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Plume-Tracking Robots: A New Application of Chemical Sensors

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Abstract. Many animals have the ability to search for odor sources by tracking their plumes. Some of the key features of this search behavior have been successfully transferred to robot platforms, although the capabilities of animals are still beyond the current level of sensor technologies. The examples described in this paper are (1) incorporating into a wheeled robot the upwind surges and casting used by moths in tracking pheromone plumes, (2) extracting useful information from the response patterns of a chemical sensor array patterned after the spatially distributed chemoreceptors of some animals, and (3) mimicking the fanning behavior of silkworm moths to enhance the reception of chemical signals by drawing molecules from one direction. The achievements so far and current efforts are reviewed to illustrate the steps to be taken toward future development of this technology.

Introduction

Many species of animals rely for their survival on their ability to track odor plumes. Male moths follow sexual pheromones to find their mates (Willis and Arbas, 1991) and marine crustaceans track smells to search for food (Weissburg and Zimmer-Faust, 1993; Atema, 1996; Grasso, 2001). Although their mechanisms are not yet fully revealed, these examples suggest that, if the underlying mechanisms are successfully transferred to robotic platforms, the chemical senses can be as effective as the visual (Viollet and Franceschini, 1999) or auditory senses (Webb and Scutt, 2000) in directing navigation of autonomous robots. The purpose of this paper is to give a general idea of the current state of development of robots that track chemical plumes. The potential applications for such robots include searching for hazardous chemicals and pollutant sources.

Signals Available in Chemical Plumes

The most fundamental characteristics of a chemical plume are concentration of the target chemical and flow direction. Since molecular diffusion is almost always slower than convection, a chemical plume trails downstream from its source, as shown in Figure 1A. There is no smooth concentration gradient in this instantaneous image since the eddies in the turbulent flow stretch and twist the plume. If an array of eight chemical sensors is immersed into the plume, it is exposed to the intermittent stimuli shown in Figure 2. The importance of flow direction is also seen in Figure 1A. When a searcher is in the plume, the source is always in the upstream direction. This is why many species of animals perform anemotaxis in air and rheotaxis in water (Willis and Arbas, 1991; Dusenbery, 1992; Arbas *et al.*, 1993; Weissburg and Zimmer-Faust, 1994).

Whereas animals have keen senses for detecting chemical and flow stimuli (Dusenbery, 1992), sensors for a robot to detect those signals with capabilities similar to those of animals are not yet available. In the case of chemical

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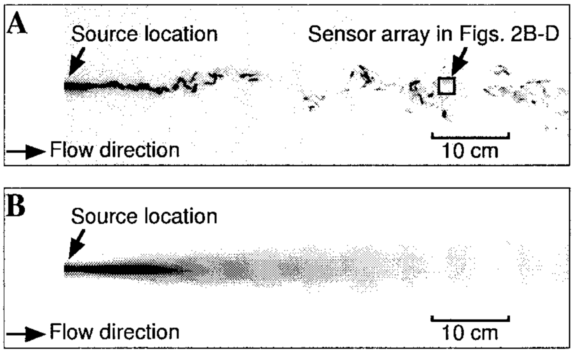

Figure 1. Images of a chemical plume in a turbulent flow. A fluorescent dye, rhodamine 6G, was released from a nozzle into a fully developed open-channel water flow. The effluent velocity of the dye matched the channel flow velocity, thus creating a passive source and avoiding the production of additional turbulence by the effluent itself. The images of the dye plume were captured using the planar laser-induced fluorescence (PLIF) measurement technique (Webster *et al.*, 1999). (A) is an instantaneous image, and (B) is the average of 6000 images measured at 10 frames/s.

sensors, a compromise has been made on the times of response onset and recovery, which can affect the performance of robots. For example, for our wheeled robot we chose semiconductor gas sensors that are commonly used for gas alarms to detect flammable gases and organic solvent vapors. Although these sensors have high sensitivity and fast response, it takes more than 30 s for their responses to return to the initial levels after gas is removed. Therefore, the crawling speed of the robot had to be slowed down to a few centimeters per second (Ishida *et al.*, 1996). Such slow sensors can be beneficial when time is not a critical issue. When averaged over long enough times (typically several minutes), chemical plumes have continuous concentration gradients, as shown in Figure 1B. By smoothing the fluctuating signals, slow sensors make it easier to acquire this gradient information.

Iterative measurements of time-averaged gradients until a robot reaches an odor source may need hours, however, and most applications do not permit such long search. Attempts have been made to extract rapidly changing signals from dull sensor responses by filtering or differentiation of sensor outputs (Nakamoto *et al.*, 1996b; Webb, 1998). Another option is to use faster sensors, such as quartz crystal microbalance sensors, although their sensitivities tend to be lower than those of semiconductor gas sensors. For underwater plume tracking, amperometric microelectrode sensors are promising. In the amperometric mode of sensing, a constant voltage is applied between a microelectrode and a counter electrode so that electrochemical reaction of a target chemical substance takes place on the electrodes. The signal measured is a current proportional to the concentration. A short response time comparable to that of animals' chemoreceptors (100 ms) can be easily achieved (Moore and Atema, 1991; Kikas *et al.*, 2000).

The direction of airflow can be detected by an array of hot wire sensors (Ishida *et al.*, 1994). However, wind slower than 5 cm/s is hard to detect (Lomas, 1986), and detection limits lower than this are required in some indoor environments. If a robot is used to detect gas leaks in industrial or domestic buildings with moderate air-conditioning, it often

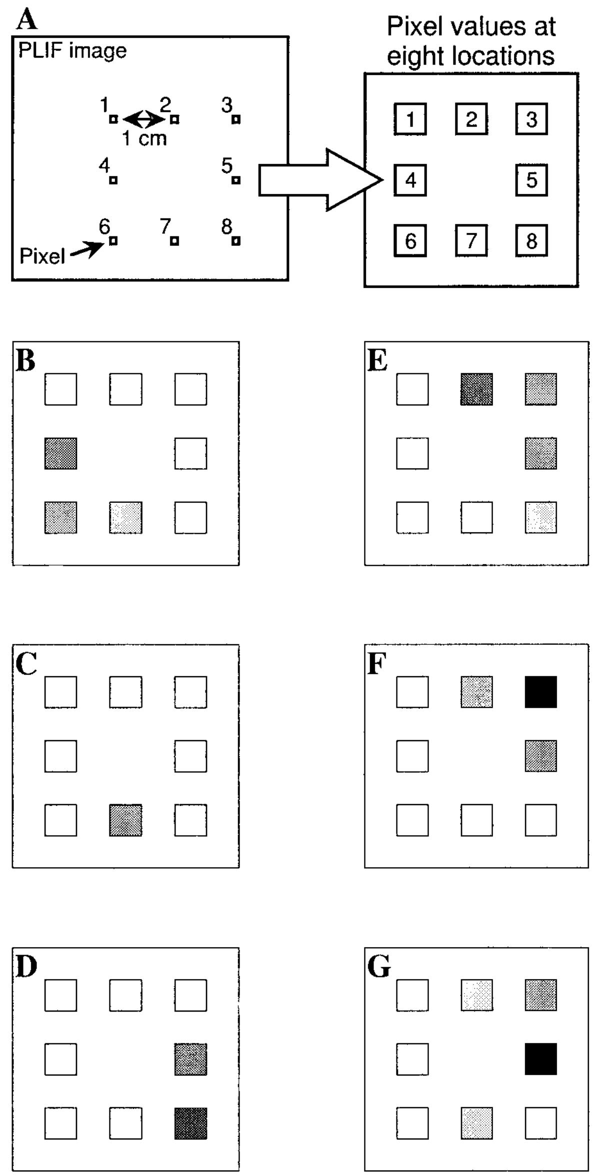

Figure 2. Concentration change in a plume represented by stimulus patterns exposed to chemical sensors. Eight pixels are chosen from PLIF images representing an array of eight sensors. The gray-scale value of each pixel is then drawn in a blown-up picture as shown in (A). Darker pixels represent higher concentrations. (B)-(D) are a series of stimulus patterns when the array position is 50 cm downstream from the source (Fig. 1A), and (E)-(G) are the patterns when the eight pixels surrounding the source are observed in successive 0.2-s intervals. The size and the location of the array shown in (B)-(D) are depicted in Figure 1A.

encounters wind fields with velocities less than 5 cm/s (Pluijm *et al.,* 1986). Search strategies that do not require flow sensors should be considered in this case. Chemical sensor arrays and the odor compass described later have been developed to address this issue (Nakamoto *et al.,* 1996a; Ishida *et al.,* 2000). The detection limits of various types of flow sensors are lowered in water because of the higher viscosity, heat capacity, and density of water compared to air (Lomas, 1986; Roberson and Crowe, 1997).

Realization of Various Aspects of Plume Tracking

Multiphase search algorithm

Animals show different types of behaviors in different situations (Dusenbery, 1992). Our multiphase algorithm for a wheeled robot was divided into anemotactic and chemotactic strategies (Ishida *et al.,* 1996). Although this combination was devised after many experiments using robots, each of those two is a fundamental search strategy seen in many animal species (Dusenbery, 1992; Arbas *et al.,* 1993). The anemotactic strategy is based on moths tracking pheromone plumes. The key feature implemented into the robot is to track a chemical plume by using wind direction, as a moth shows upwind surges when it perceives a pheromone (Willis and Arbas, 1991). When the robot by chance leaves the plume, it tries to relocate the lost plume by moving back and forth across the wind. This fail-safe mechanism, known in moths as casting flight (Willis and Arbas, 1991), is extremely important for successful plume tracking because of the random nature of a turbulent plume.

Another important feature of the multiphase algorithm is chemotactic search. It was added to the multiphase algorithm to cope with winds coming from multiple directions simultaneously (Ishida *et al.,* 1996). In a domestic or industrial building, the main source of wind is an air conditioner, and a robot often encounters winds from multiple air-supply openings. However, the anemotactic strategy described above failed in a clean room with two air-supply openings (Ishida *et al.,* 1996). In the experiments, an ethanol vapor source was placed near one of the openings. A plume extended from it approximately 1 m until the wind from another opening merged into a side of the plume. In such a case, care should be taken to employ the anemotactic strategy. When the detected concentration is low, the robot might be in the merging area where unstable winds often direct an anemotactic robot to wrong directions. Anemotaxis should be activated only when a high concentration is detected, thus only the wind from the source direction is considered to exist.

In the multiphase algorithm, the robot is programmed to employ the chemotactic strategy first, and anemotaxis is activated only when a concentration above a predefined threshold is detected. This change in strategies helps to prevent the robot from being trapped in the area where the wind direction is not stable (Ishida *et al.,* 1996). The robot is also programmed to change its strategies from anemotaxis to chemotaxis, or *vice versa,* when one strategy makes no significant progress for 60 s (Ishida *et al.,* 1996). This ensures timely changes in strategies even when the predefined threshold is inappropriate.

To accomplish fully autonomous search, there still remain many questions, including how to locate a plume for the first time in the absence of any chemical signals, and how to decide when the odor source has been located so as to terminate the search. These issues have been more fully discussed by Dusenbery (1989) and Ishida *et al.* (1998).

Array mode of information acquisition

Use of an array of sensors should provide more information than a pair or a limited number of chemical sensors, thus enhancing simple gradient detection. Extensive and spatially distributed arrays of chemoreceptors are used by many animals, including arthropods (Keller and Weissburg, 2000). Various array configurations and signal processing algorithms are being investigated in simulations (Ishida *et al.,* 2000), and they are being evaluated by their ability to acquire flow vector and source location. For example, consider an array of amperometric sensors with fast and linear response. Since their outputs faithfully trace the input stimuli, the stimulus pattern shown in Figure 2 can be regarded as the output pattern of the sensors. Keller and Weissburg (2000) showed that blue crabs use not only their antennules but also chemoreceptors on other appendages for tracking odor plumes. A crab of 1 cm in size would experience similar response patterns. As mentioned in the previous section, amperometric microelectrode sensors have response fast enough to yield such output patterns, and an array of this size can be easily fabricated and mounted on an underwater vehicle.

As seen in Figure 2, the observed responses are highly intermittent since they show instantaneous concentrations with no integration over time. This intermittency enables tracking of patches of the plume. When a patch passes over the sensor array from sensor 6 through 7 to 8, the flow direction and speed can be determined from this change in the response pattern (Fig. 2B–D).

Figure 2E–G shows the response pattern when the array is placed over the source location. From the responses of sensors 2 and 3, the flow can be determined to move from left to right. However, sensors 1, 4, and 6 at the upstream edge of the array do not show any response. Considering the fact that the plume always trails in the downstream direction, this response pattern indicates that the source is located within the array.

Modulation of chemical signals

Marine crustaceans flick their antennules, and terrestrial vertebrates show sniffing behavior. These actions modulate the dynamics of chemical signals at the animals' sensors. An interesting example of this signal modulation is the wing fanning of a male silkworm moth tracking a pheromone plume. Attempts are also being made to understand the fanning behavior of other animals (Breithaupt and Ayers, 1998; Breithaupt, 2001). Mimicking this mechanism, a sensing probe, termed an "odor compass," consisting of two gas sensors and a small fan to draw air to the sensors was fabricated (Nakamoto *et al.,* 1996a). Experiments showed that the effect of the fan is significant in obtaining directional cues. When an odor source is in front of the compass, odor molecules are carried towards both the left and right sensors by airflow produced by the fan. On the other hand, they are repelled by the airflow when a source is behind the compass. The obtained sensor outputs thus change according to the direction of the compass with respect to an odor source. Fanning was also found to enhance differences between the outputs of the left and right sensors. When a source is to the right of the compass, turning on the fan increases the output of the right sensor and decreases that of the left sensor. Therefore, the direction of an odor source is determined by rotating the compass and finding the direction where the sensors show the largest and matched response (Nakamoto *et al.,* 1996a).

Simulations

Simulation is a useful way to accelerate the development of plume-tracking systems, since it takes a long time to develop a new system by trial and error. There are several levels of simulations. The most common way is to simulate all the dynamics of fluid and the kinetics of sensors and robots in a computer. However, this is impractical because the simulation of turbulent flow with fine resolution requires massive computer power. Visualization techniques are more realistic methods of obtaining concentration data on a fine scale (Ferrier *et al.,* 1993; Webster *et al.,* 1999). If computer models for the kinetics of sensors or robots (or animals) are used, the simulation can be based on visualized plume data (Ishida *et al.,* 2000). This level of simulation is effective in testing algorithms and determining the specifications for robots. The next level of simulation can be performed with a "virtual plume (VP)," which is a test bench for an array of real chemical sensors (Kikas *et al.,* 2000). This system is based on the principles of multichannel flow injection analysis (FIA)/sequential injection analysis (SIA) (Ruzicka and Hansen, 1988) and the array of amperometric microelectrode sensors. A plug of chemical solution is introduced into a flow of carrier solution in tubing, divided into eight channels, and delivered to the sensors after passing through delay and dispersion elements. The delay element is a coil of tube that adjusts the timing with which a divided plug reaches the sensor at the end of the channel. The dispersion element is a small mixing chamber that adjusts the onset slope of the plug. By using those elements, VP can create various stimulus patterns that the sensor array would experience in real plumes.

Discussion

Research on plume tracking is still at its initial stages of development. Animals show a variety of behaviors, each of which is optimized for the habitat of that species. There seems to be no single search algorithm that is effective in every environment. Considering the variety of situations in which plume-tracking robots will be used, future work should use diverse algorithms and situations. Various aspects of the mechanisms underlying animal behavior have been transferred to robots through the interaction between biology and engineering. Although we should continue such efforts, we are now at a point where we can begin a synthesis of the data to develop a unified strategy for the design of plume-tracking systems. The first step toward this goal would be to evaluate the applicability of each algorithm in various situations. The limit of that algorithm will, then, be clarified, and quantitative comparison between different algorithms will be possible. The simulation techniques are expected to facilitate this progress by providing a way to compare a variety of situations quickly.

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