Chemical Source Location and the RoboMole Project

R. Andrew Russell
Intelligent Robotics research Centre
Monash University, Clayton
VIC 3800, AUSTRALIA
andy.russell@eng.monash.edu.au

Abstract

There are important economic and humanitarian applications for systems that can find the source of an odour or volatile chemical buried under the ground. These applications cover the spectrum from harvesting truffles, to finding the location of leaking gas pipes and land mines. This paper presents current progress of the RoboMole project which aims to develop robotic systems that can burrow through the ground and home-in on chemical sources. The current emphasis of the project is to prove the feasibility of the concept and to develop a suitable robot control algorithm. This paper reports on investigations of chemical vapour transport through soil, development of a robotic chemical source location algorithm and results of practical source location experiments. Proposed future directions for the RoboMole project are outlined.

1 Introduction

In the future robotic systems will help to extend human sensory capabilities. It has been estimated that our sense of smell has been degenerating steadily over the past 5 million years. This is probably mirrored by a corresponding improvement of and reliance on our visual sense. In situations where odour is important other animals, most notably dogs, are used to help substitute for our relatively poor sense of smell. Odour sensing and localisation are tasks that could be performed by robots. For this reason there is increasing interest in investigating robotic systems that can locate the source of a chemical plume. Many research groups have investigated techniques for locating the source of plumes of chemical released into the atmosphere [Sandini, et al., 1993; Russell, et al., 1995; Rozas, et al., 1991; Marques and de Almeida, 1998; Kuwana, 1995; Ishida, et al., 1999; Ishida, et al., 1996]. 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. With similar navigation and organisational benefits in mind robotic trail following has also been investigated [Webb, 1998; Stella, et al., 1995; Russell, 1995]. There has even been development of robotic systems to undertake chemical sensing underwater [Grasso, et al., 2000]. The RoboMole project is investigating the idea of creating robot systems to burrow through the ground to search out underground chemical source. Pipelines and underground storage tanks are subject to corrosion and locating the source of resulting gas or volatile chemical leaks is a significant problem. The risk of build-up of explosive gas concentrations in access pits or tunnels and the pollution of groundwater are associated with these kinds of leaks.

In this project, some preliminary investigations have been made relating to the diffusion of volatile chemicals through soil. This is described in the next section. In Section 3 the development of a reactive control strategy called the hex-path algorithm for locating underground chemical sources is outlined. Experiments were performed to verify the operation of the hex-path algorithm and these are covered in Section 4. Finally conclusions and proposals for future work are given.

2 An investigation of chemical transport through dry sand

When volatile chemicals are released underground, provided that the chemicals are not injected by a pressure difference, then movement of the chemicals is mainly governed by diffusion. The rate of diffusion is slower than in air because of the tortuous path that they must take between the soil particles. The length of this path is also affected by the size of the soil particles, becoming longer as the particle size reduces. Moisture tends to slow gas propagation because the presence of water reduces the size of the gaps between soil particles. Also, if the gaps are completely filled then diffusion takes place much slower through water. As moisture content increases propagation delay becomes greater, reaching a maximum in the almost totally saturated region below the water table.

Sand is clean and its large particles allow relatively rapid diffusion of chemical vapours. For these reasons dry sand was used in this project. Ethanol vapour served as a relatively safe and convenient target chemical. The TGS2600 tin oxide sensor manufactured by Figaro Engineering Inc. was selected to detect ethanol vapour. These sensors are inexpensive, small and sensitive to ethanol vapour. The TGS2600 sensing element exhibits a resistance that varies with chemical concentration and this is readily interfaced to an analogue to digital converter using a simple potential divider circuit.

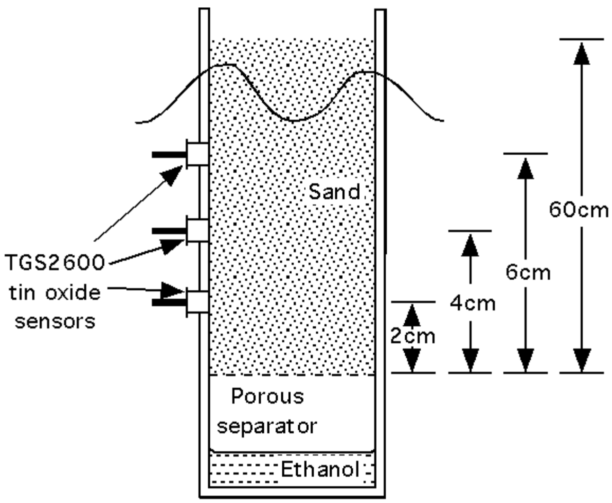

Figure 1 Experiment to estimate the rate of diffusion of ethanol vapour through dry sand.

The experimental equipment shown in Figure 1 was built to investigate diffusion of ethanol vapour through the coarse sand obtained for this project. A PVC pipe with a 2.5 cm inner diameter had holes drilled in the side to accommodate three TGS2600 tin oxide gas sensors. The holes were positioned 2 cm, 4 cm and 6 cm above a sheet of cotton material which allowed ethanol vapour through from a reservoir below the cotton material and supported a 60 cm column of sand. Figure 2 shows the response of the sensors when ethanol was introduced into the reservoir.

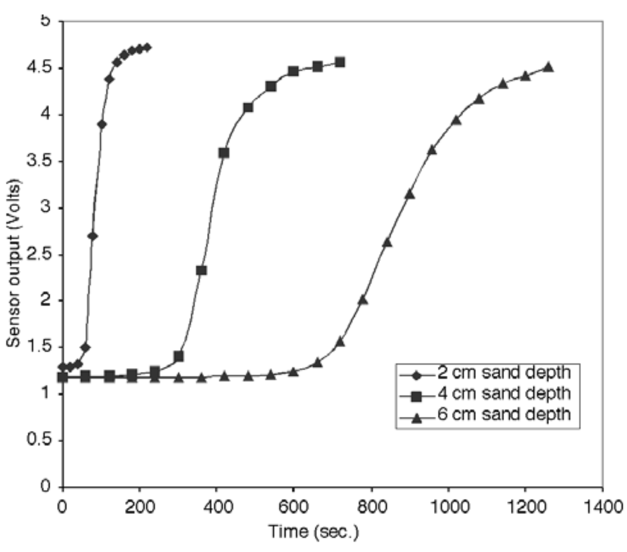

Figure 2 Diffusion of ethanol vapour through different depths of sand.

The diffusion of chemical vapour through soil without a pressure gradient is governed by Fick's second law [Abaci and Edwards, 1993]:

$$\frac{\partial I}{\partial t} = D\frac{\partial^2 I}{\partial r^2} \tag{1}$$

where:

D = diffusion constant (m^2/s) for the specific chemical
r = distance in the direction of diffusion
I = chemical concentration
t = time

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 zero chemical concentration and has concentration I_a applied across the full cross-section at $r = 0$ when time $t = 0$.

$$\frac{I}{I_a} = \operatorname{erfc}\left(\frac{r}{\sqrt{4Dt}}\right) \tag{2}$$

Equation 2 gives the chemical concentration I distance r along the volume of porous material at time t after concentration I_a was applied. From Equation 2 it appears that the time for a particular chemical concentration to propagate through a given thickness of sand (part of an infinite column) is proportional to distance squared. This agrees with the results shown in Figure 3 where the time for an ethanol concentration of 15 ppm. to propagate through a column of sand is proportional to distance squared.

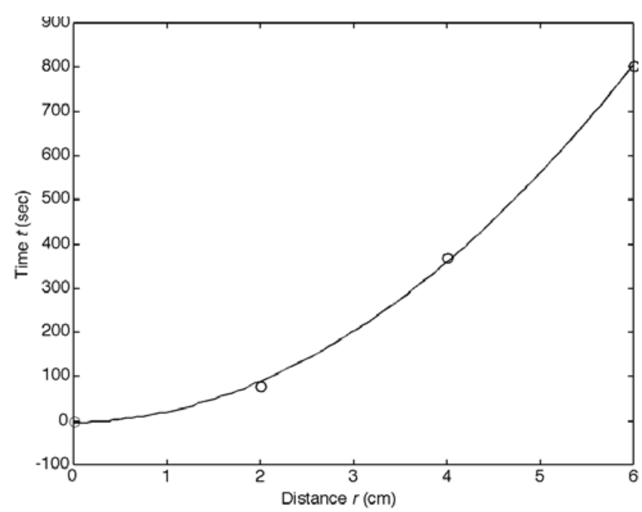

Figure 3 A plot of distance r against time t required for the chemical concentration to rise from zero to 15 ppm. The solid line represents the equation $t = 22.1\, r^2$.

From this experiment it seems that the observed transport of ethanol vapour through sand does agree with the diffusion model. It also appears that the time scale for the vapour to diffuse through the small volumes of sand used in this project will not be inconveniently long. An ethanol concentration of 15 ppm. causes a very strong response from the TGS2600 gas sensor and this concentration would take less than 3 hours to diffuse 20 cm (assuming 1-dimensional diffusion).

3 Robot control

The process of chemical diffusion produces a smoothly varying concentration. Any robot manoeuvring in this environment must move towards the source by tracking up the chemical gradient. In the robotics field a number of algorithms have been investigated for this task. When burrowing through the ground it will be advantageous for a robot to present the smallest possible cross-section. For this reason, algorithms such as the one proposed by Braitenburg for his aggressive type 2 vehicle [Braitenburg, 1984] were not considered because they use bilateral sensors.

An algorithm that uses a single sensor has been derived from observations of the *Planarian* worm [Fraenkel and Gunn, 1961]. Although the *Planarian* worm has twin odour sensors, when the chemical gradient is low the worm moves its head from side to side in order to increase gradient information. A control algorithm derived from this action is described by Holland and Melhuish [Holland and Melhuish, 1996].

The *Planarian* algorithm:

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

By referring to Figure 4 it can be seen that if the source is on the left as the robot makes its way vertically then the robot will tend to turn further anticlockwise and if the source is on the right it will turn more clockwise. In both cases the zig-zag path of the robot will tend to curve towards the source.

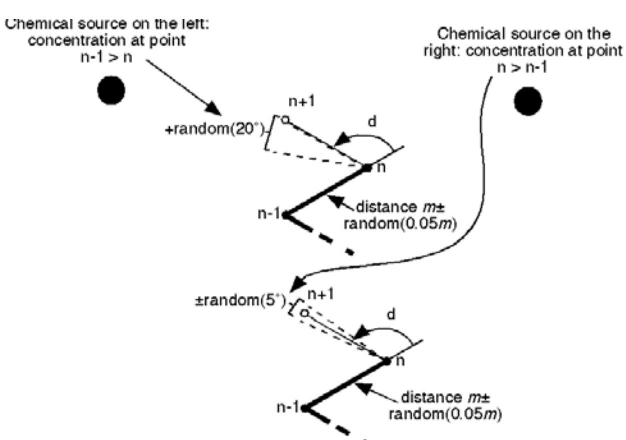

Figure 4 The *Planarian* algorithm modulates the turn angle based on readings of chemical concentration at points *n* and *n-1*.

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 turning. The effect is that the concentration is always reducing and this results in a similar turn angle magnitude at each turn. As a result this produces a stable trajectory away from the source.

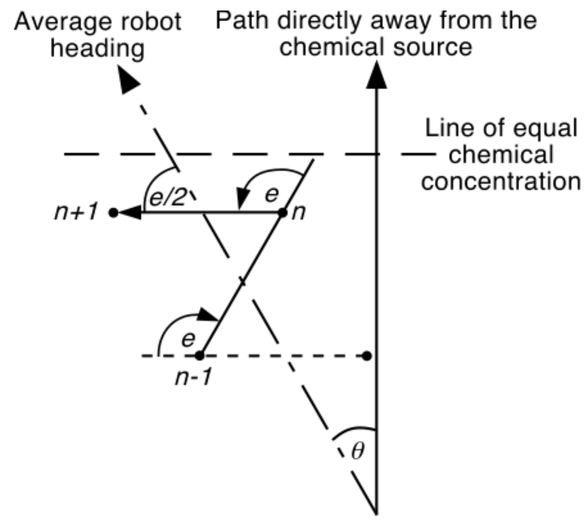

Figure 5 Conditions for pathological behaviour in the *Planarian* algorithm.

This condition is illustrated in Figure 5. Assuming for the moment that there is no random element to the turn angle and that the robot turns through angle e when the concentration falls then the condition to avoid a pathological trajectory is:

$$\theta + \frac{e}{2} > 90^{\circ} \qquad (3)$$

When this condition is met the chemical concentration will increase at point $n+1$ and the robot trajectory will start to turn towards the source. This condition can be met for angles of θ down to almost zero if e = 180˚. However, in that case the robot would make no progress toward the source at all! As e is reduced then the rate of progress is increased but susceptibility to the pathological trajectory increases. The random turn angle included in the algorithm means that the pathological trajectory will not continue for ever. However, there is no guaranteeing how long it will take for the robot to turn towards the source.

To avoid the problem of the pathological trajectory and to ensure that the robot takes successive chemical reading in undisturbed soil a new search algorithm was developed. This algorithm can be pictured as choosing a path through a hexagonal grid and has therefore been named the hex-path algorithm. Like the *Planarian* algorithm the hex-path algorithm is a set of simple reactive rules.

The hex-path 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*
}

As illustrated in Figure 6 the robot senses the chemical intensity after making a straight movement distance *m*. The robot then makes a turn of +60° or -60° based on chemical readings at points *n-1* and *n-2*. Unless the robot turns back on its pervious path the positions where sensor readings are taken are widely spaced and in undisturbed ground.

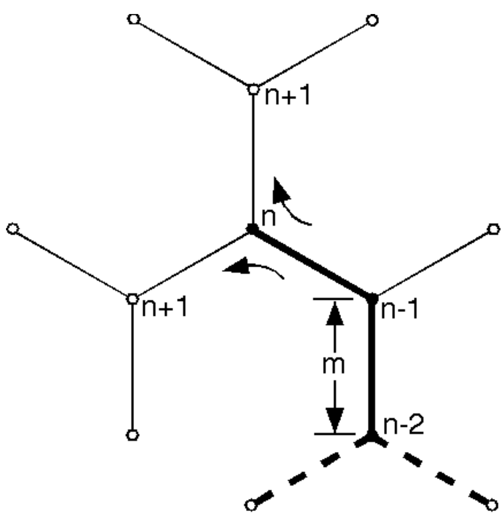

Figure 6 Robot trajectory using the hex-path algorithm.

4 Practical source location experiments

The practical experiments reported in this paper were aimed at verifying the source location capabilities of the hex-path algorithm. For simplicity a sensor probe was attached to the gripper of a UMI RTX robot manipulator arm. Only the tip of the probe penetrates the ground. At a later stage of the project a robot vehicle will be developed that can burrow though the ground and require no external structure. The sensor probe is shown in Figure 7 and consists of an aluminium tube with a TGS2600 tin oxide gas sensor mounted at one end inside an aluminium enclosure. A disk of dust mask filter material excludes finer sand particles from the sensor. Experiments were conducted in a 60 cm by 40 cm by 10 cm deep volume of sand. The target was a 4 cm diameter open topped tin of ethanol. A covering of cotton material allowed ethanol vapour out of the can while excluding sand.

Figure 7 Chemical probe about to be inserted into the sand. The cone marks the position of the buried ethanol source.

Figure 8 shows a typical trajectory of the sensor probe as it is guided towards the chemical source. The hex-path algorithm cannot control the robot trajectory until three sensor readings have been taken. Therefore, the first two movements (marked with a dashed line) are pre-programmed and chosen so that the robot initially moves away from the source.

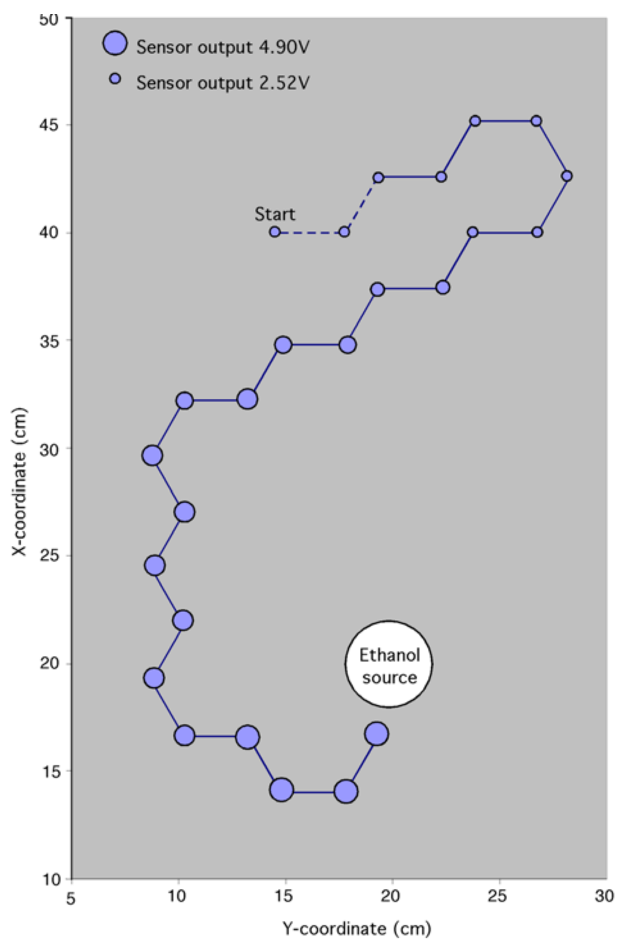

Figure 8 Experimental results of sensor probe path as the robot locates the buried ethanol source.

Figure 9 The experiment finishes when the probe collides with the ethanol source.

In Figure 9 the disturbed sand shows the path taken by the probe as it tracks towards the ethanol source. The chemical sensor takes a substantial amount of time for its output to stabilise. After each 3 cm movement of the probe the robot delayed 60 seconds before taking a chemical reading to allow the sensor to stabilise. Even with this delay the first four sensor readings are in error because the sensor had not accommodated the sudden change in ethanol concentration resulting from initial insertion into the sand. The first four readings give the false indication that concentration is rising as the probe travels away from the source. See Figure 10 for a graph of the recorded sensor readings. On the fifth reading the correct change in sensor output is registered and the probe starts to turn around to head towards the source. The experiment was terminated when the probe collided with the source.

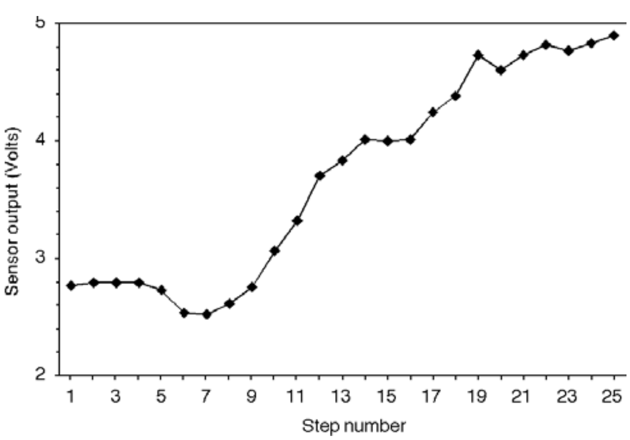

Figure 10 Gas sensor output voltage at each step in the source localisation procedure.

6 Conclusions

This project has demonstrated the feasibility of using a robotic system to locate an underground chemical source. In practical experiments an ethanol source was buried in a volume of sand and later located using a robot positioned chemical probe. A novel search algorithm, the hex-path algorithm, has been introduced which overcomes problems associated with the *Planarian* search algorithm. Initially the simple, reactive *Planarian* algorithm was thought to be ideal for this application because it only requires a single sensor. However, under some circumstances the *Planarian* algorithm can adopt a stable trajectory away from the source instead of towards it. An attempt to reduce the probability of this happening results in the robot taking chemical readings close to locations where previous readings have disturbed the soil. The hex-path algorithm takes widely spaced readings and cannot adopt a stable trajectory away from the source. The next stage of the project involves building a self-contained burrowing robot - the RoboMole of the project title.

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