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Robotic location of underground chemical sources

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SUMMARY

This paper describes current progress in a project to develop robotic systems for locating underground chemical sources. There are a number of economic and humanitarian applications for this technology. Finding unexploded ordinance, land mines, and sources of leaks from pipes and tanks are some examples. Initial experiments were conducted using an ethanol chemical source buried in coarse sand. To gain an understanding of the sensory environment that would be experienced by a robot burrowing through the ground, the factors affecting transport of chemical vapour through soil were investigated. A robot search algorithrn was then developed for gathering chemical gradient infornation and using this to guide a robot towards the source. Experiments were performed using a chemical sensing probe positioned by a UMI RTX robot manipulator arm. The resulting system was successful in locating a source of ethanol vapour buried in sand. This paper includes details of experiments to characterise the sand used in this project, the robot search algorithm, sensor probe and results of source location trials.

KEYWORDS: Chemical source location; Chemical diffusion; Robotics; De-mining.

1. INTRODUCTION

In recent years there has been increasing interest in building robotic systems that can sense and respond to chemical signals. A number of research groups have investigated ways of locating the source of plumes of chemical released into the atmosphere.[1–7] The insect world demonstrates that the laying and detection of chemical trails can be useful as an aid for navigation and to help organise large groups of workers. Robotic trail following has also been investigated.[8–10] There has even been development of robotic systems to undertake chemical sensing in the underwater environment.[11]

There are significant economic and humanitarian applications for methods of locating underground chemical sources. Such sources include land mines as well as chemicals leaking from gas pipelines and chemical storage tanks. Langer[12] suggests that odour is a very reliable means of detecting land mines as illustrated by the most effective mine detecting system – the sniffer dog. A common technique for finding underground leaks involves driving a metal bar, called a bar hole probe, into the earth and then removing it to make a hole about 1.5 cm diameter and 1 m deep. Volatile chemicals seeping into the hole can then be monitored using a combustible gas indicator. For obvious reasons, driving a bar hole probe into the ground would not be practical for the location of land mines. This technique also presents dangers when used to locate chemical leaks. In 1993 a bar hole probe was being used to test the integrity of underground storage tanks at a retail gasoline station in Hilo, Hawaii. The probe punctured an underground tank leading to the release of 2.8 kiloliters of gasoline.[13] In the project reported in this paper the possibility of building a robot system for locating underground chemical sources is investigated. Such a system would be disposable, addressing the ethical considerations in demining, it could also reduce the risk of damaging underground structures if the robot was equipped with suitable sensors to detect proximity to pipes, cables or storage tanks.

Volatile chemicals percolate through the ground and on reaching the surface are carried away by the wind. The relatively slow rate of transport through the ground compared to the air means that the underground concentration is much higher than in air. For this reason the proposal is to investigate robot systems that burrow through the ground sampling the underground chemical concentration as they go. Spatially separated measurements of chemical concentration would allow the robot to determine the concentration gradient and hence move towards the source. In this preliminary investigation only the chemical probe actually penetrates the ground. However, the eventual aim is to build a self-contained robot system that burrows through the ground to locate chemical sources.

For laboratory experiments sand was chosen as the ground material and ethanol as the volatile chemical. Section 2 describes experiments to characterise the transport of ethanol vapour through sand. Next the search algorithm for the underground source locating robot is addressed. In Section 4 the experimental equipment is described. Experimental results showing the successful location of an underground chemical source are presented in Section 5. Finally conclusions and directions for future work are considered.

2. CHEMICAL DISTRIBUTION IN DRY SAND

In order to design robotic systems for tracking sources of chemicals released underground it is necessary to appreciate the makeup of different soils and mechanisms by which chemical vapours are transported though them. Soil is a mixture of mineral particles, organic material, gasses and water containing soluble chemicals.[14] The mineral constituents of soil are classified from gravel, sand, through silt to clay in order of reducing particle size. The relative proportions of the different constituents have a bearing on how permeable the soil is for a particular volatile chemical. In perfectly dry soil the passage of gasses is mainly impeded by the tortuous path that they must take between the particles and permeability is a maximum. Increasing water content serves to reduce the permeability. Below the water table soil is almost completely saturated and gasses travel relatively slowly by diffusion through the water. In practice the permeability of different soils can vary by several orders of magnitude.

According to Bird, et al.[15] there are a variety of mechanisms involved in the movement of gasses through porous materials. These mechanisms include Maxwell-Stefan diffusion, Knudsen diffusion, viscous flow, surface diffusion, thermal transpiration and thermal diffusion. In situations where there is a concentration gradient but no variation of pressure the simplest transport mechanism is diffusion governed locally by a Laplace equation.[16] At any point in a porous medium the rate of movement of a diffusing chemical is proportional to its intensity gradient at that point:

$$F_r = AD\frac{\partial I}{\partial r} \qquad (1)$$

where:

A = area perpendicular to the diffusion direction r
D = diffusion constant (m^2/s) for the specific chemical
F_r = flux in direction r
I = chemical concentration.

Equation 1 holds for steady flow. Chemical concentration resulting from unsteady flow is given by:

$$\frac{\partial I}{\partial t} = D\frac{\partial^2 I}{\partial r^2} \qquad (2)$$

For the 1-dimensional case a volume of porous material is considered to extend infinitely in direction r and to have a uniform cross-sectional profile. It is assumed that chemical flow only occurs in direction r. The porous material starts with a uniform chemical concentration I_0 and has concentration I_a applied across the full cross-section at $r=0$ when time $t=0$.

$$\frac{I - I_a}{I_0 - I_a} = \operatorname{erf}\left(\frac{r}{\sqrt{4Dt}}\right) \qquad (3)$$

Equation 3 gives the chemical concentration I distance r along the volume of porous material at time t after concentration I_a was applied. From this equation it is seen that the time it takes for a particular chemical concentration to move in direction r is proportional to r squared.

For experiments in underground chemical source location an important factor is the rate of chemical diffusion. This governs how long it will take to establish a detectable chemical profile around the source. To determine the speed with which ethanol diffuses through the sand, the experimental equipment illustrated in Figure 1 was constructed.

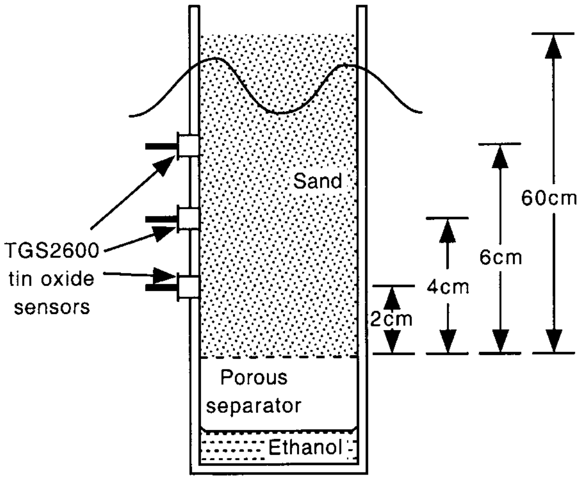


Fig. 1. Experiment to estimate rate of diffusion of ethanol vapour through dry sand.

A porous separator made of cotton material supported a column of sand above a container of ethanol. Ethanol concentration was measured using TGS2600 tin oxide gas sensors manufactured by Figaro Engineering Inc. The sensors were protected from the finer particles of sand by a single layer of thin cotton material and positioned 2 cm, 4 cm and 6 cm above the bottom of the sand column. Figure 2 shows the circuit used to energise the TGS2600 sensor's heater and monitor the tin oxide sensor element resistance.

In order to allow the sensors to stabilise, the heater voltage was applied 1 h before the start of each experiment. Ethanol was then introduced to the reservoir below the sand column and at the same time the output of the sensors was logged. Figure 3 shows a recording of sensor output voltage plotted against time from the introduction of the ethanol for the sensor 2 cm from the porous separator.

The sensor circuit is a potential divider and therefore sensor output voltage V_{out} is related to sensor resistance R by the equation:

$$R = \frac{V_s * R_s}{V_{out}} - R_s \qquad (4)$$

where:

V_s = supply voltage (5V)
R_s = series resistance (10k)

In order to determine the ethanol concentration detected by the sensor the approximate relationship between gas concentration and sensor resistance described by Watson[17] was used:

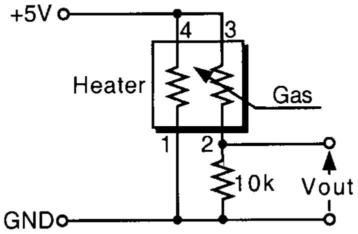


Fig. 2. Circuit to energise the TGS2600 sensor.

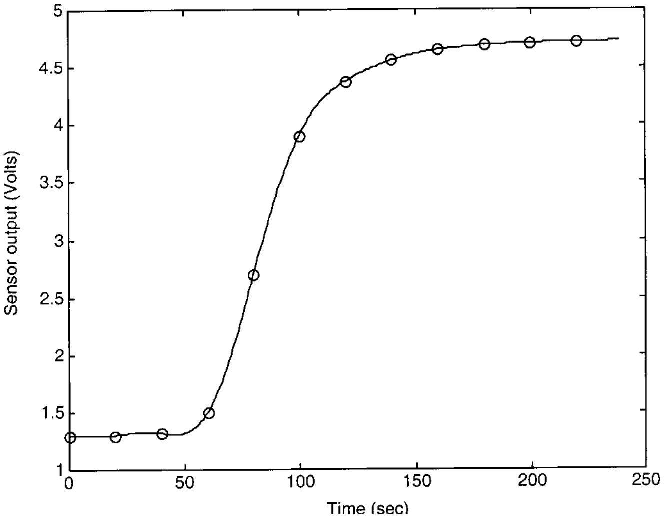


Fig. 3. The output of a tin oxide sensor when ethanol vapour diffuses through a 2 cm layer of dry sand.

$$\frac{R}{R_0} \cong KC^{\alpha} \qquad (5)$$

From the manufacturer's data sheet for the TGS2600 graphs of the sensor response for ethanol were used to estimate values of $\alpha = -0.31$ and $K = 0.67$. This equation does not hold for extremely high or low chemical concentrations.

From Figure 3 the sensor voltage for clean air is 1.3V and this corresponds to a sensor resistance R_O of 28,500Ω. From Equation (5) a gas concentration of 15 ppm will result in a sensor resistance of 8,240Ω producing an output voltage of 2.74V. From Figure 3 this output voltage occurs 80 s after applying the ethanol.

The vapour pressure of ethanol at 23°C is 52.2 mm. Therefore, at one atmosphere of pressure the concentration will be 52.2/760 = 0.068 mole fraction. For every mole of air (29 kgs) there will be 0.068 moles of ethanol (46*0.068 kg). The weight fraction of ethanol 3.13/29 = 0.108. Therefore when air at 23°C and 1 atmosphere is saturated with ethanol vapour the concentration will be 108,000 ppm. Substituting the known values of ethanol concentration, distance and time into Equation (3) gives a value of diffusion coefficient for the sand used in this experiment of $1.7*10^{-7}$ m^2/sec.

Using this value of diffusion coefficient a value was found for the time required for detectable quantities of ethanol vapour to diffuse to the sensor probe insertion point. In the experiments reported here that distance was less than 20 cm. As an approximation one-dimensional diffusion was assumed to hold. From Equation (3), one-dimensional diffusion over this distance would take 1.6 h to produce a readily detectable ethanol concentration of 1 ppm at the insertion point. To allow a margin for error the equipment was left for 3 h to allow the chemical distribution to be established throughout the sand.

3. THE ROBOT SEARCH ALGORITHM

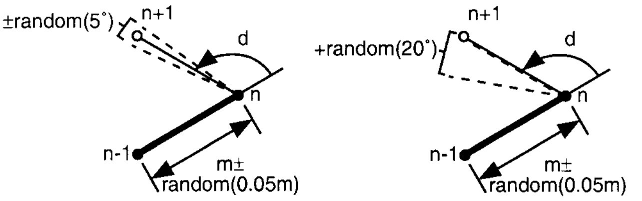
The robot search algorithm has to perform two tasks. It must direct the robot towards the chemical source and it must also gather information about the chemical gradient to ensure that the robot is making progress towards its target. In the robotics literature a number of algorithms have been considered for locating a chemical source in situations characterised by a smoothly varying chemical distribution. Such situations do not include the effects of turbulent flow. For this project algorithms that require multiple sensors were discounted for the sake of simplicity, removing the requirement for matching the responses of multiple sensors, and limiting the size of the sensor probe.

Holland and Melhuish,[18] identify two robot control algorithms that require only a single sensor. These are based on reported observations of the bacterium *E. coli*[19] and the *Planarian* worm.[20] The *E. coli* bacterium has no precise control over its heading and can only move forwards in an approximate straight path or tumble to randomise its direction. The *E. coli* search algorithm is made up of repeated straight 'runs' separated by direction randomising 'tumbles'. If the sensed conditions are improving the straight runs tend to be longer and if they are getting worse the runs become shorter. Thus *E. coli* will maintain a particular heading if conditions are improving but rapidly choose another random heading if they are getting worse. The response is asymmetrical. It takes much steeper changes in the concentration of attractant/repellent to increase the frequency of tumbling than it does to decrease it and the increased tumbling frequency persists for a much shorter time. Given the minimal control that *E. coli* has over its movement this algorithm produces surprisingly effective results. However, the length of path taken by the bacterium is highly variable and usually much longer than the path generated by the *Planarian* algorithm. For these reasons it was decided not to use the *E. coli* algorithm in this project.

Although the *Planarian* worm has twin odour sensors it employs a side-to-side sweeping motion of its head to increase the effective chemical gradient when the chemical gradient is small. The effect of this is that the *Planarian* moves forward in a zig-zag path where the angle turned with each change of direction is modulated by the recent change in chemical concentration. In their paper Holland and Melbuish present a control algorithm that contains random perturbations to both turn angle and step length.

3.1. *The Planarian Algorithm*

In the diagram illustrating the *Planarian* algorithm (Figure 4) a chemical concentration reading has been taken at point n − 1 followed by a movement to point n. If the concentration at n has increased then the source is to the right and a relatively small turn to the left is performed. A decreasing



If chemical concentration increases between sample n-1 and n

If chemical concentration decreases between sample n-1 and n

Fig. 4. The *Planarian* algorithm response to increasing and decreasing chemical concentration.

concentration occurs if the source is to the left and this results in a larger turn in that direction.

The algorithm is described more formally as:

```
repeat {
        if current sensor reading is an improvement on the
        previous reading
             then  rotate $d°$ ±random (5°) in the opposite direction to last time and move
                   forward $m$ units ±random (0.05 $m$)
             else  rotate $d°$ +random (20°) in the opposite direction to last time and
                   move forward $m$ units ±random (0.05 $m$)
}
```

This algorithm has an inherent flaw. If the robot is heading directly away from the source the algorithm allows the robot to keep moving away without attempting to turn.

This behaviour is illustrated in Figure 5. The robot will adopt a stable trajectory away from the source when the chemical concentration reduces consistently with each forward movement. The range of headings for which this will occur depends on the angle that the robot turns. As turn angle approaches 180° the chances that the robot will adopt a stable trajectory away from the source reduces towards zero. Unfortunately, increasing the angle of turn also reduces the rate of progress of the robot. For the application of finding a chemical source sensor readings must be taken in undisturbed soil and therefore the robot control strategy should take widely spaced readings. This requirement conflicts with the use of a large turn angle to avoid stable trajectories away from the source. For these reasons another algorithm was developed with the aim of avoiding the problem of stable trajectories heading away from the source and advancing sufficiently quickly that sensor readings are taken in undisturbed ground.

3.2. *The Hex-Path Algorithm*

Like the *Planarian* algorithm the robot moves forward a fixed distance m and then turns to one of two new headings.

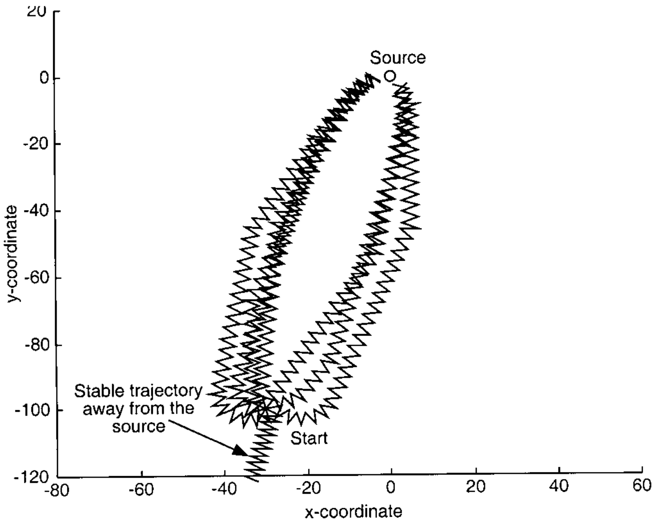


Fig. 5. Robot trajecories genberated by the *Planarian* algorithm. Eight initial headings were chosen for the robot at 45° intervals.

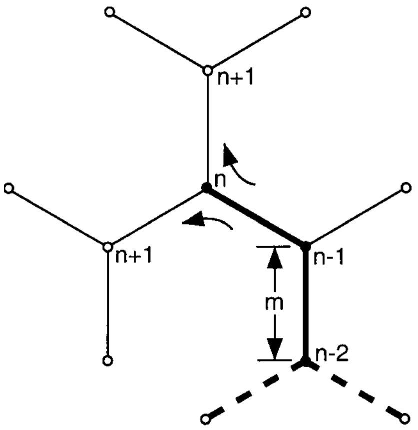


Fig. 6. The robot path produced by the hex-path algorithm.

The change of heading after movement n is either +60° or −60° depending on sensor readings taken at the end of movements $n-2$ and $n-1$. As shown in Figure 6 the robot trajectory can be viewed as a path through a hexagonal grid and this is the origin of the algorithm's name. Unless the robot doubles back on its previous path sensor readings are taken at widely spaced locations in undisturbed ground. The choice of turn direction is explained in the following description of the algorithm.

```
repeat {
        if (intensity at $n-2$ > intensity at $n-1$) and
        (rotation direction at $n-1$ was anticlockwise) or
        (intensity at $n-2$ < intensity at $n-1$) and (rotation
        direction at $n-1$ was clockwise)
        then rotate anticlockwise 60° and move forward $m$
        else rotate clockwise 60° and move forward $m$
        }
```

Figure 7 shows example trajectories for the *E. coli*, *Planarian* and hex-path robot control algorithms produced by a Matlab simulation. The numbers of steps 4 units long required to move from the start to within 5 units of the

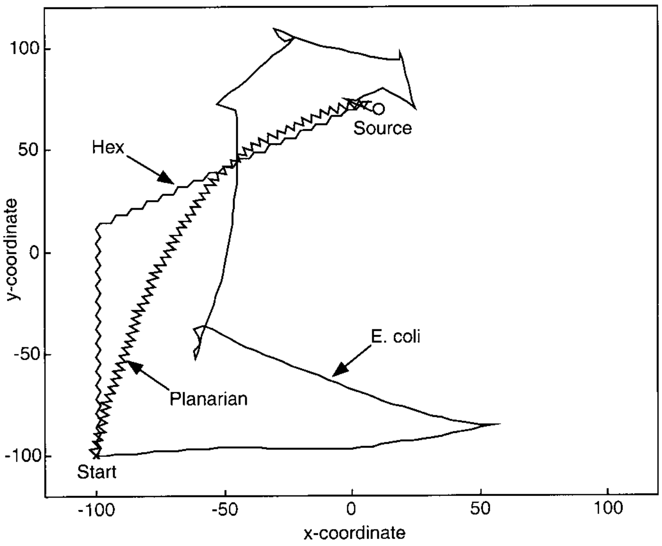


Fig. 7. Examples of the *E. coli*, *Planarian* and hex-path robot control algorithms.

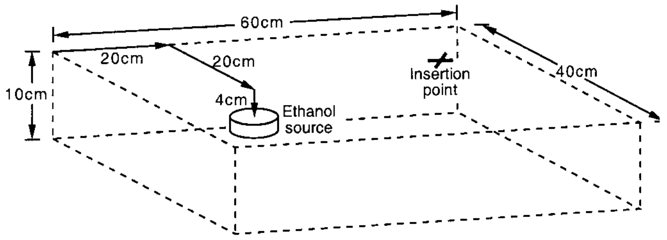


Fig. 8. The positions of the chemical source and sensor insertion point within the volume of sand.

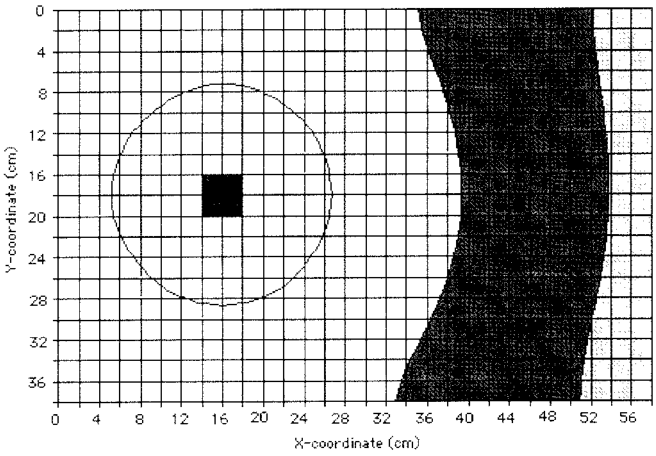
source were 155 for the *E. coli* algorithm, 112 for the *Planarian* algorithm and 69 for the hex-path algorithm. The length of the *E. coli* path is highly variable and for the *Planarian* algorithm the magnitude of the turn angle has a large effect on total path length.

4. THE EXPERIMENTAL EQUIPMENT

Experiments were performed in a plastic container 60 cm long by 40 cm wide and filled to a depth of 10 cm with dry sand. The chemical source consisted of an open topped metal can 4 cm diameter and 2 cm deep half filled with ethanol. A covering of cotton material over the open top of the can excluded sand while allowing the ethanol vapour to escape. This source was buried and covered by 4 cm of sand at the location shown in Figure 8.

Within the experimental region ethanol vapour diffused from the source throughout the volume of sand. Results of finite-element modelling of ethanol concentration are given in Figure 9.

Adjacent regions in the plot represent changes in concentration by a factor of 10. For the simulation it was assumed that the surface concentration of chemical was zero and that the sides and bottom of the container were impermeable. At the depth of the chemical source it is seen that there is a radially decreasing chemical concentration and this is information that will be gathered by the chemical sensor.



Horizontal cross-section at a depth of 4 cm.

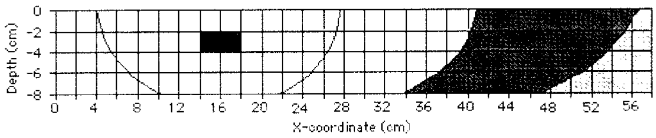


Fig. 9. Horizontal and vertical cross-sections of the experimental region showing chemical concentration on a logarithmic scale.

At a later stage of the project a fully self-contained robot system will be built that can burrow through the ground like a mole. Currently a UMI RTX robot manipulator arm is used to guide a chemical probe through the sand. Only the sensing tip of the probe penetrates the sand. The probe contains a Taguchi Gas Sensor TGS2600 manufactured by Figaro Engineering Inc. This tin oxide sensor is marketed for detecting air contaminants but has a very strong response to ethanol (for example: sensor resistance in the presence of 15 ppm ethanol divided by sensor resistance in clean air is 0.3). The sensor output was converted to digital form by the 12 bit analogue to digital converter in a National Instruments Lab-PC interface board.

A cross-section view of the sensor probe is shown in Figure 10. The tube and sensor enclosure are made of aluminium. Finer particles of sand are excluded from the sensor by a disk of filter material cut from a dust mask. The four electrical connections to the sensor run up the supporting tube the top of which is held by the gripper of the RTX robot.

A control program written in Pascal interrogates the A/D card, implements the search strategy, performs the inverse kinematic calculations for the robot arm and sends the resulting motion commands to the RTX robot. A photograph of the robot guiding the sensor probe towards the chemical source is shown in Figure 11.

5. EXPERIMENTAL RESULTS

After burying the chemical source 3 h were allowed for the chemical concentration to stabilise throughout the volume of sand. An airflow was established over the surface of the sand using a cooling fan to ensure that the surface concentration of ethanol was essentially zero. Without the fan negatively buoyant ethanol vapour tends to concentrate

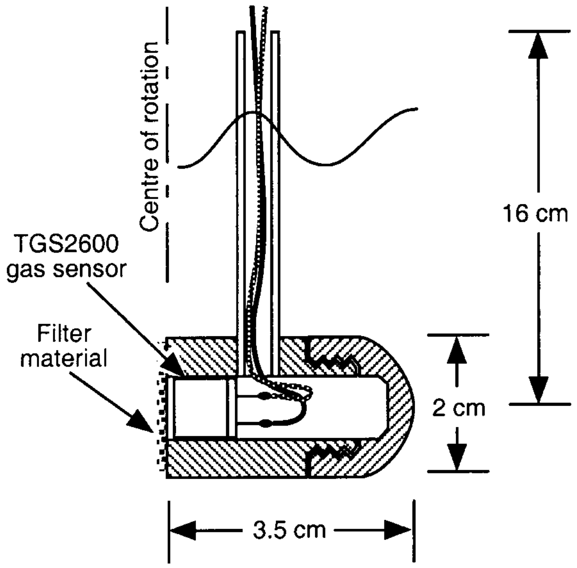


Fig. 10. A cross-section view of the chemical sensor probe.

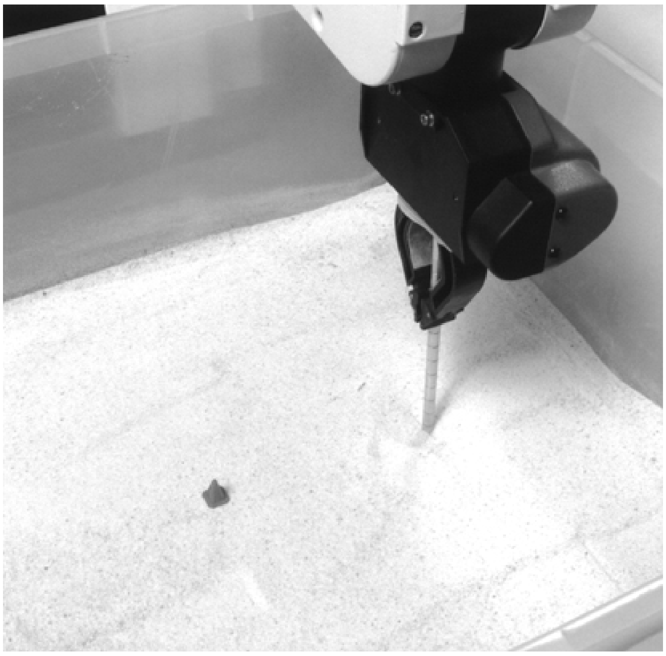


Fig. 11. A photograph of the RTX robot moving the sensor probe through the sand towards the chemical source.

above the surface and distort the chemical distribution in the sand.

For the Hex Algorithm two moves must be made before the algorithm can take over control of the robot. These two movements are shown by the dashed line in the plotted robot trajectory. These moves are deliberately chosen so that initially the robot is heading away from the source. Figure 12 shows a typical robot trajectory. When the probe is first inserted a chemical reading is taken and then the robot proceeds by moving forwards 3 cm, taking a chemical reading and then turning either clockwise 60° or anti-clockwise 60°. The measured chemical sensor output is indicated by the size of the circle at each turning point. Recording stops when the sensor probe makes contact with the source.

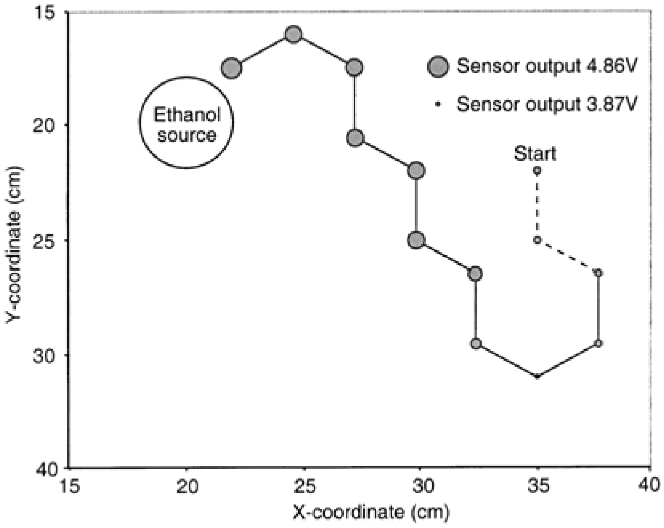


Fig. 12. Experimental results of sensor probe path as the robot locates the buried ethanol source.

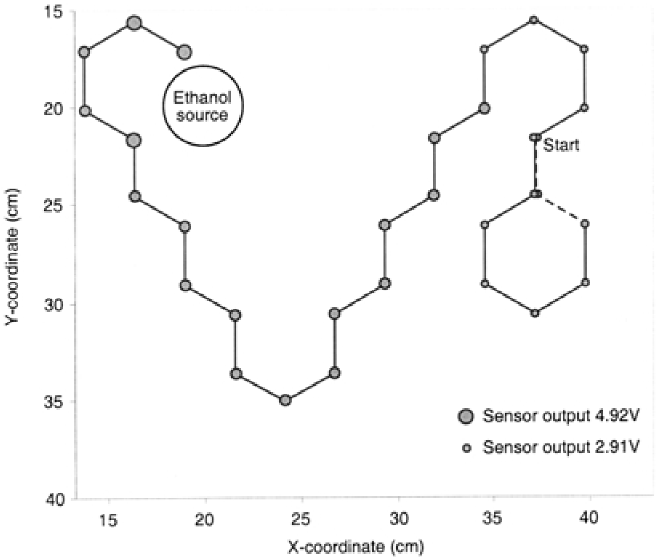


Fig. 13. Sensor probe trajectory when insufficient time was allowed for the chemical sensor output to stabilise.

The Taguchi gas sensors take a long time to fully respond to changes in gas concentration. For the experiment documented in Figure 12 a delay of 60 s was allowed each time the sensor probe was moved to allow the sensor output to stabilise. Figure 13 shows the results of an experiment where only 15 s was allowed for sensor stabilisation. Even though this caused the incorrect chemical gradient to be registered on a number of occasions the hex-path algorithm was still able to guide the robot to the source.

6. CONCLUSIONS

There are many potential applications for chemical sensing robots and finding buried sources of volatile chemicals is one of them. In this project a novel robot control algorithm was developed for the task of locating underground chemical sources. The hex-path algorithm overcomes problems identified with the *Planarian* algorithm. These problems are the generation of spurious trajectories when the robot is heading away from the chemical source and taking sensor readings in ground disturbed by previous readings. Using the hex-path algorithm a robotic system was able to locate a source of ethanol vapour buried in sand. The chemical source tracking performed in this project was limited to a two-dimensional search at constant depth. A natural progression would be to extend to three dimensions to allow the robot locate chemical sources at different depths. As noted earlier, one of the eventual aims of this project is to develop a completely self-contained robot system that can burrow through the ground to find chemical sources. For any particular application there must be a suitable chemical sensor. The speed of response of this sensor will have a direct effect on how fast the robot can track towards the source.

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