Using lobster noses to inspire robot sensor design

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Robots are needed to locate the sources of toxic chemical plumes. Lobsters, which track odor plumes for many ecologically crucial activities, can provide inspiration for robot designers. Before accurate search strategies for robots can be developed, how odor molecules are captured by the lobster's chemosensors must be understood. A recent study by Koehl et al. shows how lobster olfactory antennules alter the patterns of concentration in turbulent odor plumes during odor sampling.

Published online: 17 May 2002

There are many situations in which an object leaks chemicals into the air, water or into another fluid. When air or water is moving, it creates an odor plume downstream of the source. In most cases, turbulence causes the plume to be fragmented into a collection of intermittent filaments of high odor concentration interspersed with clean fluid [1,2]. When the odor source is toxic, radioactive, explosive or otherwise dangerous, it is important to locate, identify and deactivate the source. One type of dangerous odor source is plastic mines, which leak nitrogen residues that can be detected by an appropriate sensor. Because these sources are so hazardous, the Office of Naval Research and the Defense Advanced Research Projects Agency have funded research to create robots and unmanned vehicles to locate and identify plastic mines by navigating up their odor plumes.

Because many animals rely on chemical cues to find food, habitat, mates or to avoid predators [3–5], part of the funding has been allocated to study how animals track odor plumes. The researchers hope to generate sensor information and behavioral strategies that can be used to design and program robots. This is part of the growing trend of biomimicry, which uses nature as a model for designing engineering systems.

How do chemical sensors work?
Several approaches have been used to understand how animals process chemical signals. Some scientists have concentrated on the neurobiology of the chemoreceptor cells, carefully applying known pulses of odorant to exposed chemosensory cells and recording their responses to determine which signal features are important to the animal [6]. This work suggests that, at least in laboratory situations, odor signal characteristics such as filament width, concentration and the rate of increase over time of concentration might be important cues for lobsters. Other researchers have outfitted stationary moths with a third artificial antenna and compared the odor signal arriving at the antenna with the output from projection neurons (cells that process information from chemosensory cells) to show how some signal features are processed by higher neurons [7]. These experiments indicate that the chemosensory cells and the higher order neurons that process the output of chemosensory cells respond to fine-scale features of the odor signal.

Before signal processing by chemosensory cells and higher order neurons occurs, the chemical signal present in the environment is filtered by the physical interaction between the chemosensors and the surrounding fluid. This key issue was addressed in recent experiments by Koehl et al. [8].

The experiments
Koehl et al. took a recently shed exoskeleton from the Caribbean spiny lobster (Panulirus argus) and filled it with epoxy so that it wouldn’t float. They replaced one of the lobster’s antennules (long slender antennae covered with hair-like structures that detect odors) with a computer-controlled wire. Before each experiment, they slipped a real antennule onto the wire. The lobster was put into a large recirculating tank of water (called a flume, where pumps and baffles create currents and turbulence levels typical of lobster habitats) 1 m downstream of the ‘odor’ source, facing the current. The source, rhodamine dye, was oozed into the tank at a controlled rate. This dye has similar diffusive properties to real life odorants (e.g. amino acids) but is visible when illuminated by a laser. The interactions between the dye and the moving water created a dye plume that consisted of concentrated dye filaments interspersed with clean water. The dye filaments moved downstream toward the lobster at ~10 cm second⁻¹.

Lobsters sample their olfactory environment by flicking their antennules vertically in front of them in an up and down stroke. The computer controlling the antennule was programmed to flick the robotic antennule through the water at the same speed that a lobster would move it. The rapid downstroke lasted ~100 ms but it took 300 ms to return the antennule to the original position. There was a 400 ms pause between successive flicks. As the lobster flicked its antennules through the water, it encountered dye filaments along the antennule. A sheet of laser light illuminated a two-dimensional slice of the fluid flow in the path of the flicking antennules (Fig. 1).

Koehl et al. took high-resolution movies of the lobster flicking its antennules in the light sheet. These images were analyzed to determine when and where the dye came into contact with the lobster’s sensory hairs along the antennules. The investigators wanted to know how the fine-scale patterns of odor filaments along the antennules varied during different strokes of the flick. The patterns of dye in the sensory hairs was also compared with the patterns of dye encountered by a ‘virtual antennule’, which swept through the same portion of the plume at the same velocity as the real antennule. This information helped them to understand how the presence of the antennule and its movement affected the pattern of filaments.

The ability of the fluid (and the odor contained within the fluid) to penetrate...
the array varies considerably with the speed with which the lobster moves its antennules. Koehl and her colleagues found that the lobster moves its antennules just fast enough during the downstroke to push the water and the dye into the brush of sensory hairs. During the downstroke, the patterns of concentration along the sensory hairs change quickly as new dye filaments penetrate the sensory array. When the antennule is flicking down, the mainstream current carries the patterns of dye along the antennule so that the fine structure of the odor plume is partially blurred by the end of the downstroke. On the return stroke, the antennule moves more slowly and the water and dye are not able to move between the hairs. No new fluid enters the array and the current pattern of filaments in the sensory hairs is preserved until the next rapid downstroke. This lingering of odors might help the lobster to identify the chemical constituents of the odor as well as identify important signal characteristics carried in the spatial pattern of the odor filaments along the antennule. The next downstroke flushes out the sampled fluid and allows new fluid to penetrate the sensory hairs. Thus, each sample of the plume structure is discrete in space and time.

Significance
Although it is not known precisely which odor signal features are important to plume-tracking lobsters, these experiments demonstrate that each flick of a lobster antennule captures a detailed map of the odors in the water. This highly detailed information is available to the lobster’s chemosensors. Because odor plumes in lobster habitats tend to be patchy and intermittent, the ability to collect fine-scale odor structure information might be important and could explain the speed and efficiency with which many animals track odor plumes [9,10]. In addition, these experiments suggest that it is crucial that the antennule move asymmetrically during the flick so that each flick is discrete. Finally, the data indicate that the two parts of the olfactory flick have different, complementary functions.

To follow the lobster model, plume-tracking robots should have movable antennae bearing arrays of hair-like chemosensors of which the shapes, arrangement on the antennae and movement through the surrounding fluid allow for fluid penetration during one part of a sampling stroke but not during the reverse part of the stroke.

Future directions
There are several areas ripe for further exploration. One crucial area that remains is to figure out which signal features of odor plumes in environmentally relevant flow environments (as opposed to controlled odor pulses in the laboratory) are important to a plume-tracking animal (or robot). These experiments must somehow involve recording output from chemosensory cells that are exposed to realistic odor filaments and flow characteristics. Another area of future study is to examine the fine scale odor structure at the chemosensors of animals tracking plumes in environmentally relevant flow habitats. By correlating odor structure with plume-tracking behavior, investigators hope to understand how animals navigate up odor plumes to their sources. The behavioral rules might then be used to program robots to track plumes. Ongoing developments in plume-tracking robots include the increasing availability of small, fast sensors that should make it easier to mimic the structure and deployment of lobster sensors [11,12].

Acknowledgements
I thank M.A.R. Koehl for helpful discussions about the general principles involved in her work as well as the specifics of her Science paper.

References

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Nanostructures as tailored biological probes

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A new generation of spectroscopic dyes is gradually becoming available to biological researchers, from an unexpected source: materials chemists who study the synthesis and properties of nano-sized inorganic objects. Research into tailoring the optical properties, surface chemistry and biocompatibility of metallic and semiconductor nanoparticles, exemplified in part by a recent report by Mirkin, Schatz and coworkers, is fulfilling the promise of these nanostructures as customizable substitutes for organic molecular probes.

Published online: 10 May 2002