

Odor-modulated Navigation in Insects and Artificial Systems

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Two pieces of information are absolutely required to locate a source of chemicals from a distance. The first and most obvious is the presence of the chemical cue, and the second is the direction of the flow of air or water carrying the chemicals. Insects orienting to wind while walking in terrestrial environments appear to use the mechanical deflection of their antennae to detect the direction and magnitude of the flow they are moving through (Bell and Kramer, 1979). Thus, in these cases the antennae are providing information on both the presence (and absence) of odor and the direction of the flow. Many flying insects locate resources such as food and mates using windborne odors (Willis and Arbas, 1991; Arbas *et al.*, 1993). Flying insects also use mechanosensory deflection of their antennae, in addition to deflection of mechanosensory hairs on their faces, to detect their speed and direction of movement through the air (Arbas, 1986). This information is then integrated with visually detected flow field feedback showing their movement with respect to the environment (David, 1986) to determine their steering movements (Olberg, 1983). Thus, the visual flow field feedback used to stabilize and control their flight behaviour also provides the information on wind speed and direction necessary to steer and control flight with respect to the wind during odor tracking behaviour (i.e. wind information is the result of the difference between intended and actual course) (David, 1986). One of the most studied flying odor tracking systems is that of male moths tracking female sex attractant pheromone to locate mates (Arbas *et al.*, 1993).

Perhaps the most remarkable olfactory task achieved by insects is that of locating distant resources using airborne chemical cues. It is currently thought that two primary mechanisms underlie flying insects' ability to perform this behavior: (i) an odor-modulated, visually mediated orientation to the wind direction; and (ii) an odor-activated internal program of turns. The blending of these two mechanisms is thought to generate the upwind zigzagging paths that we observe from insects tracking odors in flight (Figure 1B). It is well established that these two mechanisms are both modulated by characteristics of odor plumes, resulting in predictable changes in the structure of the tracking behavior. It is not yet clear whether vision contributes significantly to the odor tracking behavior of walking insects. However, recent experiments revealed that the structure of the walking paths of pheromone tracking cockroaches look remarkably like those observed from flying insects, and thus may be governed by similar mechanisms (Figure 1A). These new results suggest that zigzagging into the wind may possess elements that enable odor trackers to more successfully adapt their behavior and locate important resources using odor information. We are using robots that can move in two and three dimensions to test hypothetical control algorithms based on our results and the results of similar behavioral studies.

Our recent experiments with wheeled robots tracking wind-borne plumes of ionized air (Figure 1C) have shown that there are trade-offs between algorithms that generate rapid tracking but low probabilities of source location, and algorithms that generate very slow tracking but much higher probabilities of source location. While algorithms that alter the robot's steering and turning behavior

according to the local plume concentration generate tracks that are both rapid and highly successful at locating the source. Wheeled robots are a good way to test hypothetical control algorithms underlying the olfactory orientation of walking insects, but not for flying insects. We have recently developed a gantry robot that is capable of tracking windborne plumes in three dimensions (Figure 1D). This robot will eventually have all of the sensors possessed by the pheromone tracking moths and use them to control its motion.

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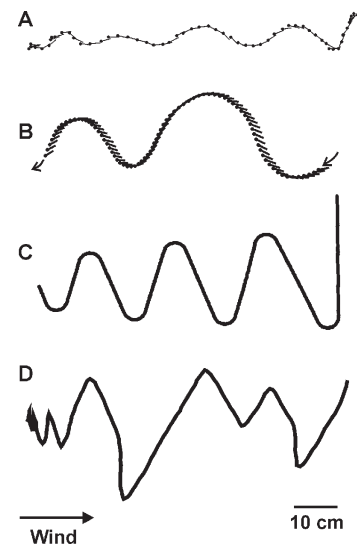


Figure 1 Tracks of flying and walking male insects tracking wind-borne plumes of female pheromone together with those of robots with biologically-inspired controllers tracking plumes of ionized air. (A) Path of a walking male cockroach, *Periplaneta americana*, tracking pheromone in 25 cm/s wind. (B) Path of a flying male moth, *Manduca sexta*, tracking pheromone in 100 cm/s wind. (C) Path of a wheeled robot tracking a plume of ionized air in a 1 m/s wind. (D) Path of a gantry-robot moving a bilateral detector pair along a three dimensional trajectory tracking an ionized air plume in a 1 m/s wind. Note that all of these movement paths were recorded in the same or nearly the same laboratory wind tunnel. For all of these tracks the wind was blowing from left to right.

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