	71.5	7291.2	7223.2	28.3	2
5	3600	3600	3654.8	3649.4	73.8	3651.2	3614.2	53.2	3
6	0	0	-56.3	238.9	245.4	6.1	5.0	7.8	1
avg.					103.4			25.3	

Table 3 Result of air temperature and volume measuring experiment

Point No.	Air Volume(m^3/h) Robot	Air Volume(m^3/h) Human	Temperature (℃)
1	241.5	240.0	21.3
2	271.6	250.0	21.0
3	233.2	250.0	21.1
4	238.4	230.0	21.1
5	220.4	210.0	21.1
6	218.2	210.0	21.1

CONCLUSION

The robot has been built and successfully tried out on an actual building construction site. Our robot recognises the ceiling air diffuser as a quadrangle element consisting of connecting lines following processing for edge detection. For reliability in this, the lighting must be stable and illuminate normal to the ceiling air diffuser. Our goal for developing the robot was to reduce personnel, (free from strenuous labour), and improve efficiency and accuracy. This has been largely achieved and further improvements will develop with usage.

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