Taste and Search in a Robotics Context

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Abstract

There is increasing interest in developing robots that can sense and respond to plumes of volatile chemicals released into the atmosphere. However, chemicals with a molecular weight greater than 300 have very low volatility and do not produce detectable plumes. Such chemicals can be detected by taste and this paper describes a robot called TASTI that is equipped with a sensor for detecting chemical deposits on the ground. Search is an important and necessary ability for many biological organisms. Three biologically inspired search algorithms are being investigated as possible techniques that will allow TASTI to locate patches of chemical deposited on the ground using its chemical sensing tongue. This paper describes the algorithms and presents preliminary results of practical experiments.

1 Introduction

In the context of sensing the Macquarie Dictionary [1981] defines taste as:

> 'To try the flavour or quality of (something) by taking it into the mouth.'

It is well known that our sense of smell plays a large part in our appreciation of the food we eat. The overall Gestalt is made up of odour detected by the nose, texture felt via tactile sensors in the surface of the tongue, palate, etc., discomfort registered by the trigeminal nerve and the five chemical sensations (sweet, sour, salt, bitter and umami) sensed by the taste buds. For the purposes this paper taste will be restricted to the detection of chemicals by dissolving them in a carrier fluid and then applying the solution to a suitable sensor as an analogue of the way taste buds function.

It might be thought that a robot would have very little use for the ability to taste chemicals. However, only environmental chemicals with a molecular weight below 300 are sufficiently volatile to form detectable chemical plumes in air. A robotic nose would be unable to detect chemicals with a high molecular weight. Equipping a robot with the equivalent of a tongue greatly increases the range of chemicals that it could detect.

For roboticists biology is a great source of inspiration and there are a number of creatures that sense low-volatility chemicals by essentially licking the ground. Saliva or a similar medium dissolves the chemical deposits on the ground and the solution is then applied to taste-sensory nerve endings. Snakes are one group of animals that taste the ground. They gather scent particles from the air and ground with their forked tongue. The tongue is then inserted into a sensory site in the roof of its mouth called the Jacobson's organ. From there information concerning the identity of the scents is passed to the snake's brain [Klauber, 1972]. Many species of insects taste through their feet as described in the very accessible account by Dethier [1962] and they use this information for locating food and avoiding unpleasant chemicals. The design for a robotic tongue uses these biological examples and especially the human taste sense as a guide.

The aim of this project is to demonstrate the feasibility of developing robotic systems for detecting non-volatile chemical deposits on the ground and programming them with search algorithms observed in nature. This development could be used to help understand chemical location in flies, ants, etc. and provide a means of communication between robots by recoding information in the environment in the form of chemical markings. Compared to the use of volatile chemical markings non-volatile chemicals would persist for much longer. Robots equipped with tongue sensors could be used to locate chemical spills and also to ensure that cleaning operations in chemically contaminated areas have been completed successfully.

The following section describes the robotic tongue that has been developed for detecting non-volatile chemical markings on the ground. Section 3 provides a brief description of TASTI the mobile robot that carries the tongue sensor. The robot search algorithms being investigated in this project are described in Section 4 and some preliminary experimental results are given in Section 5. Conclusions and proposed future developments for this project are presented in the final section.

2 A Chemical Sensing Tongue

The sense of taste in humans is registered by taste buds located over the tongue and back of the throat [Geldard, 1972]. They normally respond to chemicals dissolved in saliva and for this reason the chemicals must be water soluble. Taste buds are onion-shaped groups of about sixty cells commonly associated with small papillae or protuberances on the surface of the tongue. One of the functions of the papillae seems to be to retain chemical laden saliva so that the taste buds have time to respond. Once the tongue has detected a chemical additional saliva is produced. As well as assisting with the ingestion of palatable substances and the elimination of objectionable ones, this saliva helps to cleanse the taste buds. Any artificial tongue would need similar elements including:

- a source of solvent to dissolve the target chemical,
- a chemical sensor to detect the chemical,
- a means of retaining the chemical solution in contact with the sensor, and
- some way of cleansing the sensor after the sensing process is complete.

The essential components of the robotic tongue developed for this project are shown in Figure 1.

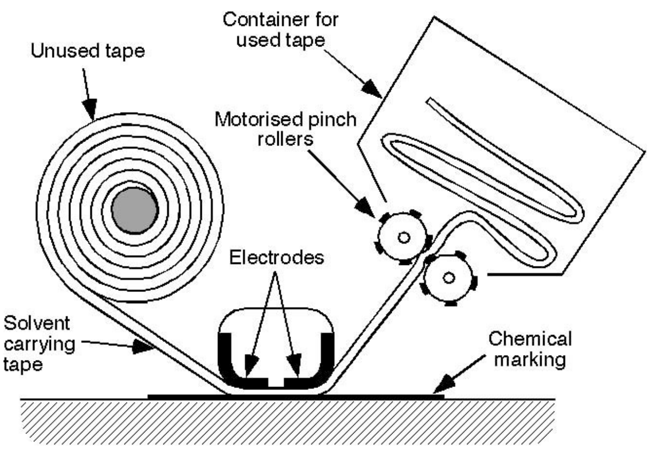

Figure 1 A schematic diagram of the robot tongue.

A conductivity sensor is a simple method of detecting chemicals in solution and this formes the basis of the robotic tongue developed for this project. Conductivity sensors cannot discriminate different ions but they do give an indication of total ion concentration. The conductivity between two electrodes immersed in an aqueous solution of an ionic compound is proportional to ion concentration. There is also a strong dependence on temperature with increased temperature tending to increase conductivity. The sensor electrodes were made from two rectangles of gold foil glued to a block of PVC plastic. The gold electrodes are separated by a 1mm gap. When an ionic solution bridges the gap between the electrodes their conductivity increases. The use of gold electrodes was intended to reduce corrosion and this was further helped by energising the electrodes with an ac signal. The variable resistance of the conductivity cell is used to control the frequency of an RC oscillator. The actual sensor reading is the number of transitions in the oscillator signal counted over 0.1 seconds. In order to detect dry deposits of ionic compounds on the ground they must be dissolved in distilled water and the resulting conducting liquid arranged to bridge across the gap between the two electrodes. As illustrated in Figure 1 a length of 5mm wide cotton tape dampened with distilled water is used as a medium for carrying the water. When the sensor is pressed against the ground the tape makes good contact with the electrodes and any ionic compound contacted by the tape is rapidly dissolved and increases the conductivity between the electrodes. Figure 2 shows that conductivity between the two electrodes and hence sensor frequency are proportional to the concentration of NaCl dissolved in the water. In theory the sensor frequency should approach the ‘dry’ frequency when no salt is present. However, it appears that as purchased the cotton tape used in this project is not completely free of soluble ionic compounds and this sets a lower limit to the sensitivity of this version of the robotic tongue.

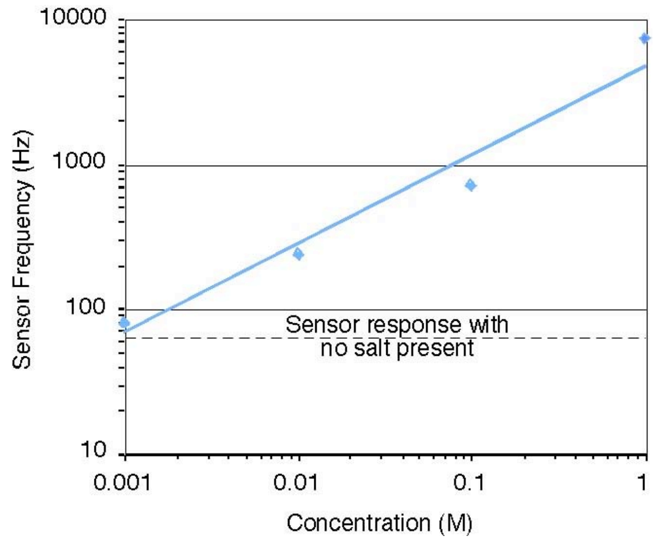

Figure 2 Sensor frequency related to chemical concentration.

In terms of other chemical sensors used in robotic applications [Russell, 2001] the tongue sensor response time is quite rapid. Figure 3 shows conductivity readings from the robotic tongue taken every 0.1 seconds. After the first reading was taken (at time 0 sec.) the robot was commanded to lower the sensor to the ground and the second reading (at time 0.1sec) was taken before the sensor actually touched the ground. The next reading (at time 0.2 sec.) indicates that conductivity was already starting to increase and after 0.5 seconds (the time at which sensor readings were taken in the searching experiments) a strong response was recorded. Sensor conductivity continued to increase as further NaCl dissolved from the floor and increased concentration in the cotton medium.

Once a section of the cotton tape contains dissolved salt it can no longer be used to detect chemical deposits. A fresh section of tape is then wound into position across the electrodes from a spool and this action also serves to wipe the electrodes clean. Every time the sensor is lowered to the floor it leaves a patch of moisture on the ground (like the fly specks left by the feet of flies). Eventually the tape would dry out so after five sampling sequences the tape is advanced even if no chemical is detected. Figure 4 shows a photograph of the robot TASTI carrying the conductivity sensor. The radio control servo on the left of the photograph is used for raising and lowering the sensor.

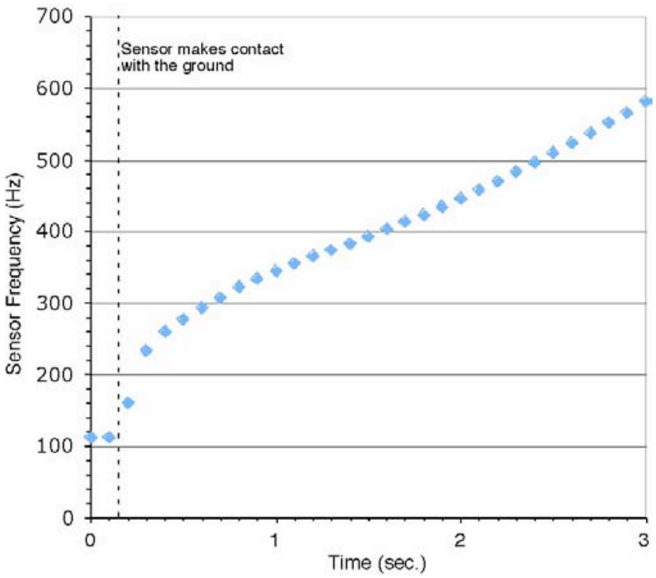

Figure 3 Sensor system time response.

3 TASTI the robot

For practical experiments involving taste-based mobile robot control the mobile robot TASTI (The Autonomous Sensory Tongue Investigator) has been developed. This 24cm diameter robot is formed from a stack of three disks. The lower disk carries two geared motors driving side-by-side wheels. Wheel motion is monitored by optical encoders attached to each wheel. Teflon skids provide stability for the robot by making a third point of contact with the ground. A printed circuit board containing power conditioning and interface electronics is attached to the middle disk and the top disk carries an Infineon C167 microcontroller for controlling all of the robot's systems including the electronic tongue sensor. A photograph of the robot is shown in Figure 4.

4 Search Strategies

Biological creatures employ a range of search strategies depending upon their capabilities and the physical characteristics of the target being sought. The process of locating the source of a chemical plume released into the air divides naturally into a number of distinct phases. In general these phases will require input regarding odometry and airflow as well as chemical concentration. Initially, the chemical plume must be contacted followed by tracking the plume upwind towards its source and finally identifying the actual source [Russell, Thiel, Deveza and Mackay-Sim, 1995]. In order to find discrete patches of chemical on the ground a different kind of strategy must be adopted in the form of a local search [Dusenbery, 1992]. A local search involves a central point or focus. This point is assumed to be associated with the highest probability of finding the goal or to be the location where finding a goal would be of most benefit. The density of search is concentrated around the focus and falls off with radial distance.

In this project the search is for chemicals deposited on the ground. TASTI will perform the search by a repeated sequence of moving forward a fixed distance, testing the ground and then changing its heading. The key difference between each search algorithm will be in the method of updating the robot's heading.

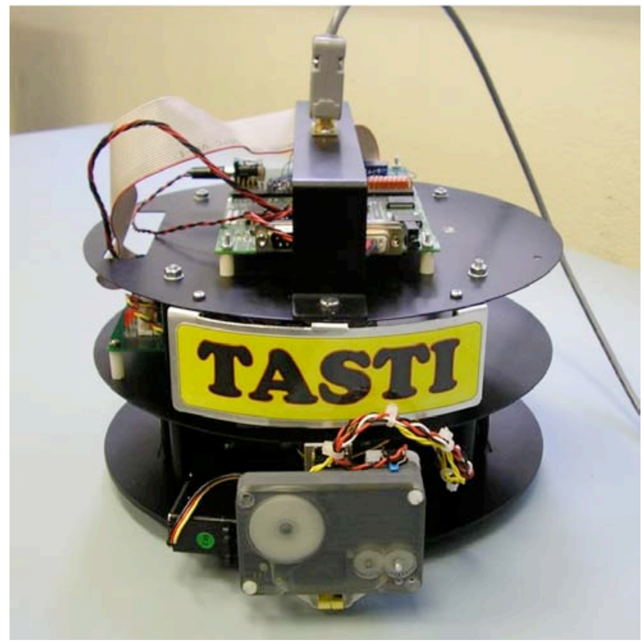

Figure 4 TASTI the robot

4.1 Spiral Search

If a search is to be performed outwards from an initial point with no preferred orientation then a spiral search would seem to be a reasonable choice. Although there have been reports of spiral searches being observed in nature these have not been confirmed beyond doubt [Dusenbery, 1992]. A spiral search is efficient and in theory provides complete coverage of an expanding area with no overlap. However, any error in navigation will leave areas unexamined. If this strategy were implemented on a robot with no accurate absolute navigation sensor then accumulated odometry errors would rapidly degrade the quality of coverage.

Even though the biological inspiration for the spiral search may not be certain and the possibility of problems caused by accumulated odometry errors this will be the first search algorithm considered in this paper. A circular spiral search involves following the path of an Archimedean spiral with $r=r_d\theta/\pi$. The quantity r_d is the range at which the goal can be detected by the searcher and θ is angle in radians subtended by the spiral at the focus. In the case of a search for chemical patches on the ground the pitch of the spiral would represent the smallest diameter expected for the chemical patch rather than r_d the range at which the goal can be detected. In practice the spiral pitch would be further reduced to allow for the fact that sensing is not performed at every point along the search path. For the spiral search the following equation determines the new robot heading based on the forward movement distance, how many movements the robot has performed since starting the search and the required pitch of the spiral:

$$heading_i = heading_{i-1} + \operatorname{atan2}\left(1, \sqrt{\frac{pitch * i}{\pi * step}}\right) \quad (1)$$

where:

i = the number of steps taken by the robot
heading = robot heading in radians
step = distance between sampling points
pitch = separation between successive spirals

Figure 5 shows the robot path generated using Equation 1 to choose the new robot heading after each forward movement. The robot would lick the ground after each forward movement and the search would terminate when the chemical concentration exceeded a set threshold.

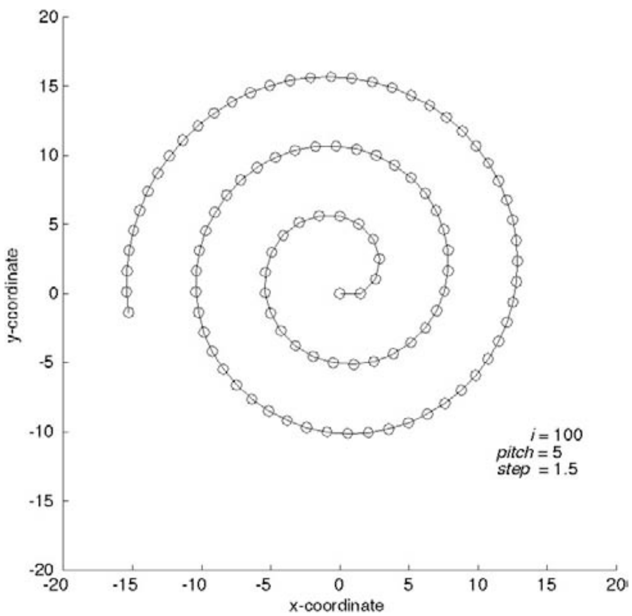

Figure 5 A spiral search

4.2 Radial Search

A radial search involves a repeated sequence of moving a set distance away from the focus and then returning. For each outward journey a new heading is chosen. This strategy has been observed in a number of creatures including harvester ants [Dusenbery, 1992]. The efficiency of the radial search is improved if the outward and inward paths form a loop so that a greater area is covered. For this project a looping form of radial search has been developed and is encapsulated in the following equations describing the change of heading of the robot:

$$heading_i = heading_{i-1} + \frac{4\pi}{n}\left(\sin\left(\frac{2\pi i}{n}\right)\right)^2 \quad (2)$$

if $\operatorname{rem}(i,n) == n/4$ then

$$heading_i = heading_i + \frac{2\pi}{petals} \quad (3)$$

where:

i = the number of steps taken by the robot
heading = robot heading in radians
petals = the number of petals in the search pattern
n = the number of robot movements in one petal (divisible by 4)

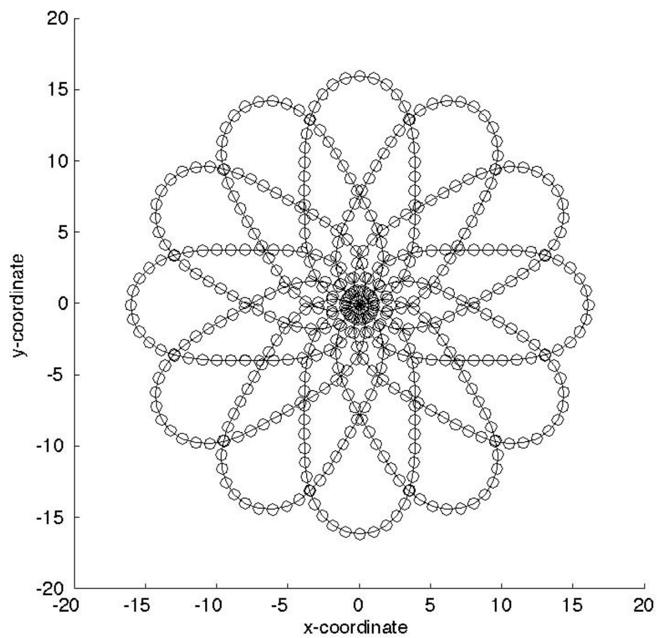

Figure 6 A radial search comprising 12 loops.

The overall size of the search pattern is governed by the distance the robot travels between sampling points and the number of loops in the pattern controlled by the variable *petals*.

4.3 Ant-Based Search

Many biological search patterns seem to have a significant random element. The searching pattern of the desert ant *Cataglyphis bicolour* has been studied quite extensively. Although individual segments of the search path seem random the overall pattern is concentrated at the focus and the density of paths falls off steadily with distance. Wehner and Srinivarsan [1981] have studies the searching behaviour of the desert ant and developed an algorithm that generates a similar path. The algorithm uses a sequence of random signals generated by the following equation:

$$V(p) = \frac{1}{m}\sum_{i=1}^{m}\sin\left(2\pi\left(\frac{ifp}{500} + \phi_i\right)\right) \quad (4)$$

where:

f = cutoff frequency for filtered white noise (f = 1)

ϕ_i = random relative phase. In our case (0.53, 0.5, 0.76, 0.56, 0.3, 0.04, 0.73, 0.94, 0.11, 0.36, 0.32, 0.52, 0.72, 0.78, 0.57, 0.28, 0.72, 0.34, 0.84, 0.67)

m = number of frequency components (m = 20)

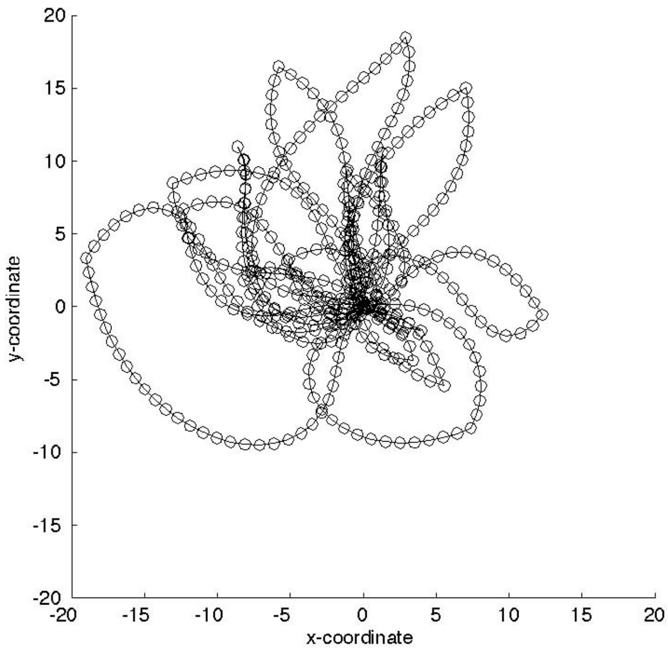

Figure 7 The ant search pattern.

The search proceeds by alternately moving away from and then back towards the focus. The decision to turn back towards the focus is made when the distance from the focus to the robot exceeds the layer variable. The layer variable n is initialised to 1 and then increments by 1 each time the robot exceed the layer value. When moving back towards the focus the robot changes direction when its distance from the focus falls below 0.7 (this is a arbitrary value chosen as 0.7 for this project) . When positioned at coordinates x, y the robot radius is:

$$radius = \sqrt{x^2 + y^2} \quad (5)$$

After moving each step the robot chooses a new heading with respect to a radial line from the focus and passing through the current robot location.

If direction==outwards

$heading_i = bearing_{i-1} + \text{atan}(Q(i-1))$

If direction!=outwards

$heading_i = bearing_{i-1} + \pi - \text{atan}(Q(i-1))$

where:

$$bearing_{i-1} = \text{atan}\,2(y_{i-1}, x_{i-1}) \quad (6)$$

$$Q(i-1) = \frac{K}{n} radius_{i-1}\; V(i) \quad (7)$$

Scaling constant K = 20

An example of the search pattern produced by this algorithm is shown in Figure 7. For this algorithm the robot must keep an accurate track of its location with respect to the focal point of the search.

5 Practical tests of the search algorithms

Having developed a practical robotic tongue and installed it on a mobile robot the next stage of the project was to investigate the ability to search for chemical patches on the ground. Initial tests were conducted with an implementation of the spiral search algorithm. TASTI started the search at the origin and facing in the positive x-direction. A circular 250mm diameter patch of salt solution was painted on the ground at location (400mm, -400mm). After a while this dried to leave a fine frosting of salt crystals adhering to the parquet floor.

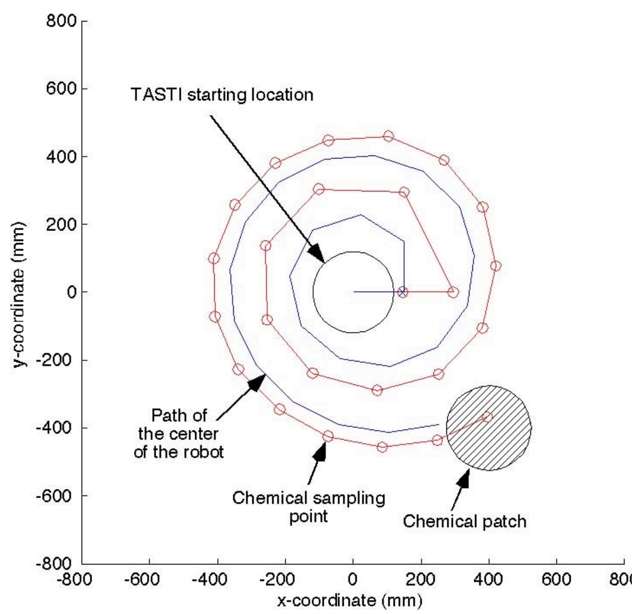

Figure 8 Spiral search path of TASTI the robot.

A number of spiral searches were successfully completed and Figure 8 shows results from one of these. The red line shows the path taken by the tongue sensor and the circles marked on this path indicate points where chemical concentration was sensed. The blue line indicates the path of the centre-point of the circular robot. Having a sensor offset from the centre of the robot means that the sensing points are not positioned very close to the ideal spiral pattern. This is especially true at the start of the spiral. There are two solutions to this problem. The first solution is to modify the search algorithm to compensate for the problem of the offset sensor. The second and preferred solution is to rebuild the robot so that the tongue sensor can be located at the turning centre of the robot.

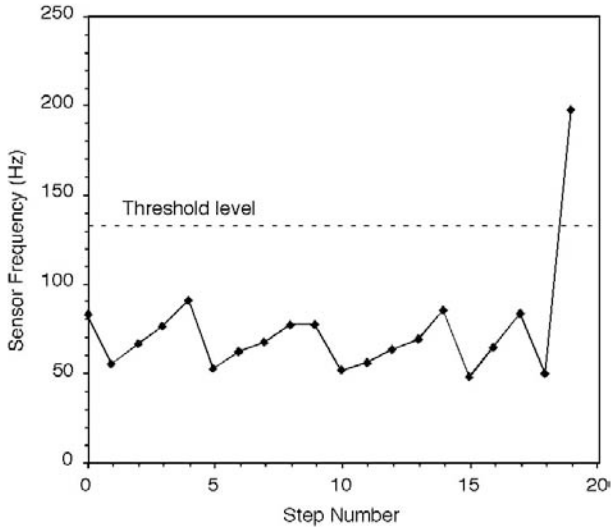

Figure 9 Tongue sensor readings during the spiral search.

In Figure 9 it can be seen that there is a small cyclic variation in the tongue sensor output as it performs a spiral search. This may be caused by picking up low-level contamination from the floor and then removing it every 5 samples when the ribbon is automatically wound on. When the tongue sensor contacted the salt marking at sample 19 this produced an unmistakable response that exceeded the threshold of detection and the search terminated.

6 Conclusions

This paper has reported on an investigation involving robotic location of non-volatile chemical deposits on the ground. The small mobile robot TASTI carries a novel tongue sensor that can detect ionic compounds on the ground. Three biologically inspired search algorithms have been investigated. For the spiral and radial search patterns simple robot control algorithms were developed and the algorithm for the third ant inspired algorithm was taken from a paper by Wehner and Srinivarsan [1981]. In preliminary experiments using the TASTI robot effective searching behaviour was observed. These experiments using the spiral algorithm highlighted the fact that the sensor placement on the robot is not ideal for following the search paths considered in this paper. Before looking further at the search algorithms a new TASTI robot will be constructed with a more favourable geometry.

Potential applications for this technology include checking the effectiveness of decontamination measures applied to areas contaminated by toxic chemicals and locating chemical spills. This kind of biologically inspired robot can also be used to test theories relating to the algorithms that control the actions of biological creatures. In future work a more sophisticated chemical sensor will be developed that can give more specific information about the nature of chemicals it detects.

Acknowledgments

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