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Sensory Navigation of Autonomous Cleaning Robots

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***Abstract* - This paper addresses a general problem of sensory navigation for autonomous cleaning robots (ACR) in unknown environments. Although absolute self-localization and accurate environment modeling still remain unsolved, a delicately designed mobile robot still can carry out a task practically. Under this strategy, we propose a cleaning robot system, which works without any environment map and global self-localization. It has a three-layer structure. The lower layer consists of general hardware: ultrasonic sensors, infrared sensors, incremental encoders, DC motors, vacuum, etc. Upon these sensors is the sensory behavior layer, which includes several motion templates. These intelligent motion templates can deal with most situations, seldom making the robot trapped. The upper layer is the task-based navigation layer, which carries out the tasks of environment learning, cleaning, and homing. Finally the experiment results show that this strategy works well, even the robot knows little about the environment.**

Index terms - Autonomous cleaning robot, Sensory navigation, Environment modeling, Self-localization, Coverage path planning.

I. Introduction

For autonomous cleaning robots (ACR), sensory navigation is a basic problem, including leaning the environment, covering every part of the room floor efficiently, and going back to the charging dock. But some key problems in mobile robotics still remain unsettled, for example, self-localization, environment modeling, and robot vision. These problems are so fundamental that sensory navigation is still not easy for the ACR. Many researchers have proposed some methods to solve the complete coverage path planning problem for cleaning robots, such as line sweep deposition [1], scanning path [2], motion template [3], cost function [4], neural network [5, 6], etc. But these methods have the assumption that environment modeling and global self-localization are available. How to implement is a big problem. Reference [2] carried out an experiment on a robot platform in an area of 10 square meters with a large obstacle inside. Scanning path was used to fill the cleaning area and the orientation error was corrected by exploiting straight-line features on the ceiling. But this method is still far from practical application.

Since global self-localization and accurate environment modeling cannot be settled, why not develop a lower-level intelligent entity, which can work in an easy way? In this paper, a cleaning robot system, which works without any environment map and global self-localization, is described. It has a three-layer structure. The lower layer consists of general hardware: ultrasonic sensors, infrared sensors, incremental encoders, DC motors, vacuum, etc. This ACR uses ultrasonic sensors to perceive, and incremental encoders mounted on the wheels to locate itself in a small area. And upon the sensors is sensory behavior layer, which concludes several motion templates: point turning, line following, wall following, side shifting, obstacle rounding. These intelligent motion templates can deal with most situations, seldom making the robot trapped. In the task-based navigation layer, three processes according to the specific tasks are built: environment learning, cleaning, and homing. The environment leaning uses the strategy of "groping and exploring" [7]; A local coverage path planer based on dead reckoning generates a cleaning path for the robot; To find the charging dock, the homing process exploits a priori that the charging dock must be aside the wall.

II. System Description

The lower layer can be mainly divided into 6 parts: perception part, local self-localization part, DC motors, charging dock, dust-collecting part, and power supply.

A. Perception part

The ACR has ultrasonic sensors and a bumper to perceive the environment. Ultrasonic wave is a kind of acoustic wave. It has the same velocity in a certain kind of medium, while on the interface of two different media, the reflection occurs. Based on this principle, the distance to obstacles can be measured by the time between sending and receiving the signal (time of flight). The expression is:

$$s = \frac{vt}{2} \qquad (1)$$

Where, t is the time of flight; s is the distance between the robot and obstacles; v is the velocity of sound wave in the air.

In the system, there are 13 pairs of ultrasonic sensors (a sender and a receiver for each pair), 7 pairs for the front side and the rest for the left and right side, shown as Fig. 1. For easy reference, the sensors are labeled as follows: s_{fi} is the i^{th} front sensors, $i \in \{0...6\}$; s_{Lf} and s_{rf} are the front ones on the left side and right side; s_{Lb} and s_{rb} are the back ones on the left side and right side. The sensor readings are processed into TOO-CLOSE, CLOSE, NORMAL, FAR by three thresholds. And when obstacles are beyond the sensors' range, the reading is NONE.

The bumper covers the whole front. When all the ultrasonic sensors cannot work, it can give a good protection.

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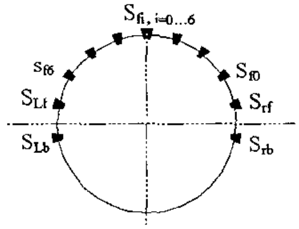


Fig.1 Layout of ultrasonic sensors

B. Local self-localization part

The local self-localization system is composed of two incremental encoders mounted on the robot wheels. The pose of a mobile robot is denoted by a three-dimensional variable ($x(t)$, $y(t)$, $\theta(t)$). The $x(t)$, $y(t)$ are coordinates in some Cartesian coordinate system and $\theta(t)$ is the robot's heading direction. The following nonlinear state equation describes the time-domain kinematic model of the ACR:

$$\begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\theta}(t) \end{bmatrix} = \begin{bmatrix} v \cdot cos\theta(t) \\ v \cdot sin\theta(t) \\ \mathrm{R} \cdot (\omega_l - \omega_r)/\mathrm{W} \end{bmatrix}. \tag{2}$$

Where, ω_L, ω_r is the angular velocities of the right wheel and the left; R denotes the radius of the wheels; W represents the distance between the two wheels. So the linear velocity is

$$v = \mathrm{R}(\omega_\mathrm{L} + \omega_\mathrm{r})/2. \tag{3}$$

But there are many uncertainties in pose estimation, including unequal wheel diameters, misalignment of wheels, finite encoder resolution and sample rate, uneven floors and slippage of wheels, etc. But within a short period, the pose estimation is accurate enough to carry out the local coverage path planning and obstacle rounding action.

C. The charging dock

The charging dock is the home for the robot, where it can recharge the battery and wait for the next duty. It concludes two separate parts: one is on the robot, including a side infrared receiver, a back infrared receiver, and two electrodes; the other part is on the charging dock, including an infrared sender and two electrodes. When the ACR loses the dock's location because of the accumulated errors, the infrared sender helps the ACR to find the dock. When the robot detects the signal by the side receiver, the dock is nearby. And the back receiver helps the robot's two electrodes point to the corresponding electrodes on the dock.

D. DC Motor driving

The driving part includes two DC motors, two incremental encoders, and a serial of gear transmission system. The part can drive the robot turn at any radius. The velocity can be calculated by using (3).

E. The rest

Fifteen years ago, when SANYO's control and system research center developed the cleaning robot, the wired power supply was preferred [8]. Now the capacity to weight rate of battery is high enough for ACR to work up to one hour. So, a battery pack of 24*4.1 Ah is used. This makes the robot move freely among the rooms.

Finally, the dust-collecting part is a small vacuum, which is fixed tightly in the ACR. During moving on the floor, the covered path is cleaned by this system.

III. INTELLIGENT BEHAVIORS

In this layer, a set of sensory motion templates are designed on the basis of above described sensors. They are point turning, line following, wall following, side shifting and obstacle rounding, which are all primitive.

A. Point turning template

When $v_L = -v_r$, the robot turns around the middle point of the shaft clockwise or counterclockwise. The turning angle is calculated by

$$\Delta\theta = \int 2 \cdot v_\mathrm{L} / \mathrm{W} dt. \tag{4}$$

Where, v_L is the velocity of the left wheel; v_r is the velocity of the right wheel.

B. Line following template

The robot gives the same speed to both motors: $v_L = v_r > 0$. So the robot follows a line track until the front sensors see something, that is, $\exists\ s_{fi} <$ NORMAL, $i \in \{0...6\}$, shown as Fig. 2. This module can be used to drive the robot move to the side of an obstacle or wall.

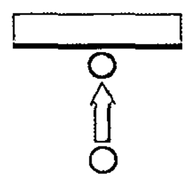


Fig. 2 Line following module

C. Wall following template

Before cleaning, the robot should know the size and complexity of the environment. Because of short sight, the robot just gropes alone the wall like a blind man, shown as Fig. 3. The distance between the wall and robot is kept about five centimeters with the help of ultrasonic sensors.

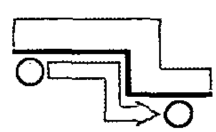


Fig. 3 Wall following template

There are three kinds of wall segments: "—" shape, "┘" shape and "┐" shape, shown as Fig. 4. Different control strategies are used for different shape segments. In the following section, we take the clockwise wall-following control for detailed discussion.

- "—" shape:

Most wall segments are "—" shaped, with no abrupt turning. To get real-time performance, only the front side-sensors are used for the robot's motion control. Table 1 shows the control strategy.

TABLE I

WALL-FOLLOWING CONTROL STRATEGY

Sensor data	s_{Lf} = FAR or NONE	s_{Lf} = CLOSE	s_{Lf} = TOO_CLOSE	s_{Lf} = NORMAL
Motor-driving command	$v_L < v_r$	$v_L > v_r$	$v_L > 0$, $v_r = 0$	$v_L = v_r$

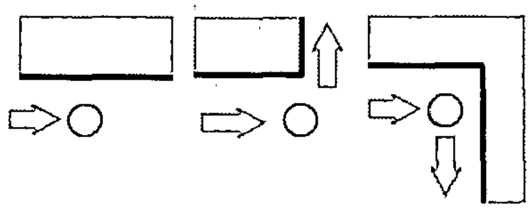
This way, the robot follows a smooth and close track beside the wall. Sometimes, the false sensor readings make the robot go too close to or even run into the wall. In this case the bumper works, giving the alarm to the system.

- "┘" shape:

If s_{Lf} = NONE and s_{Lb} < FAR, the robot comes to an abrupt "┘" shaped corner. To keep close to the wall, a delicate strategy is adopted. First go straight until s_{Lb} =NONE; Secondly, turn with $v_L = 0$ and $v_r > 0$ until the s_{Lb} or s_{Lf}= NORMAL.

- "┐" shape:

If $\exists s_{fi}$ = NEAR, $i \in \{0\ldots6\}$, the robot goes into a "┐" shaped corner. Then the robot enters the point turning template, until the condition is satisfied: $\forall$ s_{fi} = FAR, $i \in \{0\ldots6\}$.



(a) "—"shape (b) "┘"shape (c) "┐"shape

Fig. 4 Shapes of the wall segments

D. Side shifting template

This module is based on the wall following template. The only difference is that the side shifting template is given a travel distance perpendicular to the sweep direction, which is the width of the robot. This way, two adjacent cleaning paths leave little uncovered area between them, shown as Fig. 5.

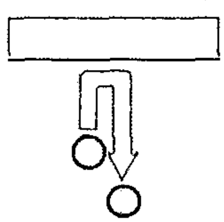


Fig. 5 Side shifting template

E. Obstacle rounding template

In some cases, the robot needs to go around the obstacle. Two requirements must be satisfied:

- After the obstacle rounded, the original direction must be kept: $\theta_{in} = \theta_{out}$.
- During all the process, the robot must keep close to the obstacle. Only this way, the vicinity of the obstacle will be cleaned.

The robot first uses the wall following template to round the obstacle, and when the condition

$$\begin{cases} \sum_k \Delta x_k > \text{Threshold} \\ \sum_k \Delta y_k = 0, k = 0,1,2\ldots \end{cases} \tag{5}$$

is satisfied, the robot ends the template and enters the point turning template to find the original direction. Fig. 6 shows the process.

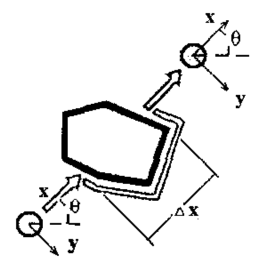


Fig. 6 Obstacle rounding template

IV. TASK-BASED NAVIGATION

On above described basic behaviors, the robot can do many things, such as learning the environment, cleaning of complete coverage, and finally finding its way home, shown in Fig.6. The environment leaning uses the strategy of "groping and exploring". Firstly the ACR runs out of the dock, and uses the wall following template to walk alone the wall. It keeps going until it receives infrared signal by its side receiver. Then it stops beside the dock and approximately knows the size and shape of the environment, shown as Fig. 7 (a). For path planning, the ACR adopts local complete coverage path planning, utilizing the reliable self-localization ability in a relative small area. Combined with random path planning, this strategy can provide robust and efficient cleaning path, shown as Fig. 7 (b). These two sections have been addressed in other papers [9, 10, 11, 12]. So sensory navigation of homing is discussed in details here.

When finishing the cleaning task, the robot needs to find the way home. So it can recharge its battery pack and wait for the next duty. Because no global self-localization and accurate environmental map, the robot has no idea where the home is. But a priori that the dock is aside the wall can greatly increase the possibility of finding the dock for the robot. The process follows the steps:

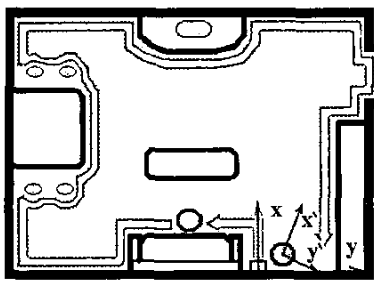
Step1: Enter point turning template to select a homing direction;

Step2: Enter line following template until finding an obstacle;

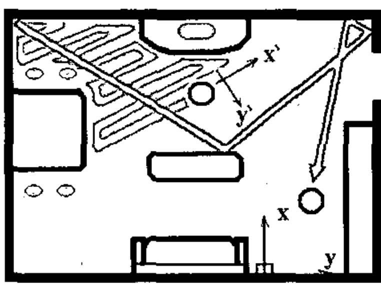
Step3: Enter the obstacle rounding template. Then there are two possible events:

- The obstacle is isolated, which the robot can round. When (5) is satisfied, go to Step 1.
- If the obstacle is the wall, then the robot will never find an exit. So the robot keeps following the wall until finding the charging dock.

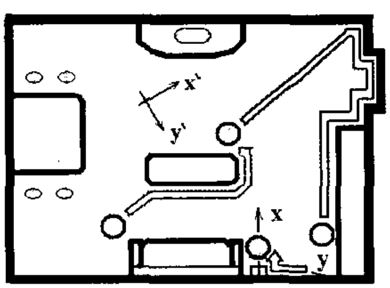
Fig. 7 (c) shows the process. After the environment leaning and cleaning processes, the coordinate system on the robot has shifted and rotated apparently according to the world coordinate system because of the accumulated errors. In most cases, the x axis heading rotates clockwise within 180°, even in large meeting rooms. So the homing direction is selected as the robot's x axis heading and the obstacle-rounding direction selected as counterclockwise. This way, the robot finds the shortest path on the way home in most cases.



(a) Environment modeling



(b) Cleaning



(c) Homimg process

Fig.7 Sensory navigation

V. Conclusion

In this paper, an autonomous cleaning robot is described, which has no environment map and global self-localization. The three-layer structure makes the robot work robustly and efficiently in ordinary home environments, even based on general hardware. In our future work, global self-localization and environment modeling will be our emphasis. With these two problems settled, the robot's performance will be greatly improved.

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