EMERGENT ROBOT SEARCH BEHAVIOUR IN A SENSORY GRADIENT

University of Glasgow, Department of Aerospace Engineering

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Eric A. Gillies

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1.0 Introduction

The task of planning and executing a path for a mobile robot to go between an initial point and a goal point in an obstacle filled domain is a fundamental problem. However, if the goal point emits a chemical signal which disperses in the environment, the mobile robot need only follow the chemical gradient to reach the goal and avoid any obstacles. The on-board computation required to execute this guidance strategy is minimal as the computation of the best path to the goal is, in effect, selected by the path of the chemical particle emitted from the goal point which first reaches the robot sensors. Several animals exploit this property of chemical dispersion to navigate towards food, home or a mate (Dusenberry 1993)(Bell & Carde 1984).

In this paper, the diffusion of a chemical signal from a goal point is simulated numerically and the path taken by an autonomous mobile robot using two different guidance strategies, which are inspired by two different strategies employed by animals, is also simulated. The results show that the robot can indeed find the goal and avoid obstacles and need only perform very simple computations. However, more surprisingly, the robot also displays complex behaviour when the goal point is missed, either by deliberately overshooting the goal or as a result of inaccuracy in the guidance system. The observed complex behaviour of the robot is similar to several types of local search pattern observed in animals (Dusenberry 1993). These search patterns are often believed to be pre-programmed or instinctive behaviours initiated by animals when sensory information is not available (Dusenberry 1993)(Bell & Carde 1984). The robot, however, is not pre-programmed with a search routine and so the search is shown to emerge from the simple guidance strategy and the sensory gradient.

2.0 Dispersion of Chemical Signals in Still Air

In a completely still fluid, such as air, a point source of chemical disperses by molecular diffusion. The spread of the chemical is due to the random movements of individual fluid particles. The chemical diffusion equation is,

$$\frac{\partial I}{\partial t} = D\nabla^2 I \qquad (1)$$

where D is the binary, molecular diffusion coefficient and I is the concentration of the chemical. Molecular diffusion is a very slow process (typical values of D are around 0.02 cm^2/sec in air) and is a very inefficient means of information transmission. The concentration distribution, resulting from molecular diffusion about a point source, is Gaussian. However, even in still air, turbulence has a large effect on chemical dispersion. Even in an atmosphere of zero average velocity, turbulent eddies are present and move around as a result of small temperature and pressure fluctuations. In a field of homogeneous, rotationally symmetric turbulence (as would exist in a closed room or forest clearing or patch of ocean etc.), the most probable concentration distribution about a point source is again Gaussian, just as in the case of molecular diffusion. Therefore, in still air, turbulent chemical dispersion is described by a similar type of equation to molecular diffusion, with the molecular diffusion coefficient replaced by the eddy diffusion coefficient D_e. Although the predicted distribution of chemical resulting from the eddy diffusion equation is only the probable distribution, and is therefore only approximate, the actual distribution in still air is often very close to that predicted by this method (Batchelor 1952). Turbulent eddies of a size greater than 5cm but less than 100cm have an effect on chemical dispersion (Mankin et al 1980) and in still air these eddies result in an eddy diffusion coefficient D_e of 0.1 to 10 cm^2/sec.

2.1 Numerical Solution of the Eddy Diffusion Equation

The eddy diffusion equation can be written as a finite difference analogue and solved for a given set of boundary conditions on a regular Cartesian grid model of the environment. Equation (1) is supplemented with the boundary conditions of

$$\begin{aligned} I(t;\mathbf{x}_g) &= 1, \mathbf{x}_g \in \Omega \\ I(t;\mathbf{x}_b) &= 0, \mathbf{x}_b \in \partial\Omega \\ I(0;\mathbf{x}\ ) &= 0, \mathbf{x}\ \notin \mathbf{x}_g \end{aligned} \qquad (2)$$

where Ω represents the domain, $\partial\Omega$ the boundary and obstacles and $\mathbf{x}_g$ the coordinates of the goal point. The boundary conditions therefore represent a chemical source of unit intensity at the goal and instantaneous absorption of chemical at boundaries. The finite difference solution of (1) is

$$\begin{aligned} &I_r(k+1) - I_r(k) = \\ &\frac{\tau D_e}{h^2} \sum_{\substack{m=1 \\ m\in N(r)}}^{M} (I_m(k) - MI_r(k)) \end{aligned} \qquad (3)$$

where h is the grid spacing, τ is the timestep and $N(r)$ and M the respective set and number of neighbouring grid points of r (Schmidt et al 1993). For non-oscillatory convergence the grid spacing and timestep are set so that

$$D_e = \left(\frac{h^2}{1+M}\right)\frac{1}{\tau} \qquad (4)$$

For very still air (or other fluid) there should only be small differences between the actual instantaneous distribution and the probable distribution resulting from (3) (Batchelor 1952). These small fluctuations are modelled, qualitatively, by adding normally distributed noise terms to the resulting distribution. The noise field is varied at each time step.

3.0 Guidance Methods

Two common guidance methods that animals use in chemical gradients are *tropotaxis* and *klinokinesis.*

Klinokinesis is the simplest strategy and only needs one sensor. The animal discerns the chemical gradient by sensing the chemical concentration at one spatial point and then moving to another point and sensing the concentration again. The direction of animal locomotion is then changed by an arbitrary amount if the temporal change in intensity is unfavourable. This type of guidance is called indirect guiding as the animal turns are not biased with respect to the orientation of the sensed gradient.

Tropotaxis involves multiple sensors (usually bilateral). Using tropotaxis, the animal aligns itself to the maximum chemical gradient by turning such that it senses the same concentration at each of its symmetrically placed sensors. Because the distance between the sensors is limited by the size of organism, tropotaxis is only possible when the chemical gradient is relatively steep (ie. when close to the goal) and the difference in signal between the sensors is above a detectable threshold. In contrast, klinokinesis can be successful much farther from the goal as the sampling distance can be varied to suit.

For an autonomous robot, tropotaxis is the best method to implement for avoidance of obstacles, because it ensures that the robot never moves towards an obstacle. Klinokinesis only determines the chemical gradient after robot movement. Just as with an actual animal, the robot is assumed to only detect chemical signals and *differences* in chemical signals above a certain threshold value. Normally distributed noise is added to the sensor measurements to model, qualitatively, any sensor noise. Noise terms are also added to the changes in direction, resulting from the guidance rule, to simulate random errors in locomotion.

Tropotaxis is implemented using two symmetrically placed sensors at either side of the simulated robot. The robot turns according to the following rule,

$$\theta(t+1) = \theta(t) + \mu \frac{(I_l - I_r)}{(I_l + I_r)} \qquad (5)$$

where θ is the direction of robot movement and l and r refer to the left and right hand sensors respectively. The constant μ determines how sharp a turn is executed at each step. At each timestep the robot updates its direction according to its sensors and moves forward. Far away from the goal, the difference in sensor measurements is below the measurable threshold and so the robot movements are random and result from a combination of the locomotory, sensory and also the chemical gradient noise terms.

A simple form of klinokinesis is also implemented in the robot simulation. The robot is made to travel forwards in a straight line and sense the chemical concentration at each step. If the robot detects that the chemical concentration is decreasing then it makes a turn of $45^0$to the left. Small, normally distributed noise terms are added to the robot locomotion such that the path taken by the robot is not exactly straight (as would be the case with a real animal) and such that the turn is never exactly 45^0. These locomotory noise terms are important for the success of klinokinesis.

3.1 Simulation Results

Various different domains are simulated, both with obstacles and without. Figure 1 shows the path generated by following a simulated chemical gradient using tropotaxis in a maze. The complex task of path planning is resolved by simple orientation to the chemical gradient. Figure two shows the robot successfully navigating round a T shaped obstacle to a goal point. If the robot is not instructed to stop once the goal point is reached or if the goal point is not arrived at exactly (either because the random sensory and locomotory noise terms are such that the robot just misses the goal point) then more interesting behaviour results. In this case the robot then, still following the chemical gradient using tropotaxis, executes a series of figures of eight around the expected position of the goal. One of these figures of eight is shown in figure 2. This looping behaviour is further shown in figure 3, where the robot is placed in a simulated empty 10mx10m box with a chemical source in the centre. The robot is seen to move straight to the centre goal point but, failing to exactly find the source, is then seen to execute a series of loops around the goal. The pattern of loops is very similar to a looping local search pattern often utilised by animals to find a goal. Figure 4 also displays the apparent searching behaviour of the robot, but this time the robot is confronted with three separate chemical sources. This figure shows the more or less random movements of the robot prior to crossing the measurable threshold of chemical signal and then a more direct guidance towards one of the three sources. The looping behaviour around the first goal results in the robot being attracted frequently by the other goals and vice versa. The density of robot searching about the goal point (or search focus) is shown in figure 5. This figure can be compared to the searching density of ants looking for their nest. The density of ant searching is shown in figure 6. Figure 7 shows the associated ant trails while searching for their nest. Idealised trails of animal looping search patterns are shown in figure 8. The local search patterns employed by animals are seen to be very similar to the patterns observed in the robot behaviour.

The robot paths resulting from the klinokinesis guidance algorithm are shown in figures 9 and 10. Here the robot is guided towards a single chemical source in a 20mx20m box. Such a simple guidance strategy does lead to the robot finding the goal *as long as the noise terms are included*. A successful robot path intercepting the goal is shown in figure 10. The usefulness of the random locomotory noise terms added to the klinokinesis rule is highlighted in figure 11, where the noise terms are removed. With no noise, the simple klinokinesis rule leads to the robot orbiting the goal. The random locomotion errors present in figures 9 and 10 however make it much more likely for the robot to intercept the goal point. The circling behaviour of the robot around the goal point can also be thought of as a search behaviour. The density of this type of apparent searching is shown in figure 13.

4.0 Discussion

It is documented that searching patterns in animals (such as the ants in figure 6 and 7) are pre-programmed and are executed by animals when they do not have sensory information (Dusenberry 1993)(Bell & Carde 1984). The animal searching patterns are not thought to be as a result of a guidance rule (Dusenberry 1993). However, the robot shows similar behaviour which has not been pre-programmed and is a result of the topology of the chemical gradient together with the guidance rule. The robot moves towards the goal point using tropotaxis but apparently searches the immediate area of the goal if the goal has been recently removed or if the environmental noise is sufficient to make tropotaxis inaccurate. Animals execute a pre-programmed search routine when their guidance rule does not cause them to intercept their goal, while the robot apparently searches around the goal when its guidance rule is insufficient for an exact interception. Because the robot and the animal behaviours are so similar (both in character and also circumstance) it might be conjectured that some animal search patterns are not pre-programmed behaviours and are the direct result of the animal following a guidance rule which, because of inaccuracy or uncertainty, does not result in an exact interception of the goal point.

It is also shown that the very simple klinokinesis guidance rule used for guiding the robot is much more efficient when some environmental or locomotory noise is added to the robot (as would be the case in nature). In general, noise is detrimental to the efficiency of a guidance algorithm (Dusenberry 1993). However, a small level of noise is necessary for the simple robot klinokinesis rule to work.

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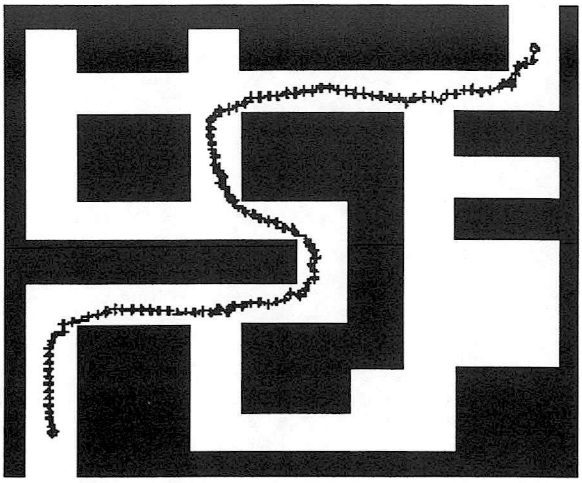

Figure 1. Obstacle avoidance using chemical gradient (tropotaxis)

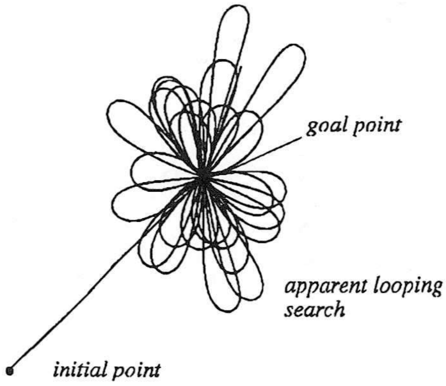

Figure 3. Appearance of looping search pattern using tropotaxis. Domain is 10m x 10m.

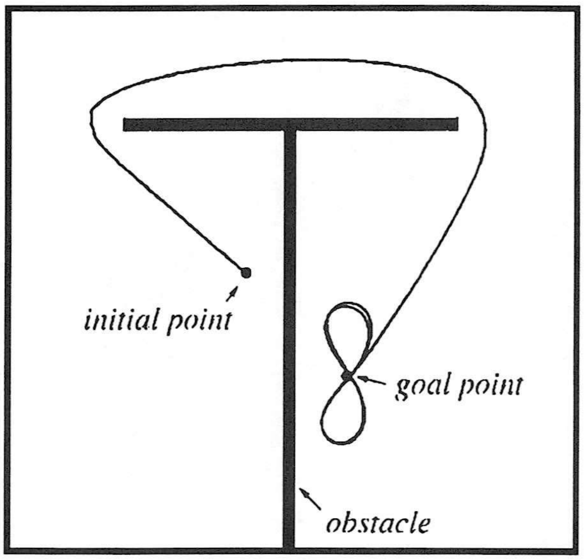

Figure 2. Obstacle avoidance using chemical gradient (tropotaxis). Appearance of looping search pattern.

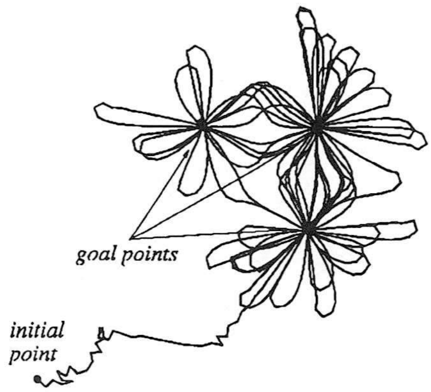

Figure 4. Multiple sources.

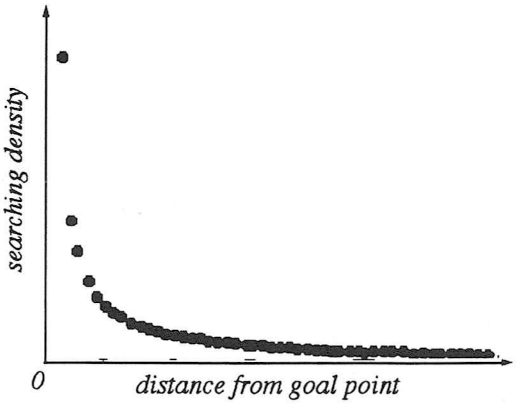

Figure 5. Search density of robot using tropotaxis.

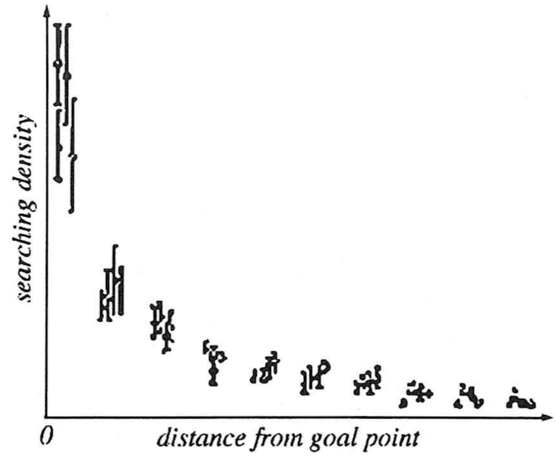

Figure 6. Search density of ants (pre-programmed pattern). Adapted from Dusenberry 1993.

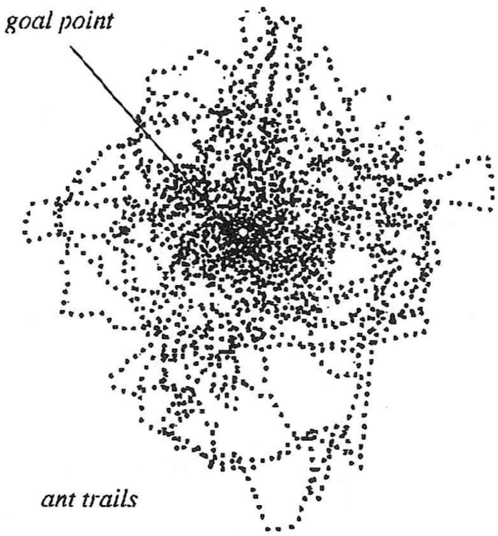

Figure 7. Search paths of ants (pre-programmed pattern). Adapted from Dusenberry 1993.

Figure 8. Idealised animal search patterns. Adapted from Dusenberry 1993.

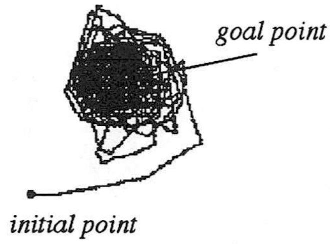

Figure 9. Apparent robot search pattern using klinokinesis. Domain is 20mx20m

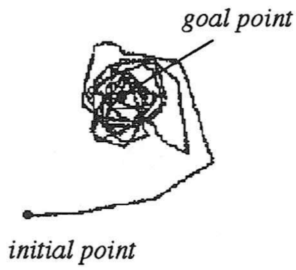

Figure 10. Goal finding using klinokinesis.

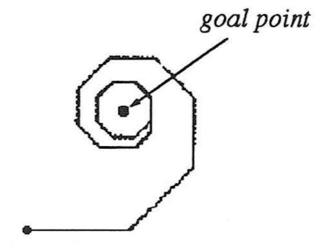

Figure 11. Klinotaxis with no environmental noise.

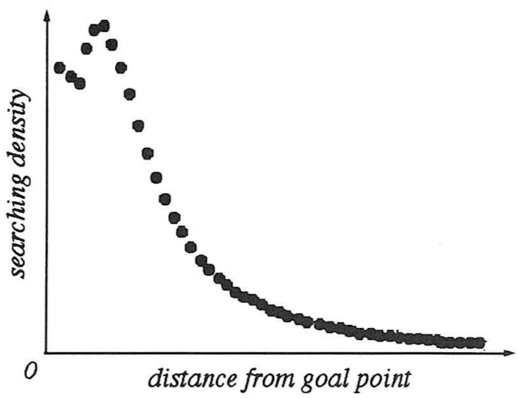

Figure 13. Search density using klinokinesis.