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Human-Inspired Chemical Sensing for Mobile Robots

R. Andrew Russell, *Member, IEEE*

Abstract— **The pattern of airflow has a significant influence on the ability of both animals and robots to detect and locate sources of volatile chemicals. This paper describes a project to build a robot chemical sensing system based on observations of airflow around the human body. These observations indicate that in low-velocity airflow air warmed by body heat rises and carries odorants from near ground level towards the nose. This implies that under the right conditions large areas of the human body act to collect and direct odour chemicals to the nose. The aim of this project is to investigate the feasibility of this odour collection mechanism by building a robotic odour sensing system working on this principle and to compare it with the same chemical sensor system when not heated. The results indicate the improved sensitivity of the heated sensor system. This paper describes the sensor system and gives results of sensor tests and odour source location experiments performed using it.**

I. Introduction

As humans we do not credit ourselves with a very refined sense of smell. Perhaps in earlier times before refrigeration and other methods of food preservation odour was a good indication of how safe food was to eat. Now, apart from enjoyable situations such as when eating a fine meal or appreciating a scent or perfume we rarely give much thought to odours. In critical situations such as the detection of explosives or contraband drugs through to finding victims of earthquakes and other disasters we employ animals with very sensitive noses trained to search out specific odour sources.

Because of the benefits of creating technological equivalents of sniffer dogs there has been increasing interest in developing robotic systems that can respond to chemical signals. Such systems would have advantages over their biological counterparts including requiring reduced care and maintenance, having unlimited attention span and no need for training.

In the design of many odour sensing robots little if any consideration has been given to airflow, its effect on chemical sensor readings and ways to control airflow in order to improve the value of sensor information. In this project the hypothesis being investigated is the proposition that in human odour sensing the rising flow of air caused by body heat has a beneficial effect for odour sensing by gathering odour molecules over large areas of the body surface. This hypothesis is investigated by building a novel robot chemical sensing system based on a vertical heated cylinder. Four chemical sensors around the top of the cylinder detect chemicals carried upwards by the rising air. With respect to the heated cylinder the sensors occupy a similar position to the human nose sampling heated air rising from the arms, legs and torso.

R. A. Russell is with the Intelligent Robotics Research Centre of Monash University, Clayton, VIC3800, Australia (phone: +61 3 9905 3462; fax: +61 3 9905 3454; e-mail: andy.russell@monash.edu).

II. Mobile Robot Chemical Sensor Systems

The application of odour sensing to robotics was proposed as early as 1984 when Larcombe and Helsall considered uses for chemical sensing robots in a report to the European nuclear industry [1]. Probably the first practical application of chemical sensing in robotics was described by Rozas, et al. [2]. The electronic nose on their mobile robot consisted of a group of tin oxide chemical sensors mounted in a metal box with a fan to draw air into and out of the box. It was claimed that this arrangement provided a directional sensing capability. However, the exact construction of the sensor system and its precise directional characteristics are not clear. Since then there has been increasing interest in the challenges of providing robots with a sense of smell [3], [4]. In many early experiments chemical sensors were attached to the outside of the robot or even on booms extending from the robot structure. It is not clear to what extent airflow characteristics around the robot body and the omni-directional characteristics of the sensors were considered in these experiments. As outlined by Settles [5] in chemical trace sampling insufficient attention is paid to airflow during air sampling.

However, a number of more recent experiments have employed windvanes or other means of assessing airflow direction [6]. By combining data from simple chemical sensors with details of airflow more information is available about the arrival direction of chemical plumes. This information can be used by robot control algorithms to choose a search direction towards a chemical source.

It is probable that the majority of creatures that search out the source of odour plumes in air also use a combination of chemical and airflow sensing. For this reason biology is an excellent source of ideas for roboticists developing chemical tracking robots. As an example, a directly bio-inspired chemical source location system has been described by Ishida, et al. [7]. It has been observed that male silkworm moths flutter their wings as they follow pheromone plumes towards the female. When performing this behaviour the males are walking and seem to flutter their wings to create an airflow from head to tail which draws pheromone laden air towards their odour sensing antennae. Ishida, et al. built a robotic chemical sensing system using a similar principle and demonstrated that it could be used to track odour plumes in 3-dimensions. The

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aim of this project is to investigate another biomimetic form of robotic chemical sensing for source location based on the human odour sense.

Figure 1. A Schlieren photograph visualising heated air rising from the human body. (courtesy Prof. G. Settles, Penn State University)

III. Odour Sensing in Humans

The human sense of smell is reported to be in decline. It is thought that the human development of trichromatic vision several millions of years ago resulted in a reduction in our dependence on smell [8]. However, we are able to detect, remember and locate the source of a large number of odours. This is particularly the case if we resist allowing what we see to dominate our awareness.

The possibility that there could be a mechanism at work in our sense of smell that gathers odour chemicals and directs them to our nose is suggested by Schlieren photographs like those produced by Professor Gary Settles. Schlieren photographs can make visible subtle differences in the density of heated air. Fig. 1 shows the extent of heated air rising from the human body. It seems possible that the rising air could carry odour molecules arriving over large areas of the body surface and direct it towards the nose.

In studies of the indoor environment this possibility has been considered as a mechanism for carrying particulate matter (PM) to the nose. However, a paper by Schmees, et al. [9] seems to rule out this possibility:

> "The rationale for this part of the experimental inquiry was that, in most indoor working environments, the human body would be warmer than the surrounding air and therefore there may be thermal influences on air movement around the body that might in turn influence the inhalation of airborne particles. In general, however, the pictures show no evidence that the airflow pattern in the immediate breathing zone of the mannequin was influenced in any way by the heat emanating from the heated mannequin."

In this investigation an adult human-proportioned mannequin was positioned in a wind tunnel and smoke traces were used to visualize airflow. Tests were performed for both an unheated and heated mannequin. Measurements were only taken upwind of the mannequin and with it facing into the wind. Under these conditions heating the mannequin seemed to have little effect on airflow. However, another investigation by Heist, et al. [10] found that:

> "A very different flow pattern is seen downstream of the heated manikin. The flow field is characterized by a strong vertical updraft … The magnitudes of the air velocities in the updraft are on the order of 0.1 m/s, approximately 10 times greater than for the unheated case. This flow pattern is quite capable of transporting PM originating near the floor into the breathing zone."

Therefore, it seems possible that convection currents produced by a vertical heated surface could gather chemical signals and direct them towards chemical sensors. For this reason, it was decided to develop a robot sensor system based on this principle.

IV. Sensor System

An essential part of the proposed sensor system is a heated surface and for this reason it will be referred to as the heated sensor system or more briefly, the heated sensor.

A. Heat Source

The sensor system itself consists of an aluminium cylinder 72mm diameter by 190mm tall. The cylinder contains hot water at a nominal temperature of 50˚C for these experiments. This temperature was selected because it is recommended as the safe maximum for domestic hot water systems.

By filling the cylinder with hot water and recording the temperature decay to 36.8% of its initial value above ambient the thermal time constant was determined. To check that the temperature decay is accurately modelled as an exponential fall the cylinder temperature C_{temp} was calculated as:

$$Ctemp = Amb + (Max - Amb)e^{-\frac{t}{\tau}} \quad (1)$$

where:

Amb = ambient temperature (18.8˚C)
Max = cylinder maximum temperature (84˚C)
t = time
τ = thermal time constant of the cylinder (80 min.)

It was found that there was good agreement between the calculated values of C_{temp} and experimental values and in fact the goodness of fit between the two sets of data R^2 = 0.994.

Now, if the whole of the cylinder and contents can be considered as a lumped capacitance heat reservoir then the total heat content Q is equal to the overall heat capacity C times the temperature t. If the heat capacity of the cylinder mainly results from the water it contains (0.820kg) then taking into account that the specific heat capacity of water c_p = 4181 J/kg.K. Then the heat capacity C of the cylinder is 0.820*4181 = 3428J/K.

The thermal time constant τ is:

$$\tau = R\,C \tag{2}$$

Therefore [11],

$$R = \tau / C = 80{*}60/3428 = 1.4\ ^\circ\mathrm{C/W}$$

To maintain a temperature 30˚C above ambient would require 30/1.4 = 21.4W. This is a large power requirement for a sensor system carried by a small robot. Therefore, if extended mission time was required then some material like a low melting-point wax could be used to maintain a stable temperature as the wax solidified and returned its latent heat of fusion.

B. Chemical Sensors

In previous experiments the author has used a number of different chemical sensors including some based on tin oxide. These sensors display a reasonably fast response to the presence of the target chemical of the order of seconds. However, they have a very long recovery time of the order of tens of seconds. Recently, relatively new sensors produced by Applied Sensor Inc. have demonstrated improved sensitivity and time response. These sensors are made using micro electro mechanical system (MEMS) technology. Fig. 2 shows a comparison of the response of an Applied Sensor volatile organic compounds sensor compared with a conventional tin oxide gas sensor. Both sensors were introduced into an atmosphere of saturated ethanol vapour 10 seconds after recording started and removed about 26 seconds later. The improved time response of the Applied Sensors tin oxide sensor can be readily appreciated.

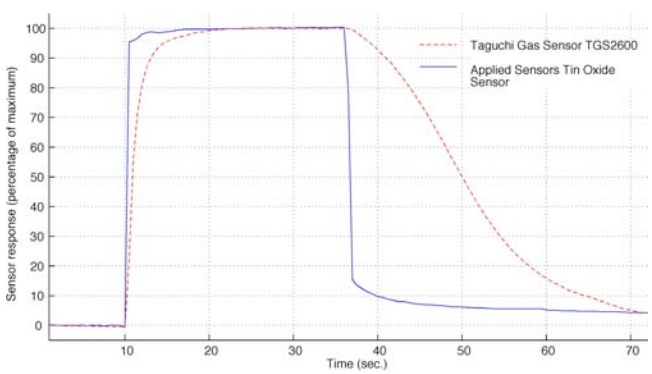

Figure 2. Time response of an Applied Sensors tin oxide sensor compared with a conventional tin oxide gas sensor.

For this reason it was decided to use four Applied Sensors tin oxide sensors in the sensor system to detect the target chemical and provide an indication of distribution of the chemical around the cylinder. The four sensors were mounted 300mm above the base of the heated cylinder on a plastic cap attached to the top of the cylinder. They were positioned in a circle at headings of 0˚, 90˚, 180˚ and 270˚ as shown in Fig. 3.

V. Mobile Platform

The sensor system is relatively tall and because the prototype system is heated by hot water it is quite heavy. For these reasons it was decided to build a three wheel chassis to carry the sensor system driven by Kornylak Corporation omni-directional Transwheels®. This configuration is low-profile, stable and very agile. The robot can move off at any heading or rotate on the spot. It can also perform a combined move and rotate in one action. The governing equations for this kind of robot are nicely summarised in the paper by Mark Ashmore and Nick Barnes [12]. Each wheel is actuated by a 12V dc motor via a 50:1 gearbox and wheel motion is detected by an optical encoder. Wheel control and sensor measurements are performed by a Renesas M16 processor that communicates with a remote laptop computer via an XBee wireless data link. Overall the robot chassis is 26cm diameter and the top of the platform is 5.5cm from the ground. A photograph of the robot carrying the red sensor system is shown in Fig. 3 (for scale, the lines ruled on the table are 200mm apart). A remote laptop computer performs robot control and data logging functions.

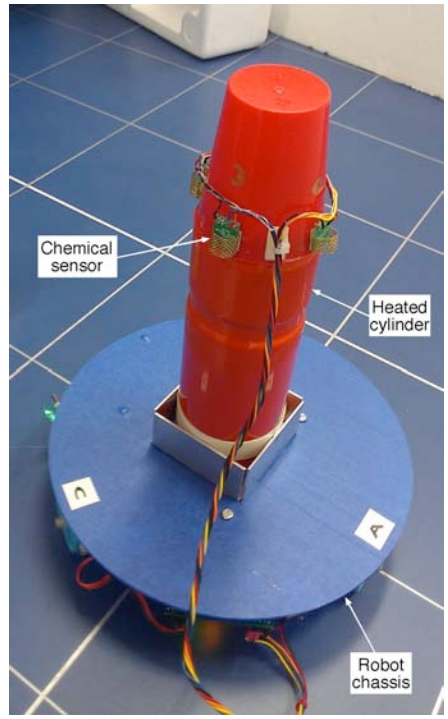

Figure 3. The omnidirectional robot base carrying the chemical sensor system.

VI. Results Circling the Chemical Source

To assess the response of the sensor system both when heated and unheated experiments were performed involving the robot circling a Petri dish containing ethanol. In these tests the robot stopped 20 times as it completed a full circle of the chemical source at a radius of 300mm. At each stop it waited 5 seconds and then recorded the four sensor readings. In the following figures chemical sensor readings are plotted as radial spokes originating from the location of the robot and with a length proportional to the change in sensor reading between clean air and measurements with the ethanol source present. Note that the robot maintained a constant heading as it circled the source. A variable transformer was used to run a cooling fan at reduced voltage (180V as opposed to the usual 240V). This produced an airflow of 0.2m/sec in the centre of the experimental area. The measurements for the unheated and heated sensor system were taken and results are shown in Figs. 4 and 5. Note that the horizontal bar at the bottom right hand side of the figures indicates the scaling factor applied to the sensor readings. It is seen that the unheated sensor produces very little output at any point as the robot circled around the source. By contrast the heated sensor produces a strong

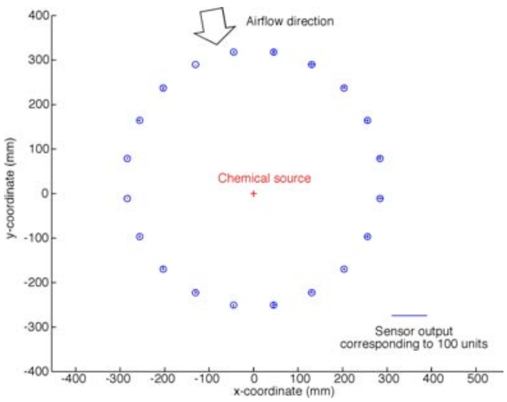

Figure 4. Sensor measurements with an unheated sensor as the robot circled a Petri dish of ethanol. Note that the robot maintained the same heading as it circled the source so the chemical sensors were always oriented at 0˚, 90˚, 180˚ and 270˚.

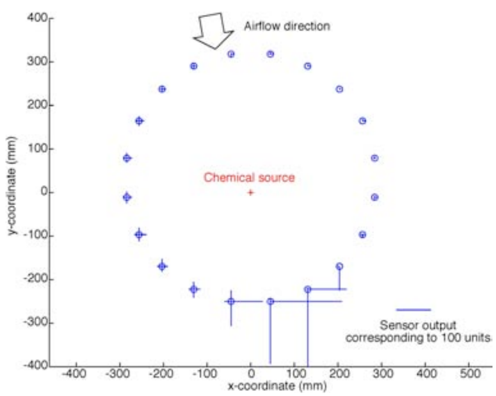

Figure 5. Sensor measurements with a heated sensor as the robot circled a Petri dish of ethanol. Once again the chemical sensors were always oriented at 0˚, 90˚, 180˚ and 270˚.

output downwind of the chemical source and mainly from those sensors on the leeward side of the cylinder. This observation agrees with the results presented by Heist, et al. [10] where they identified a significant upward flow of air on the down-wind side of a heated body. From the results of this experiment it was clear that heating the sensor system enables it to register volatile chemicals that were not detected by the unheated sensor system.

The results presented in Fig. 5 indicate that the response of the four sensors mounted on the heated sensor is related to airflow direction. To investigate this aspect of the sensor system the robot was positioned 150mm down wind of a source producing 0.5l per minute of air saturated with ethanol vapour and the robot rotated in approximately 30˚ increments. After each rotation the reading of one of the chemical sensors was recorded 10 times at 5 second intervals. The red dashed line in Fig. 6 indicates the mean of the groups of ten readings plotted against rotation angle of the robot. The flow of air around a heated cylinder situated in a constant airflow is a difficult configuration to model analytically. However, the experimental results plotted in Fig. 6 suggest an empirical model for the sensor system response consisting of a half cosine function. The solid blue line in Fig. 6 represents a half cosine function fitted to the experimental data. The goodness of fit between this model and experimental data $R^2 = 0.843$.

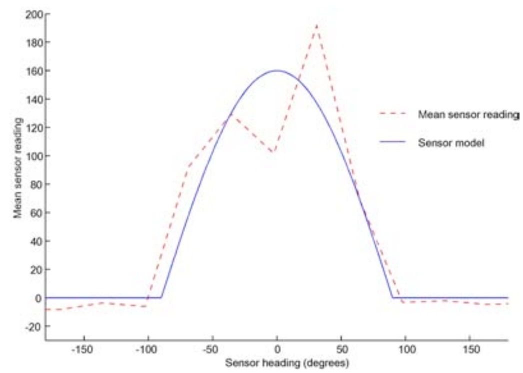

Figure 6. A comparison between the output of one sensor plotted against sensor heading (a heading of 0˚ corresponds to the down wind direction) and the half cosine sensor model.

The half cosine model is now used to estimate the intensity of the incident chemical plume as well as its arrival direction. Fig.7 shows the model of the chemical distribution incident on the cylinder at a heading of $\theta + \pi$ as well as the four chemical sensors evenly spaced around the cylinder at heading angles of 0 (for sensor 0), $\pi/2$ (sensor 1), π (sensor 2) and $3\pi/2$ (sensor 3) with respect to the robot chassis. The peak of the cosine distribution occurs at a down-wind heading of θ and has an intensity value of A. The distribution falls to zero at an angle of $\pi/2$ either side of the maximum following a cosine law and then remains at zero round the remainder of the cylinder. Each sensor n produces a response M_n to an incident chemical plume for a range of θ of $\pm\,\pi/2$ centered on the angular position of the sensor.

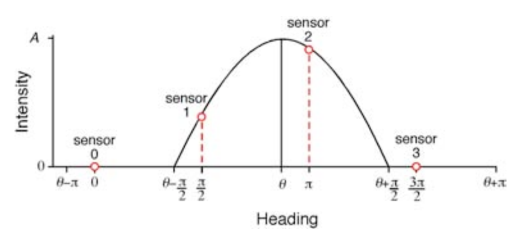

Figure 7. The half cosine model of chemical distribution around the heated cylinder.

$$M_0 = A\cos(\theta) \qquad -\frac{\pi}{2} < \theta < \frac{\pi}{2} \tag{3}$$

$$M_1 = A\cos\left(\theta - \frac{\pi}{2}\right) = \mathrm{Asin}(\theta) \qquad 0 < \theta < \pi \tag{4}$$

$$M_2 = A\cos(\theta - \pi) \qquad \frac{\pi}{2} < \theta < \frac{3\pi}{2} \tag{5}$$

$$M_3 = A\cos\left(\theta - \frac{3\pi}{2}\right) = -\mathrm{Asin}(\theta) \qquad \pi < \theta < 2\pi \tag{6}$$

For all other values of θ outside the given ranges the resulting sensor response is zero. Therefore, if the plume is present than two sensors will give a positive response (except for the situations where θ is an exact multiple of $\pi/2$).

The root sum square (RSS) of the sensor readings can be used to assess the magnitude of the distribution:

$$RSS = \sqrt{M_0^2 + M_1^2 + M_2^2 + M_3^2} \tag{7}$$

$$RSS = \sqrt{A^2\left((\cos(\theta))^2 + (-\sin(\theta))^2 + (-\cos(-\theta))^2 + (\sin(\theta))^2\right)} \tag{8}$$

Now, given the assumed distribution, at least two adjacent sensor readings will be zero (note that sensor 0 is adjacent to sensor 3). Therefore:

$$RSS = \sqrt{A^2\left((\pm\sin(\theta))^2 + (\pm\cos(\theta))^2\right)} \tag{9}$$

and in the special case where one sensor is exactly aligned with the center of the cosine distribution then three sensor readings will be zero:

$$RSS = \sqrt{A^2\left((\pm\cos(0))^2\right)} \tag{10}$$

Therefore, it is seen that RSS is equal to the amplitude A of the cosine distribution. The sensor readings can also be used to determine the heading θ directly down-wind of the prevailing airflow direction.

From (3) and (4):

$$\mathrm{atan}\left(\frac{M_1}{M_0}\right) = \mathrm{atan}\left(\frac{A\sin(\theta)}{A\cos(\theta)}\right) = \theta \qquad 0 < \theta < \frac{\pi}{2} \tag{11}$$

and (5) and (6):

$$\mathrm{atan}\left(\frac{-M_3}{M_0}\right) = \mathrm{atan}\left(\frac{A\sin(\theta)}{A\cos(\theta)}\right) = \theta \qquad -\frac{\pi}{2} < \theta < 0 \tag{12}$$

These results are only valid over a range of $0 < \theta < \pi/2$. To extend to the full range of $-\pi < \theta < \pi$ we must use the atan2 function and the other two sensor readings M_2 and M_3:

$$\mathrm{atan}\left(\frac{M_1}{-M_2}\right) = \mathrm{atan}\left(\frac{A\sin(\theta)}{A\cos(\theta)}\right) = \theta + \pi \qquad \frac{\pi}{2} < \theta < \pi \tag{13}$$

$$\mathrm{atan}\left(\frac{-M_3}{-M_2}\right) = \mathrm{atan}\left(\frac{A\sin(\theta)}{A\cos(\theta)}\right) = \theta - \pi \qquad -\pi < \theta < -\frac{\pi}{2} \tag{14}$$

Therefore, over the full range $-\pi < \theta < \pi$

$$\theta = \mathrm{atan}\,2\big((M_1 - M_3),(M_0 - M_2)\big) \tag{15}$$

Using (7) and (15) the chemical concentration at a particular location A (RSS) and the direction of airflow θ can be calculated from the chemical sensor readings. These quantities are used in the following source location algorithm to demonstrate the chemical sensing system.

VII. Source Location Experiments

A major potential application for odour sensing robots is locating the source of a volatile chemical. To provide a demonstration of the heated chemical sensor system a simple source location algorithm has been implemented. For an autonomous robot system the process of source location can be divided into three phases [13]. These phases are:

1) chemical plume acquisition,
2) plume tracking towards its source, and
3) confirmation of the source location.

Usually, confirmation that the chemical source has been found would rely on additional sensors and some task-specific information. As the focus of this project is the odour sensing system then the third phase of the source location task is omitted.

The mobile robot was programmed to perform the first phase of the source location task by taking regular chemical samples on a straight-line path every 50mm of travel until the chemical plume was located. Once chemical intensity A exceeded a pre-set threshold the robot switched to plume tracking mode for the second phase. In this phase the robot chose a direction towards the chemical source of $\theta + \pi$. The robot then moved forwards 50mm on this heading and took another reading. This process was repeated until the robot collided with the source or until it lost contact with the chemical plume.

Experiments were conducted on a table-top approximately 1.5m by 1.4m. The origin for the experiments (0, 0) was established in the bottom left corner of the arena and the chemical source (a 10cm diameter Petri dish of ethanol) positioned at location (0.6m, 0.8m). The cooling fan providing airflow was located at (0.2m, 2.0m).

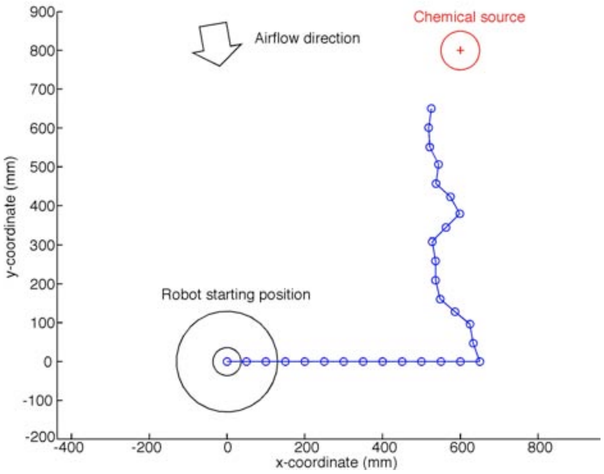

Figure 8. Robot acquiring and tracking a chemical plume when starting approximately perpendicular to the plume.

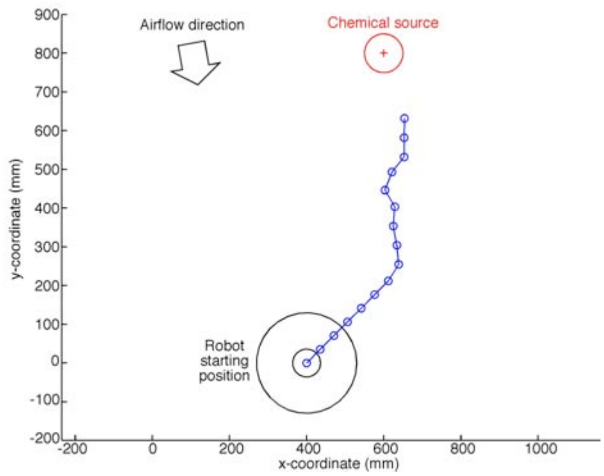

Figure 9. Robot acquiring and tracking a chemical plume when starting at a heading of approximately 45° to the upwind direction.

Fig. 8 shows the path of the robot as it acquires the chemical plume by moving approximately perpendicular to the airflow direction until it encountered the plume. The robot then successfully followed the plume until it collided with the source. Another experiment where the robot acquired the plume when travelling at a heading of 45° to the upwind direction is shown in Fig. 9. The plume-tracking algorithm assumes that the path of the plume does not alter once it has been acquired. This is because the robot is essentially heading up-wind.

VIII. CONCLUSION

This project has investigated the idea of developing a novel robot odour sensing system based on aspects of human olfaction. Schlieren photographs of heat rising around the human torso show the effect of body temperature on airflow close to the body. Also, the results of practical investigations of the influence of body heat on the transport of particulate matter to the nose by researchers investigating environmental health confirm this effect. This evidence indicates that body heat can enhance the transport of particulate matter and odours to the nose.

To confirm this effect and investigate its application to robotic odour sensing a mobile robot and heated sensor system were built. Results have demonstrated that the heated sensor can provide increased sensitivity compared to an unheated sensor and provide directional information to allow chemical sources to be located in moderate airflows.

A simple robot chemical plume tracking algorithm has demonstrate the capability of the sensor. However, this algorithm could be improved in a number of ways. The directional information provided by the sensor relates to the direction of airflow impinging on the sensor and not the odour concentration gradient. Therefore, the algorithm assumes that once in the plume then heading directly up-wind will lead to the source. However, if the plume alters course the robot will not be guided back towards the center of the plume (as it would be using concentration gradient information) and may lose contact with the plume. An improved algorithm would gather odour gradient information and steer the robot towards the center of the plume.

To conclude, biology is an excellent source of ideas for many areas of robotics and robotic odour sensing is no exception.

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