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Tracking chemical plumes in constrained environments

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SUMMARY

This paper describes an on-going project to develop robotic systems for locating chemical sources in constrained environments. There is increasing interest in applying chemical sensing to mobile robots. Locating the source of a chemical plume is seen as an important use for a chemical sensing robot. Current research tends to concentrate on source location in open and relatively obstacle free environments. Many of the applications for this technology will be areas where airflow is constrained and deflected by obstacles such as inside buildings, mines and subway tunnels. It is this kind of situation that this project aims to address.

KEYWORDS: Robotics; Chemical sensing; Sonar; Airflow; Chemical source location.

1. INTRODUCTION

The numbers and types of sensors built into a robot have a large bearing on its overall capabilities. For this reason there is a lot of interest in developing new sensors for robotic systems together with associated data processing algorithms. Chemical sensing is an example of a relatively new robotic sensing modality.[1] All biological creatures have some form of sensitivity to chemicals and many could not survive without the information provided by their chemical senses. Amongst other things, chemical sensitivity is used to find food, locate a mate, warn of harmful situations, communicate, navigate, and mark territory.[2] For this reason it seems reasonable to assume that chemical sensing will also have valuable applications for robotic systems.

In general there are two situations in which a robot can interact with chemical signals. These were first discussed in a report to the European nuclear industry written by Larcombe and Helsall in 1984.[3] The first of these situations involves chemicals carried to the robot by fluid flow from a distant source. If the substance is some form of repellent then the robot should run away from the source. For an attractant the chemical plume should be followed until the source is found. In the second situation chemical is deposited on a solid surface or percolates to the surface of the ground. The location of the chemical source can be determined by detecting the traces of chemical released into the surrounding air. These chemical markings provide a trail to follow, give other navigational information or signal the location of a buried chemical source.

The search for the source of an odour is seen as an imporant capability for robots to acquire[4–11] and one for which many uses can be imagined. If a robot could perform this task effectively it could provide a substitute for sniffer dogs. Such a system would have the advantage that the robot would be able to communicate the nature of the odour it detected to its human handlers. One of the drawbacks of sniffer dogs is that it is difficult or impossible to find out exactly which chemical species is triggering their response. In many cases it is not the target chemical but an impurity or by-product that is detected. Another problem is that sniffing is a natural action for dogs so even if their sense of smell is impaired this will be hard for a handler to determine. Such a condition could have serious consequences in some situations such as during mine clearance operations. Animals require extensive training, they must be cared for by an expert handler, their attention span is short and they suffer from fatigue. Robotic systems could offer improvements in all of these areas. There are also environments where it would be physically impossible for animals and their handlers to operate. These include high concentrations of poison gas and nuclear radiation. Robots could be hardened to withstand these conditions and could even be considered to be disposable if they became too contaminated.

The majority of current research has concentrated on odour source location in an obstacle-free environment. This is unlikely to be a realistic approximation of the real world where such robots may be required to operate. The author has been interested in developing robots for use in more realistic environments. An earlier paper[8] described an experiment where a robot was required to negotiate around obstacles to locate the source of an odour plume. In this case the obstacles were low to the ground and did not appreciably deflect the odour plume. The current experiment investigates a situation where the airflow is contained within a network of interconnected tunnels and the robot is required to deduce the correct direction to take based on multi-sensory information. This experiment is intended to simulate an indoor environment such as a mine, factory building or subway tunnel. The experimental environment is built using cardboard boxes as inexpensive and reconfigurable building blocks. A cooling fan sets up an air-current which carries the target chemical, camphor, through passageways between the boxes. The robot detects the camphor and follows it back to its source. This experiment is seen as one step towards creating a robot which can locate the source of a volatile chemical released into an environment constrained by walls and obstacles.

2. NECESSARY ROBOT CAPABILITIES

Here is a list of capabilities that a robot will require in order to track a chemical plume in a constrained environment. Particular environments may require additional capabilities specific to that environment:

Capabilities relating to chemical sensing

(i) Detect the target chemical (this is the *sine qua non* for this robot application)

(ii) 'Project' local chemical intensity readings into the environment to estimate the track towards the source. In general this requires additional sensory information.

(iii) Identify the source.

Capabilities relating to negotiating the environment

(iv) Move through the environment using an appropriate means of mobility.

(v) Sense the environment so that the robot can choose a direct and safe path towards the chemical source.

In addition, the robot must implement a strategy for locating the chemical source taking into account the capabilities listed above and the nature of the environment. The starting point for the project was a specification of the experimental environment.

3. THE EXPERIMENTAL ENVIRONMENT

For this project it was necessary to build a fairly complex experimental environment to simulate an indoor location contained by walls and obstacles. This had to be built to a small scale in order to fit into the available laboratory space. To provide an inexpensive and reconfigurable setup cardboard boxes were used to make the structure of the environment with clear plastic covering the top of the passages so that the progress of the robot could be monitored. It was assumed that in most situations some amount of airflow would be present due to such effects as forced and natural ventilation and convection. A controlled airflow was introduced into the model environment using a cooling fan connected to a variable transformer for speed control.

Figure 1 shows the configuration of the experimental environment. Each rectangle represents a 470 mm by 270 mm by 270 mm cardboard box. In experiments an odour source was placed at various points in system of passageways.

4. THE ROBOT

To keep the experiment to a reasonable size a small robot developed at Monash University, the RAT robot, was used as the experimental platform. This 100 mm diameter robot can easily negotiate the 270 mm wide passageways in the experimental environment. The design of the RAT robot is described in reference 1. This robot has a 'turtle geometry' wheel arrangement and can move forwards and backwards in a straight line or rotate on the spot. The RAT robot incorporates a 68HC11 microcontroller which controls the robot wheels, monitors all of the sensors and implements the control strategy. Figure 2 shows a photograph of the RAT robot used in this project. It carries whisker bump sensors and an ultrasonic sensor for monitoring its environment as well as an airflow sensor and chemical sensor for tracking the odour plume.

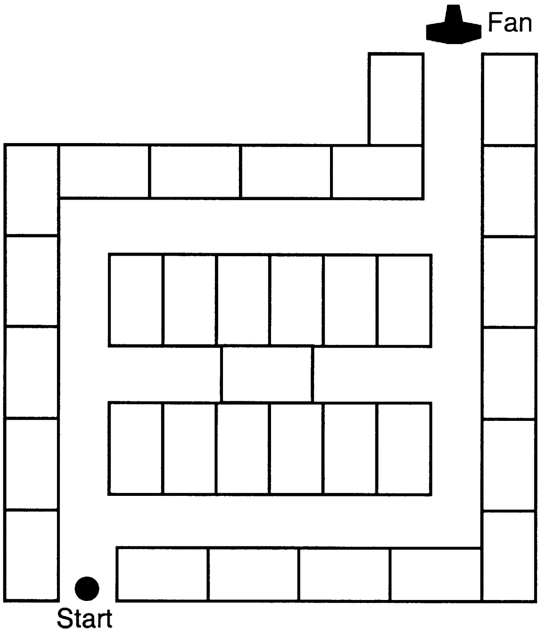

Fig. 1. The experimental environment.

5. SENSORS

As outlined in Section 2 a robot will require two groups of sensors in order to undertake the task of locating the source of a chemical plume in a constrained environment. For the chemical sensing group the robot requires a sensor for the target chemical and a sensor to provide information that will allow the chemical reading to be projected towards the source. In some situations it is possible to take two spatially separated samples and use these to work out the chemical gradient and hence the direction towards the source. In a tunnel or passageway the airflow is constrained and once a steady state is established there may be no significant chemical gradient. For this reason it was decided to measure airflow as an indicator of the direction of arrival of the chemical signal.

To negotiate the passageways in the experimental environment the robot needs to be able to follow walls and to avoid collisions when running head-on into a wall at a turn in the passageway. There are a few possible sensors for these tasks. However, taking into account size, simplicity and power consumption it was decided to use an ultrasonic sensor for wall following and whisker sensors to warn of frontal obstacles. The following sections describe each sensor system.

5.1 *Quartz crystal microbalance*

For safety and convenience camphor was chosen as the target chemical. With a suitable coating material a quartz crystal microbalance (QCM) can be used as a reasonably sensitive and stable sensor for camphor. The QCM sensor uses a quartz crystal as a sensitive balance to weigh odour molecules. A chemical coating on the crystal is chosen to

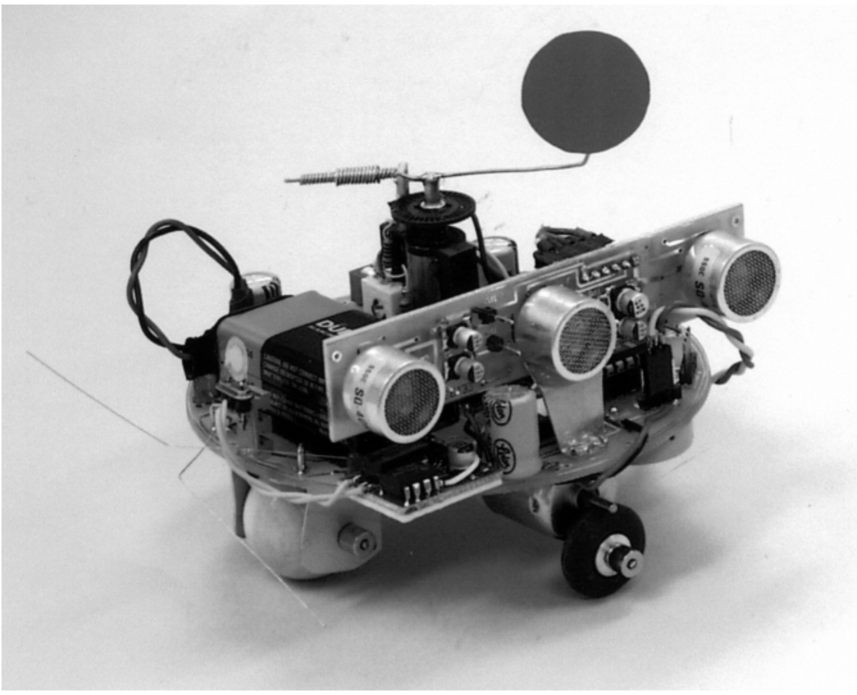

Fig. 2. The RAT robot equipped to locate an odour source in an environment of interconnected passageways.

have a specific affinity for the target odorant molecules. For camphor silicone OV-17 is a suitable coating. When air containing target molecules is drawn over the crystal some of the molecules become temporarily attached to the coating. This increases the mass of the crystal and lowers its resonant frequency. Quartz crystals that are made to provide a frequency reference are cut from a single crystal of quartz. For this application the quartz crystal plate is usually cut with a crystal orientation that minimises temperature coefficient around room temperature. These crystals are commonly available and their thickness shear mode of oscillation is very sensitive to change in mass of the crystal. Change in frequency of the crystal Δf is related to change of mass per unit area Δm by the equation:[12]

$$\Delta f = -\frac{2f^2 \Delta m}{\rho v} \tag{1}$$

where:

f = crystal frequency
ρ = density of crystal material
v = velocity of sound in the crystal material

In the derivation of this equation it is assumed that if a foreign material is added to the surface of the crystal, provided it is uniformly spread over the active area of the crystal, then this mass loading will have the same effect as increasing the crystal thickness by adding an equivalent mass of quartz. In practice the frequency of the sensor crystal is subtracted from a stable reference oscillator to produce a difference frequency in the kilo-hertz region. This frequency varies linearly with chemical concentration and will change by up to several hundred hertz when exposed to a strong concentration of the target chemical.

In the experimental scenario the robot is positioned at the point where air exits from the system of passageways. The robot waits until it detects a significant chemical concentration before venturing forwards to locate the source. To test this function the sensor was positioned at the air exit and chemical concentration measured. After recording for 50 seconds the odour source was introduced at a point 3.5 m upwind of the robot. The source was removed 50 seconds later. As can be seen in Figure 3, after a transport delay of about 20 seconds a clearly recognisable odour signal was detected at the outlet. This indicates that the camphor signal was carried by the airflow at about 1.75 m/s. At the start of the experiment airflow at the outlet was set to 0.3 m/s. However, this flow rate is the result of combining the airflow down two separate passageways.

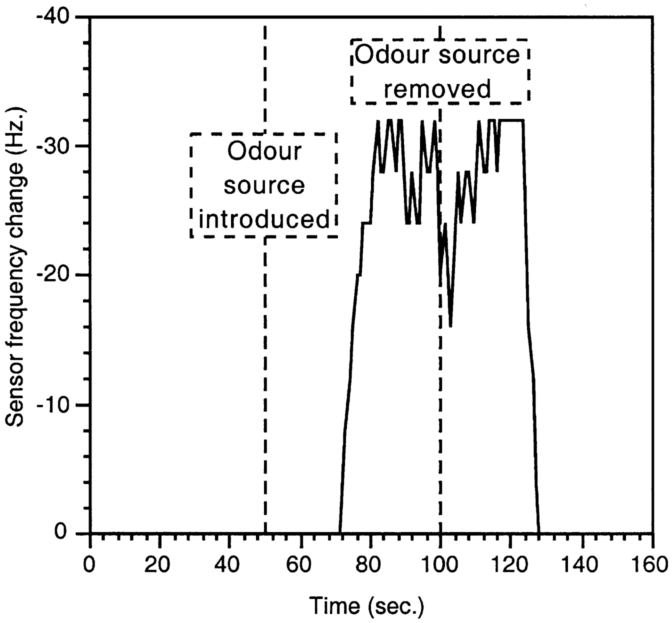

Fig. 3. Detection of an odour source in the experimental environment by a robot situated at the airflow exit.

The sensor crystal was mounted on the front of the RAT robot and can be seen in the photograph of the robot (Figure 2) in front of the battery.

5.2 Sensing airflow

The robot requires an indication of the prevailing airflow direction in order to be able to navigate towards the source. Airflow velocity must also be taken into account to ensure that the direction measurement is meaningful. The reading given by a simple windvane in a region of still air could be very misleading if the robot cannot determine that there is no significant airflow. For simplicity and to save space it was decided to combine wind velocity and direction sensing into one unit. After considering a number of different sensor configurations a novel active sensor was developed which fulfils design criteria of simplicity, small size and low power consumption.[13] The key feature of the sensor is a flat plate or paddle when the robot is travelling on an inclined surface. The motor used in the airflow sensor is the 12 volt version of the type 1616 dc-micromotor manufactured by the Swiss company Minimotor SA. In still air the velocity of the paddle will be constant; however, when situated in an airflow the paddle is slowed down when moving upwind and speeded up when moving downwind. This variation in paddle rotational velocity is monitored by an optical encoder and used to infer wind direction and velocity. The diagram shown in Figure 4 illustrates the major components of the airflow sensor. A graph showing data from the airflow sensor is given in Figure 5. During one full revolution the paddle is seen to speed up when travelling with the prevailing airflow and slow down when travelling against the airflow. The angle of the paddle which corresponds to maximum velocity is used to infer airflow direction and the difference in paddle speed between its maximum and minimum values gives an indication of airflow velocity.

5.3 Ultrasonic sensor

In this experiment the purpose of the ultrasonic sensor system is to provide information to enable efficient wall-following behaviour. The information required is orientation to ensure that the robot is running parallel to the wall and distance from the wall to make sure that the robot is maintaining the desired separation from the wall.

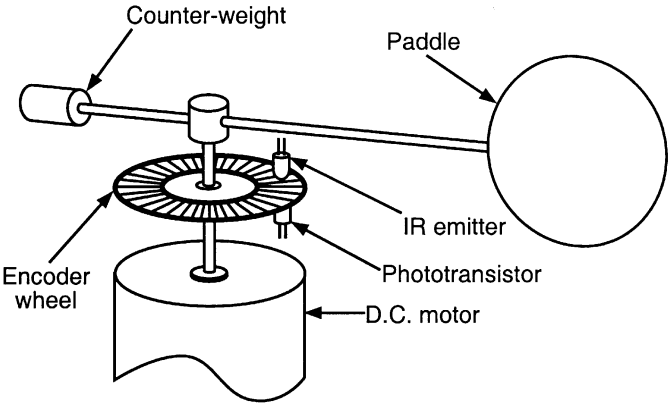

Fig. 4. A diagram of the airflow sensor.

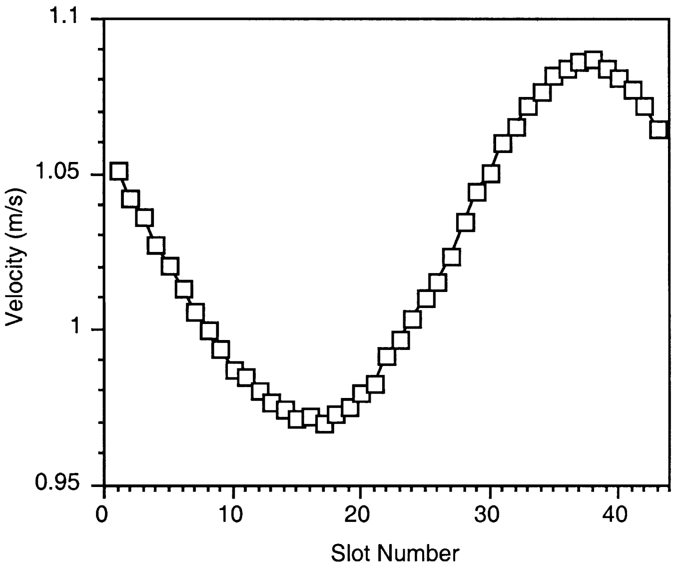

Fig. 5. Airflow sensor paddle velocity in a steady airflow for one full revolution (note that on the encoder wheel 44 slots correspond to one full revolution.

The ultrasonic sensor system, consists of a central transmitter that is fed by a five cycle burst of 40 kHz square-wave generated by the robot's on-board 68HC11.[14] Twin receivers detect the returned echo which is amplified, rectified to give a logic output when the received pulse exceeds a set threshold. The reflection of ultrasound pulses is specular and the echo that arrives at the receivers seems to come from a virtual image of the transmitter T′ reflected in the wall (Figure 6). The ultrasonic sensor can be used to determine the range and orientation of a reflecting wall using a single measurement. The bearing to the virtual image of the transmitter T′ from receiver R1 is:

$$\theta = \sin^{-1}\left(\frac{d^2 + r_1^2 - r_2^2}{2dr_1}\right) \qquad (2)$$

The perpendicular distance from the wall to the transmitter is the separation s:

$$s = \frac{1}{2}\sqrt{r_1^2 + \left(\frac{d}{2}\right)^2 - 2r_1\left(\frac{d}{2}\right)\cos\,(90 - \theta)} \qquad (3)$$

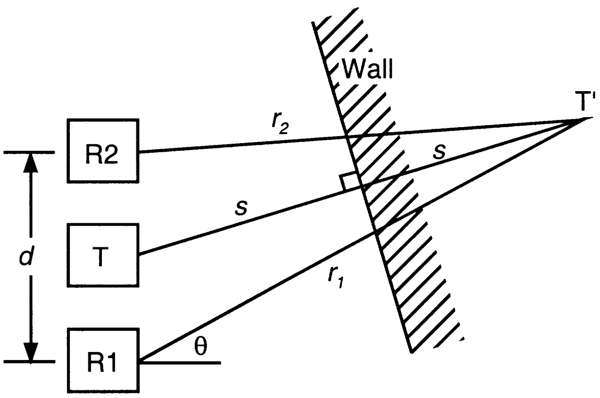

Fig. 6. Specular reflection of ultrasound produces a virtual image of the transmitter.

The values of r_1 and r_2 are calculated from the time of flight of the returned pulse:

$$r_1 \text{ or } r_2 = ct \tag{4}$$

where

c = speed of sound in air (approximately 330 m/s)
t = time of flight.

The 68HC11 microcontroller on the RAT robot does not have sufficient resources to calculate trigonometric functions and therefore separation from the wall s is approximated as half the distance r_1. This approximation will be reasonably accurate when distance to the wall is large compared to d the separation between the receivers or when θ is small. Information about the angle of the robot with respect to the wall is required during wall following. The wall following procedure has been formulated so that no explicit calculation of this angle is required.

5.4 *Whisker sensors*

Whisker sensor are made from 0.009 inch diameter steel guitar string that pass through a metal loop. When they are bent due to contacting a wall the guitar string touches the metal loop and the closed circuit signals the contact.

6. THE SEARCH ALGORITHM

6.1 *Wall following*

Fast and reliable wall following behaviour is easily produced with the aid of the ultrasonic sensor. The robot is programmed to align itself parallel to the left-hand wall and then move forward 5 cm. If the robot is too close to the wall the robot turns 6 degrees away from the wall before executing the move command. If the wall is straight then this increases the robot's separation from the wall. If the robot is too far from the wall a turn of 6 degrees towards the wall is executed to bring the robot closer to the wall. In the event that the whisker sensors detect an obstacle ahead the robot backs up 5 cm and then turns 90 degrees clockwise. Wall following is produced by executing a repeated sequence of these moves. Turning parallel to the wall is performed by a repeated sequence of sensing the relative delays of the signals arriving at R1 & R2 and then rotating a small amount to reduce the difference in arrival times. The process terminates when the difference in arrival times falls below a fixed threshold.

Figure 7 shows the track of the robot as it travels through the experimental environment using wall following. At point 'c' the robot detects the wall ahead with its whisker sensors and this triggers a response to back-up and then turn right 90°. This test demonstrates the ability of the robot to negotiate the environment using the ultrasonic and whisker sensors.

6.2 *Tracking the chemical plume*

If the robot is moving along a passageway in the chemical plume and in an up-wind direction then there are a number of situations which can occur if the robot reaches a branch or turn in the passageway. A representative sample of these situations is illustrated in Figure 8. By studying these situations a number of simple rules were formulated to govern the actions of the robot:

(i) If the robot continues to travel up-wind and still detects the chemical then keep going (even if the robot turns a corner in order to follow the left-hand wall). This rule is illustrated by Figures 8a, 8c, 8f, 8h, and 8i.

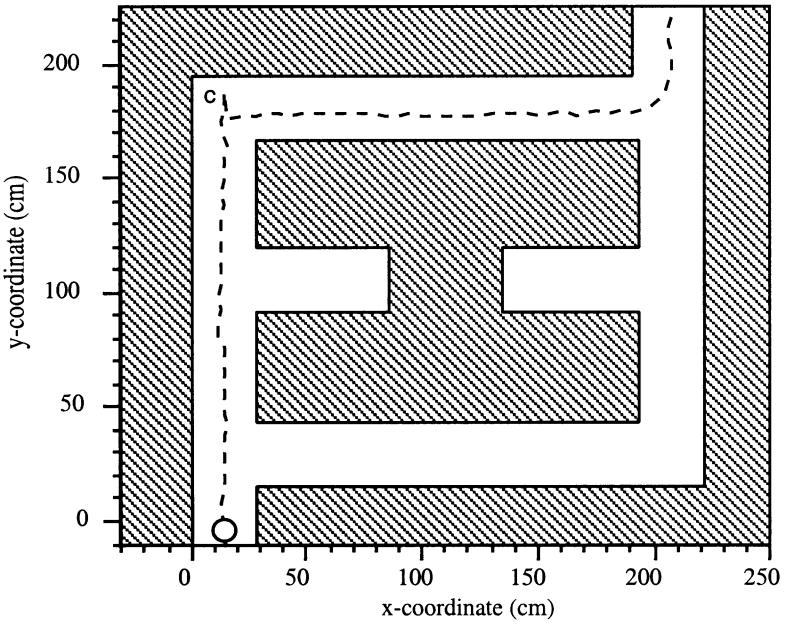

Fig. 7. The path of the robot through the experimental environment when using wall-following only.

(ii) If the robot finds itself travelling down-wind then it should turn around and come back. Figures 8d, and 8e show this case.

(iii) If the robot fails to detect the chemical then it should turn around and come back. The remaining two Figures 8b and 8g cover this situation.

For rules (ii) and (iii) a turn followed by back-tracking is required. The robot must delay for a short distance *d1* (0.3 m was chosen in this experiment) to ensure that it moves past the junction before turning. Once a turn is triggered there is a refractory distance *d2* (0.6 m) during which a further turn cannot be triggered. This gives time for the robot to return to the junction and take the next exit.

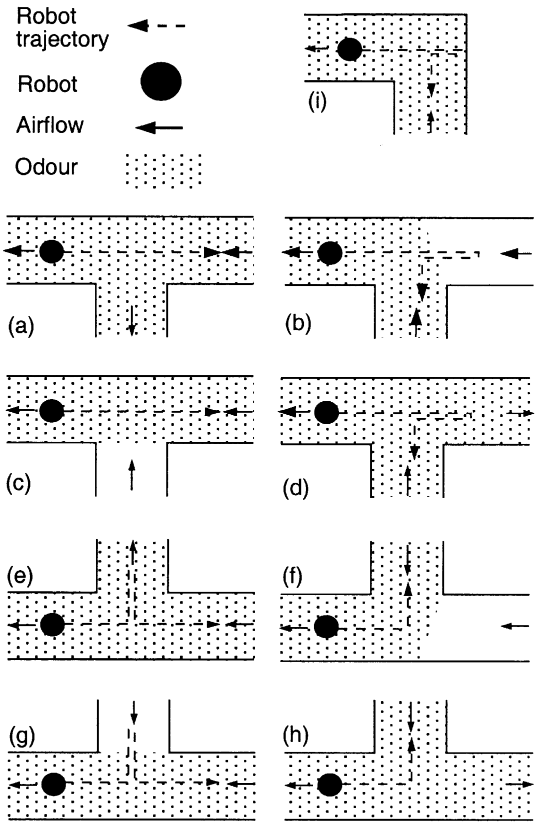

Fig. 8. Situations that can occur when the robot reaches a turn or junction in the passageway.

The control of the robot consists of a combination of the wall-following and chemical/airflow sensing behaviours. Figure 9 shows a diagram in the style of the subsumption architecture[15] which illustrates the control scheme for the robot.

7. RESULTS

At the start of the experiment the robot was placed at the point where air vented from the experimental structure. The odour source was then introduced at the point shown in Figure 10. About 20 seconds later, after the chemical had travelled to the outlet point the robot detected the chemical and started into the maze. Initially the robot followed the left hand wall and travelled along a similar path to the pure wall-following case illustrated in Figure 7. At point ‘x’ the robot responded to the loss of the chemical signal, turned 180° and started back towards the junction. The left-hand wall-following behaviour carried it round the left-hand turn and the robot was once again following the chemical up-wind. After taking two further left-hand turns the robot arrived at point ‘y’. Here the airflow velocity fell below a threshold value and the robot performed another 180° turn. Following round the left hand corner the robot collided with the odour source. Details of the robot movements around a junction in the passageways are shown in Figure 11.

8. CONCLUSIONS

A robot system has been demonstrated which can find an odour source within a network of interconnected passage-ways. To enable the robot to perform this task it was equipped with a number of sensors including a novel ultrasonic range sensor and a novel airflow sensor. This demonstration is seen as a step towards the development of chemical sensing robots which can perform some of the tasks currently undertaken by sniffer dogs.

The robot contains the minimum of sensors required to complete the source location task. In its current form the robot would only be capable of negotiating junctions of passageways which were of a similar dimension to those used in this experiment. To some extent the algorithm could be adjusted to allow for different passageway dimensions by

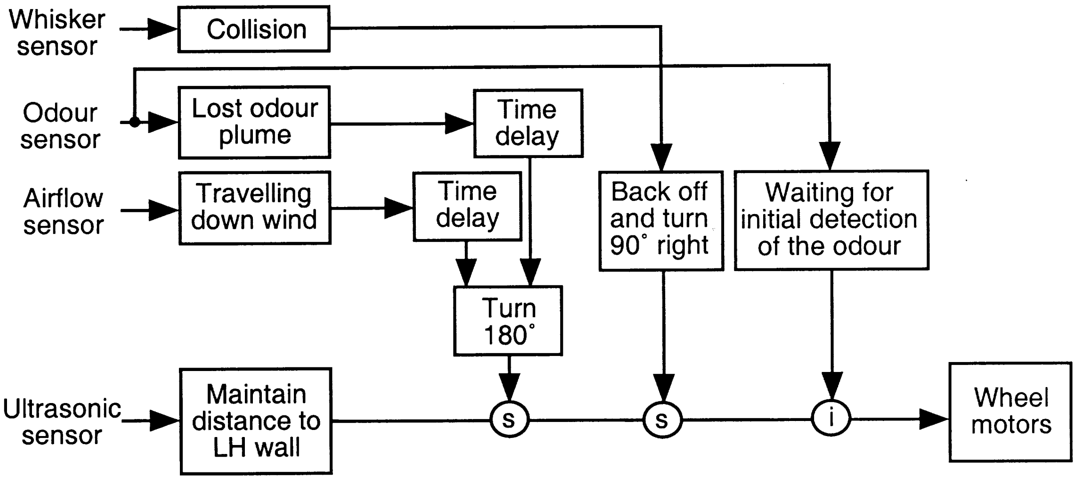

Fig. 9. A diagram illustrating the control scheme for the robot.

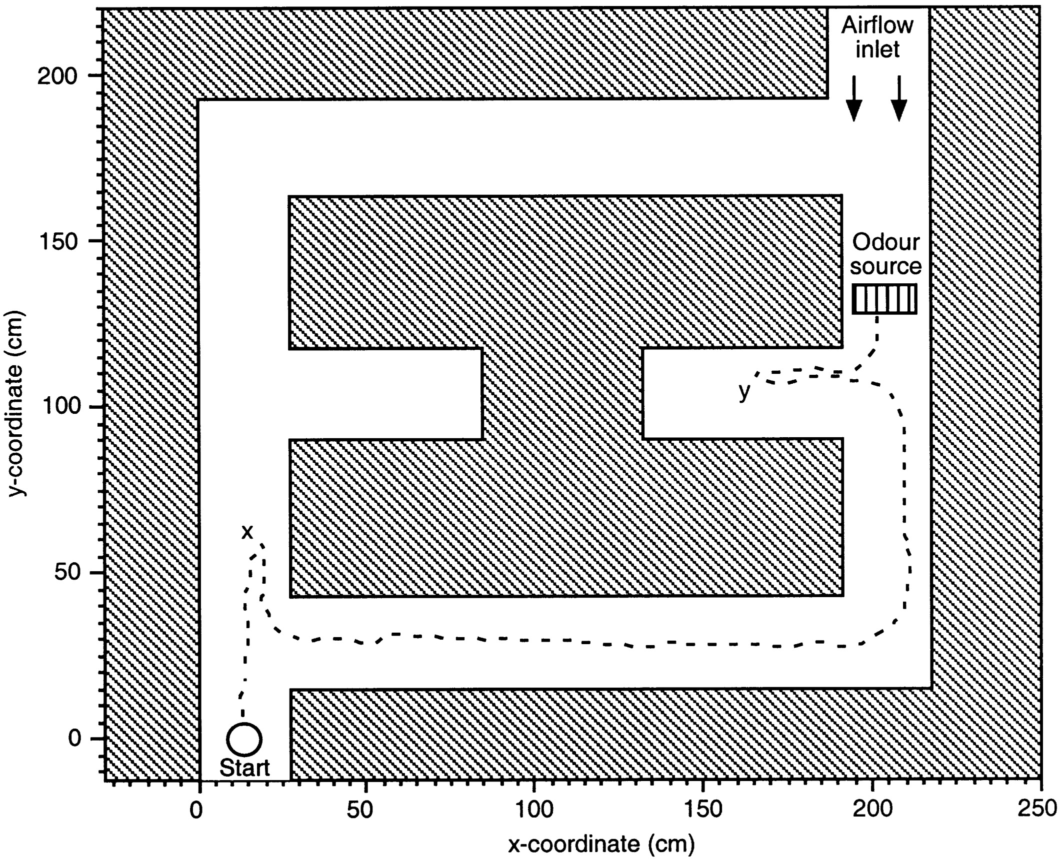

Fig. 10. Tracking a chemical plume.

varying the values of *d1* and *d2*. However, a more satisfactory solution to this problem is to incorporate more sensory information into the control scheme so that each junction could be mapped and an appropriate route chosen.

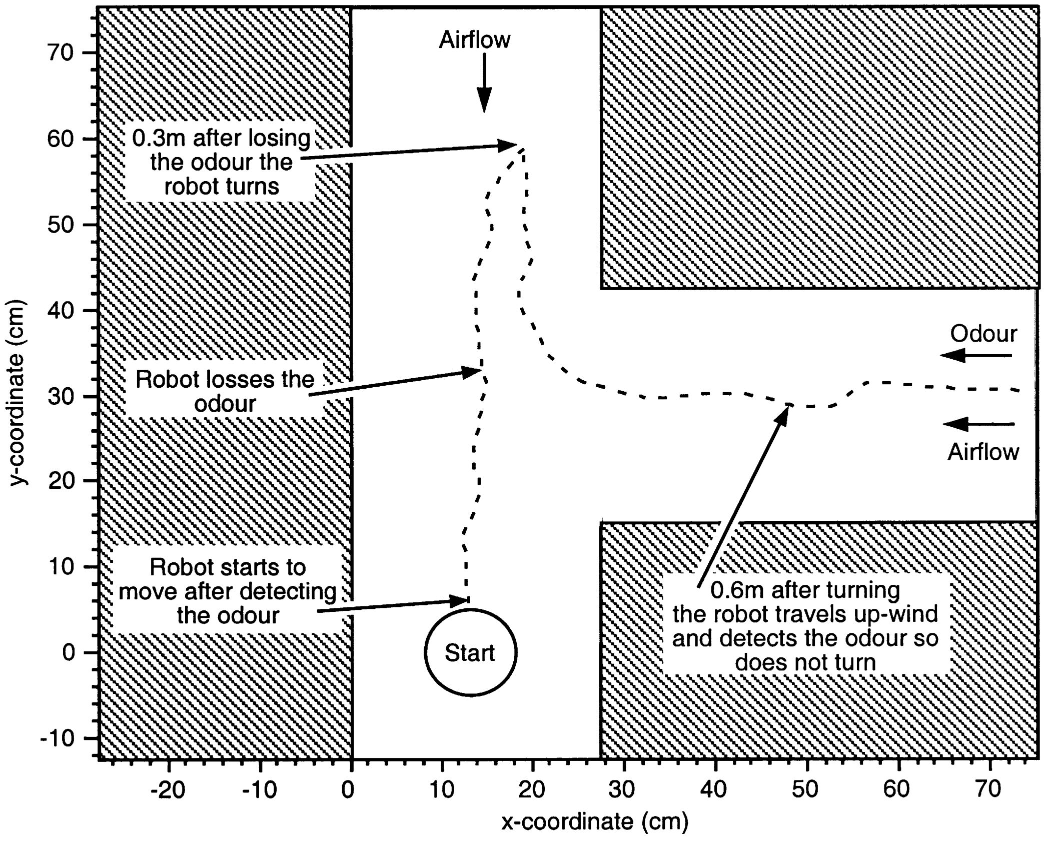

Fig. 11. The robot negotiates a junction in the passageways.

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