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Chemical Plume Tracing: Insects as Model Navigators

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13. ABSTRACT *(Maximum 200 words)*

Control of robotic vehicles maneuvering upwind along an odor plume, generated by pollutant sources or unexploded ordnance, so that they discover the odor's source is an unsolved problem. Our goals have been (1) to understand how flying insects reliably locate distant upwind sources of odor and (2) develop corresponding principles for the design of planning systems that can guide vehicles to accomplish the same task. We first determined in wind tunnel trials how the fine-scale structure of odor plumes modulates such orientation in flying insects. Encounter of filaments of odor at rates of 10 Hz or higher aims the course more toward due upwind and modulates forward velocity. We then treated a virtual vehicle and virtual odor plume that simulates odor dispersal in a varying wind field. This simulation was used to analyze performance statistics of alternative plume-tracing strategies. Plume-tracing strategies were developed based on ideas inspired by moth experiments, physical principles, and engineering methods. Some of these strategies exceed the performance of insect models by using less time (an therefore energy) to localize the odor's source.

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INSTITUTION: University of California, Riverside

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OBJECTIVE: Discover the principles of navigation used by flying insects to find distant, point-sources of odors. Apply these principles to robotic systems designed to find point sources of anthropogenic chemicals such as those emitted from buried ordinance.

APPROACH: (1) Develop methods for generating odor plumes of defined structures in wind tunnels. Develop methods for analyses of flight tracks and maneuvers in 3-D. Establish how flying moths integrate information from odor, visual and wind inputs to trace an odor plume to its source. Develop methods to measure the fine-scale characteristics of odor plumes in our wind tunnel using a propylene-air mixture as a surrogate odor. Use electrophysiological measurements (at the antennal level with electroantennograms) to determine how well such signals are detected by our model insect species. (2) Develop computer-based models of odor dispersion and vehicle movement. Implement and evaluate insect-inspired strategies for plume finding, maintenance of upflow progress, plume reacquisition, and declaration that the odor source has been found. Implement and evaluate engineering-based plume tracing strategies.

ACCOMPLISHMENTS: Constructed a 3-m-long wind tunnel and versatile pheromone/surrogate odor-delivery system to simulate natural plume structure. Developed a system to measure the precise instantaneous structure of odor plumes, using a photoionization detector (miniPID) positioned precisely via a computer on a custom-built x,y,z traverse. Developed a video-computer system to record and analyze in 3-D, tracks of insects flying in the wind tunnel.

Our wind tunnel trials with the almond moth have confirmed that a signal of 10 Hz (or higher) frequency produces accelerated, nearly due upwind flight in this model insect (Justus et al. 2002b). We also have confirmed with our miniPID/propylene measurements that the structure of the plumes generated with our flow systems indeed is comprised of a precise, pulsed structure (Justus et al. 2002a), as assumed from previous observations with a visual tracer.

Entirely novel findings are that:

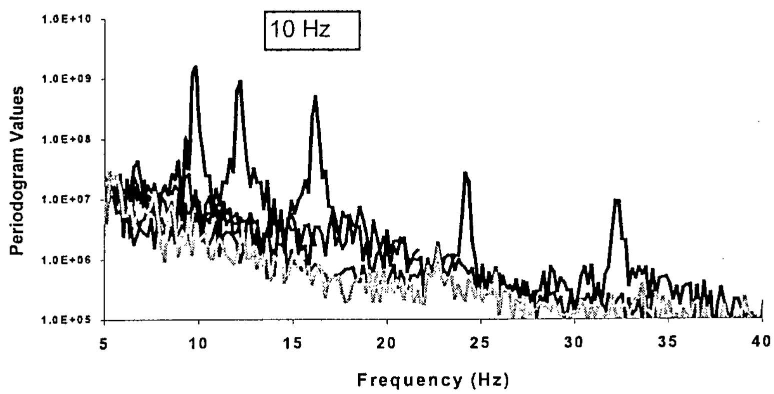
1. Moths head rapidly upwind in a homogeneous cloud of pheromone (Justus and Cardé 2002). This establishes that a 'flickering' signal is not requisite for orientation upwind. Males heading upwind, however, follow a trajectory on average 15° off due upwind. This unexpected maneuver may relate to our counterintuitive finding in simulations (point 7 below) that flight due upwind is generally not the most effective way to maintain contact with the plume while progressing upwind.

2. Moths can use an ''aim-then-shoot'' form of orientation (Wiesniewska 2001), in which a course trajectory is set while in flight, using visual

pattern below as a collimating cue. When moths remain within the plume's overall boundaries, they may head as much as 25° off due upwind, provided they continue to aim toward the same visual cues. This is an entirely new mechanism for in-flight orientation to odor, not predicted by conventional, odor-induced optomotor anemotaxis.

3. Males are capable at the antennal level of deciphering flickering signals up to 33 Hz, according to a Fourier analyses of signal perceived by male moths (Fig. 1, Bau et al. 2002). This capacity had not previously been assessed in any moth.

Fig. 1 Periodogram values after Fourier analysis for plumes pulsed at frequencies of 10, 13, 17, 25 and 33 Hz. The periodogram values show that the antenna is able to resolve filaments of pheromone presented as rapidly as 33 Hz (details in Bau et al. 2002).



4. In another model system, flight of female mosquitoes to host-emitted odors, the structure of the plume also was found to be crucial. In the mosquito species that vector yellow fever mosquito and malaria, turbulent plumes of CO_2 evoked upwind flight, whereas homogeneous clouds of CO_2 evoked only activation. In contrast, the internal structure of skin odor plumes had little effect on their attractiveness (Dekker et al. 2001).

5. Moths ''closing in'' on an odor source (''declaring it found'') slow their velocity, narrow their flight track, and then land on or very near the odor source, even if the odor source is not visually apparent. The systematic changes that occur along the plume as it is carried downwind offer ample features for detection of distance to the odor source (Justus et al. 2002a). The most probable cues, however, now appear to be changes in concentration and signal intermittency.

In nature plumes are difficult to trace because of two characteristics. First, plumes are very patchy because of turbulent diffusion. Second, a due upwind course while odor is detected does not lead to the plume's origin, because of plume meandering (''snaking'') caused by changes in wind direction and velocity. Therefore, an initial task was to devise a computationally-feasible model which mimics the patchy nature of plumes in nature, complete with their overall meander. This model (see the snapshot in Fig. 2) and its concordance with field measurements of instantaneous plume structure are provided in Farrell et al. (2002). It is important to recognize that such a meandering plume is much more difficult to trace to its source than plumes generated in unidirectional flow systems, as is the case in most all wind tunnels and water flumes.

We have coupled our plume model with a spectrum of insect-inspired orientation strategies to see which of these are useful to guide vehicles. Our simulations were over large areas (e.g., 100 by 100 m) and we used the rates of pheromone emission of the gypsy moth female and the threshold (or 10 times threshold) of response of the male gypsy moth to parameterize our runs. The full results of 1000s of simulations and several strategies of plume tracing are detailed in Li et al. (2002). The most salient findings of our simulations are that:

6. A generally crosswind movement strategy is optimal for initial contact of the plume.

7. Once detected, the ''best'' strategy for maintaining plume contact while progressing toward the odor source is to follow a counterturning trajectory such as that depicted in Fig. 3. Upon the initial detection of the plume on a given transect, the searcher turns almost straight into the wind to attain up-plume progress. As the time from the initial detection of the present transect increases, the search assumes an increasingly crosswind direction of travel. This causes the searcher to leave the plume from the opposite side of the plume than it entered, with a high degree of certainty. Therefore, when the searcher reverses its crosswind direction of travel (i.e., counterturns), it has a high probability of recontacting the plume. If recontact occurs, then the searcher repeats the counterturning maneuver in the opposite crosswind direction for the next transect.

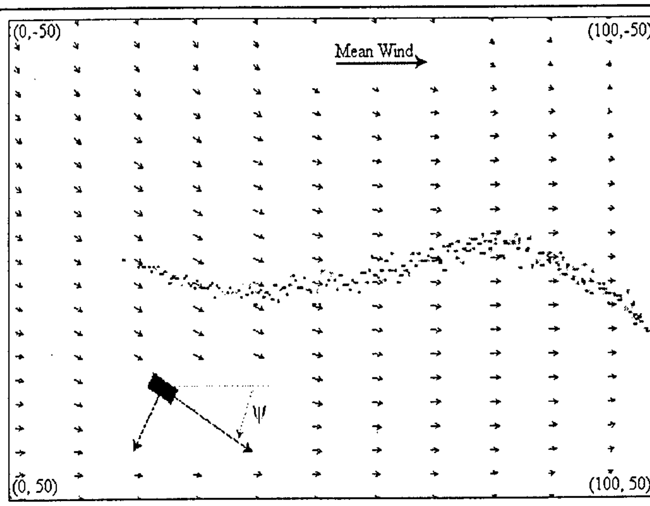


Fig. 2. Snapshot of simulated vehicle (not to scale) operating relative to a dispersing pheromone in a 100 by 100 m search area. The grey scale indicates above threshold concentration. Arrows indicate the local time varying wind vector at the tail of the arrow.

8. If the searcher loses contact with the plume, then the best reacquisition strategy is to cast right and left of the windline for a set giving up time (GUT). The optimal GUT depends on the maneuverability characteristics (e.g., turning radius versus speed) of the searcher. A GUT of about 4 seconds seems optimal, given a searcher with maneuverability characteristics similar to a moth.

9. Within 10 m of the source, heading directly upwind while in the plume diminishes time to source contact, compared to the strategy described in #7. As presently implemented, the searcher cannot discern that it is within 10 m of the odor's source, and so it does not switch to the strategy of upwind flight.

SIGNIFICANCE: Our improved understanding of insect orientation offers new approaches to testing insect-inspired models of robotic navigation to a point source of odor. Although there is more to learn about how insects find odor sources and how plumes of odor are dispersed in wind,

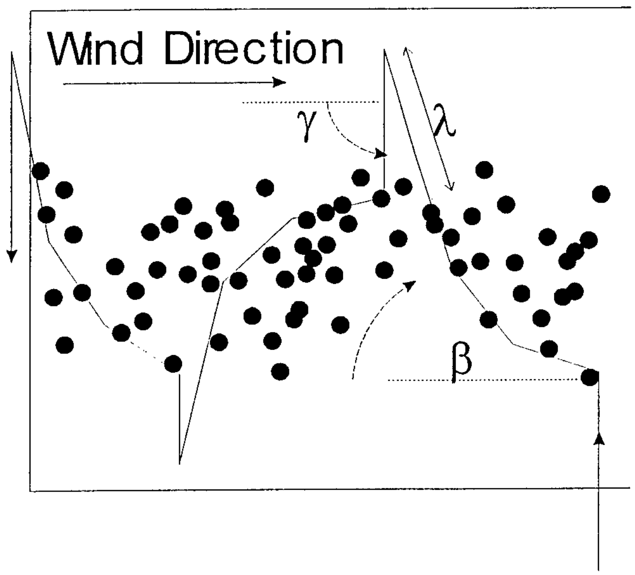


Fig. 3. Schematic planar view of above threshold odor patches (black dots) and the path take by a virtual searcher. After first odor detection, the searcher travels at an angle β(t) relative to upwind. If odor has not been detected for λ seconds, the searcher counterturns to travel at an angle γ with respect to the wind.

we have sufficient information to test a range of simulation strategies. We have developed models that (1) simulate the dispersion of odors in the wind; (2) simulate insect-inspired strategies to find odor plumes and follow them to their source; and (3) utilize odor detection events and engineering analysis to generate maps of likely odor source locations. These simulation strategies are highly efficient in their ability to quickly and reliably locate odor sources, and in their conservation of energetic expenditure. We have a sufficient understanding to apply these algorithms to command robotic vehicles (flying or maneuvering on the ground) in the field.

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