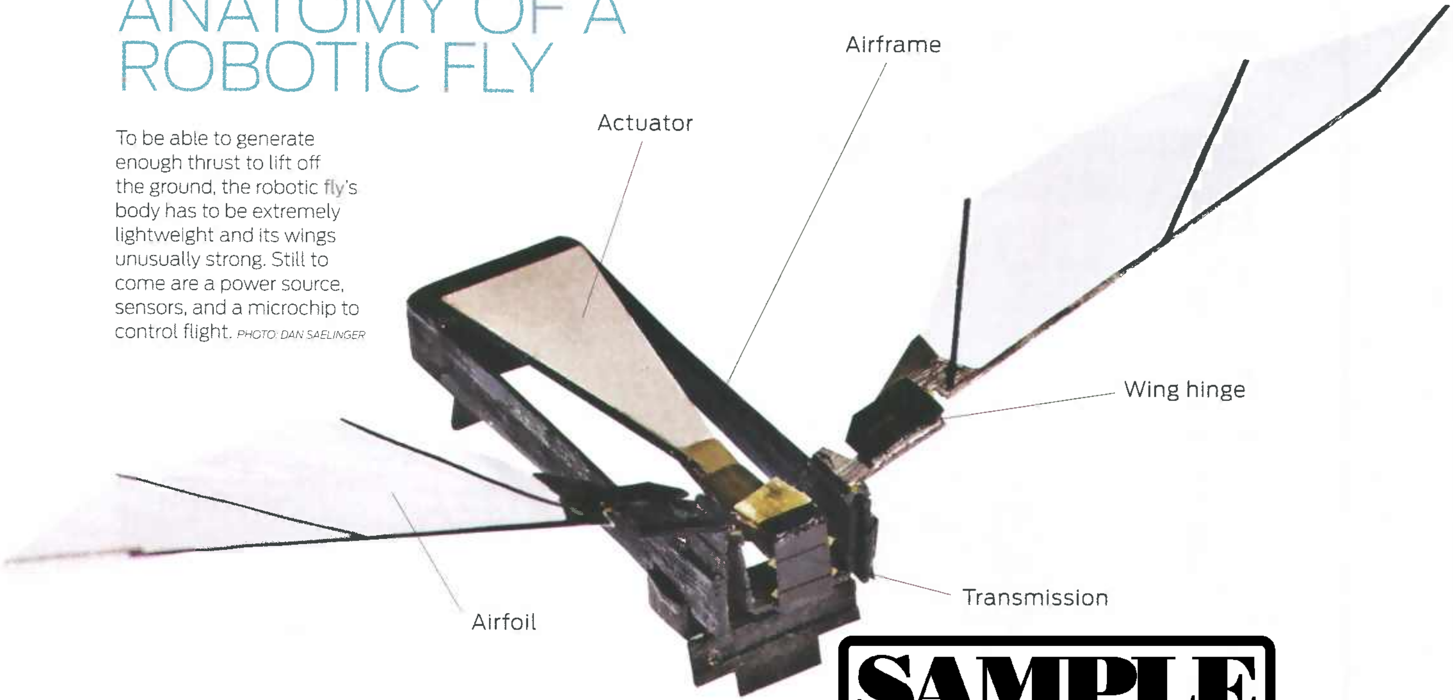
FLY, ROBOT FLY

Whether as rescue robot or flying spy, this micro-aerial vehicle could change how we look at the common housefly

By Robert Wood

ANATOMY OF A ROBOTIC FLY



To be able to generate enough thrust to lift off the ground, the robotic fly's body has to be extremely lightweight and its wings unusually strong. Still to come are a power source, sensors, and a microchip to control flight. PHOTO: DAN SAELINGER

THERE IS NO more rewarding moment for roboticists than when they first see their creations begin to twitch with a glimmer of life. For me, that moment of paternal pride came a year ago this month, when my artificial fly first flexed its wings and flew.

It began when I took a stick-thin winged robot, not much larger than a fingertip, and anchored it between two taut wires, rather like a miniature space shuttle tethered to a launchpad. Next I switched on the external power supply. Within milliseconds the carbon-fiber wings, 15 millimeters long, began to whip forward and back 120 times per second, flapping and twisting just like an actual insect's wings. The fly shot straight upward on the track laid out by the wires [see photo, "Winged Victory"]. As far as I know, this was the first flight of an insect-size robot.

The experiment was the culmination of nearly a decade of work that began in the laboratory of my then-advisor, Ronald S. Fearing, a professor of electrical engineering at the University of California, Berkeley, and later migrated to my lab at Harvard. The little flying robot, we hope, will herald a new era of practical small-scale robot design.

The insectlike robots that my colleagues and I at the Harvard Microrobotics Laboratory are creating are intended to perform rescue and reconnaissance operations with equal ease. Once they can be fitted with onboard sensors, flight controls, and batteries, they will be freed from their tethers to the lab bench to nimbly flit around obstacles and into places beyond human reach.

For example, when a severe earthquake breaks the crust of the Earth and collapses buildings, rescue workers must frantically search for survivors while breathing air full of toxic particles and making their way through rubble-strewn passageways. They must do so on their own because our most sophisticated rescue robots falter and often fail when they encounter even mild clutter.

We envision a very different approach, in which emergency personnel disperse thousands of paper clip–size flying robots throughout a disaster zone. The tiny machines would detect signs of life, perhaps by sniffing the carbon dioxide of survivors' breath or detecting the warmth of their bodies. Though some flies might smash into windows or get stuck in corners, others would slip through cracks and under fallen crossbeams. Perhaps only three members of the swarm make their way to the survivors, where they perch and expend their remaining energy broadcasting their findings to rescue workers. They may have onboard radio-frequency transmitters to communicate short, low-bandwidth chirps, to be picked up by receivers installed around the perimeter of the site. Even if 99 percent of the robots are lost, the search mission would still be a success.

Designing a robotic insect is more complicated than simply shrinking a model airplane, however, because the aerodynamics that govern flight are entirely different on the scale of insects. The basics of insect-flight aerodynamics in different patterns of airflow first became clear in 1999, when Michael Dickinson, a biologist then at Berkeley and now at Caltech, built a 25-centimeter replica of a fly's wing and simulated the viscosity of air on a small scale by submerging the wing in a vat of mineral oil. It turns out that insects use three different wing motions to create and control the air vortices needed to generate lift.

Using the results from Dickinson's models, I and others in Fearing's lab set out to replicate the insect's incredible wing motions. Part of the chal-

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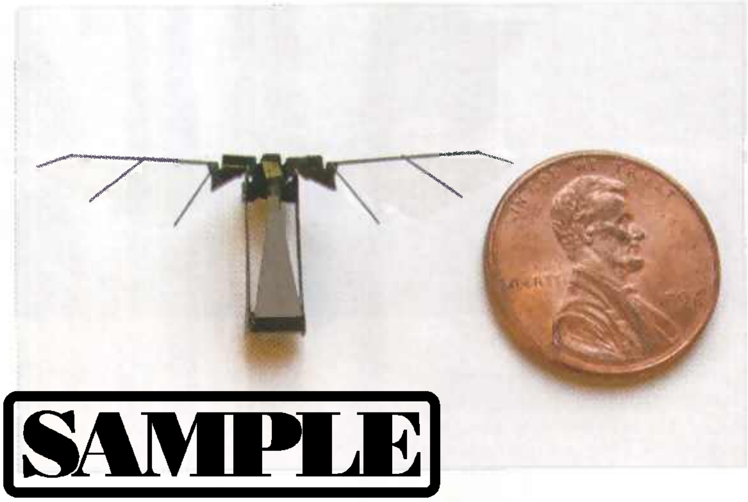
lenge is that many systems contribute to the flight of a fly, including eyes specially attuned to perceiving motion and powerful muscles that drive the wings to generate unsteady aerodynamic forces, on which the fly's maneuverability depends. Most insects control their wings by adjusting the amplitude of their wing strokes, the angle of attack, and the tilt of their strokes through tiny muscles in the thorax. Flies even have special sensory organs, called halteres, that sense body rotations during flight. These features are all key to flies' remarkable ability to hover, fly upside down, and land on walls and ceilings.



TINY FLY: Each prototype has a wingspan of 3 centimeters and weighs 60 milligrams, not including a battery and sensors. For now, the fly is connected to an external power source.
PHOTO: RANDI SILBERMAN

THE MAIN MOTIVATION for creating mobile robots is that they can go where humans cannot—to exposed points on a battlefield, for instance. Today, mainly the military can use such robots, because they cost on the order of US $100 000 each. To bring robots within the reach of law-enforcement and emergency-rescue services requires a totally new approach. We placed a great deal of importance on our choice of materials, which ultimately had to be cheap and fairly easy to work with. Durability was less important, because we envisioned a robot that could be replaced for less than $10.

We focused on the two-winged insects of the order Diptera, which includes houseflies, hoverflies, and fruit flies. Flies are the most able flyers on the planet, they're small, and they are naturally robust enough to survive collisions.

Flies achieve their astonishing maneuverability by moving their wings through complex, three-dimensional trajectories at frequencies that often exceed 100 hertz. The upstroke and downstroke patterns are almost symmetrical when flies hover but highly asymmetrical when they move forward or maneuver. Flies generate those large-amplitude, high-frequency wing strokes by using indirect flight muscles, so called because they deform a portion of the thorax rather than the wings themselves, inducing mechanical resonance in the fly's body. Smaller muscles connect directly to the wing hinge to fine-tune the wing's movements.

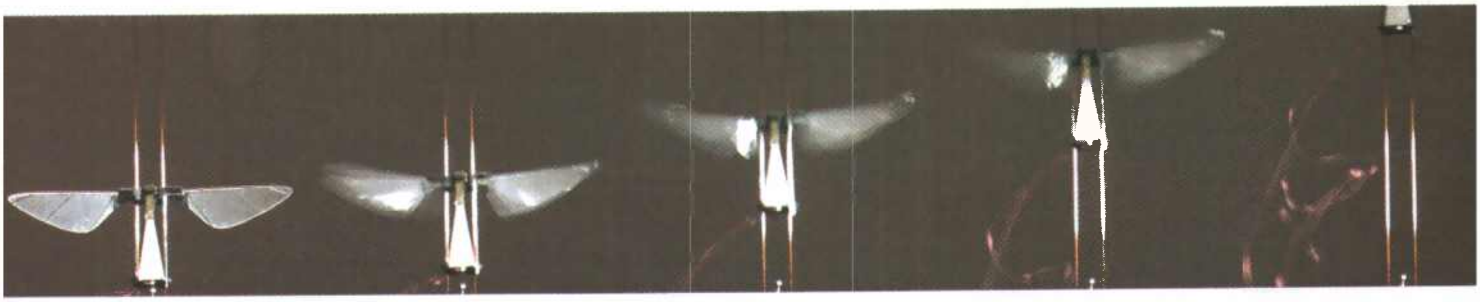
Because of the small scale, the airflow around a fly is much more viscous than that around birds or fixed-wing aircraft. For insects, flight is somewhat like treading water. A fly's wing motions generate aerodynamic forces that can change magnitude drastically in a fraction of a second. Traditional aircraft wings, by contrast, are subject to fairly steady fluid flow. Because of this difference, the analytical tools that are used to predict the performance of an airplane are of little use in predicting the flight dynamics of an insect, making our job more difficult.

Over hundreds of iterations, our robotic fly has followed its own evolutionary path to more and more closely resemble the shape of a real fly. We borrowed two basic principles from biology—the ratio of the wing area to the body mass and the wingbeat frequency. Still, we need not copy nature slavishly by putting up with limitations on invertebrate biology that electromechanical devices do not share. Take, for instance, the elastic and structural properties of the insect thorax and wings. These body parts are made of chitin, a common polysaccharide, which though tough is nonetheless substantially weaker than carbon fiber.

Our fly has all the same primary mechanical flight components of an actual fly: an airframe (exoskeleton), actuators (flight muscles), a transmission (thorax), and airfoils (wings) [see diagram, "Anatomy of a Robotic Fly"]. The function of each is simple. The airframe must provide a solid mechanical ground for the actuators and transmission. The actuators power the thorax at mechanical resonance. The transmission maps actuator movements to the desired wing motions. Finally, the airfoils must remain sufficiently rigid to maintain their shape in a number of radically different aerodynamic conditions.

Our design takes due note of the physics of the

WINGED VICTORY: The robot's maiden flight last March was a landmark in microrobotic research. As shown below, guide rails constrain the robot to fly only upward for now.
PHOTO: ROBERT WOOD



TWIST AND FLAP: To insects, flying is a lot like treading water. Flies have evolved complex mechanisms to regulate their flight, including performing intricate flapping and twisting wing movements, which the robotic fly does 120 times a second. A clamp holds the robot in place to keep it from escaping the camera's lens. PHOTOS: ROBERT WOOD

minuscule. As the parts of a robotic device shrink, surface forces begin to dominate the dynamics of motion. Bearings become less efficient because a decrease in size means an increase in the surface-area-to-volume ratio and thus in friction. However, just because we designed the robot didn't mean we knew how to make it, and mechanical components with features of one micrometer are well below the resolution of standard manufacturing techniques. Nor could we turn to processes employing microelectromechanical systems, or MEMS, which use materials that are too fragile for the forces a robotic fly must withstand. What is more, it takes a lot of time to turn out a prototype with MEMS, and our design strategy entails building a lot of prototypes.

OVER HUNDREDS OF ITERATIONS, OUR ROBOTIC FLY HAS FOLLOWED ITS OWN EVOLUTIONARY PATH TO MORE CLOSELY RESEMBLE THE SHAPE OF A REAL FLY

My approach has been to develop a process based instead on laser micromachining and thin materials, usually carbon-fiber-reinforced composites, laminated to have precisely tailored stiffness and compliance. Using these fairly simple techniques, we can make a fly prototype in less than a week.

To build a joint, we make gaps in two thin, rigid sheets of carbon fiber. We sandwich between them a thin-film polymer, which can bend repeatedly without losing its ability to flex. Four such joints, connected in series by flat, rigid carbon-fiber links of various lengths, make a microscale transmission. With a proper choice of link lengths, the transmission can amplify the small angular motions of one link into larger movements of the opposite link.

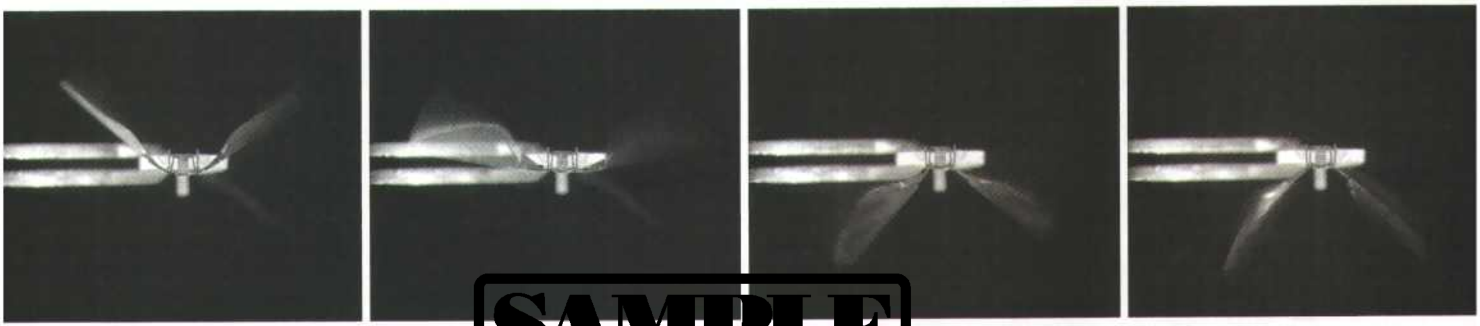
To make actuators that mimic real flight muscles, we add to the carbon-fiber-based composite a few layers of an electroactive material, which changes its shape when an electric field is applied. Designing these actuators to be as small and light as possible, while keeping them strong enough to deliver sufficient power, was our first key accomplishment. The power density of our robot's actuators comes to more than 400 watts per kilogram, some four times that of an ordinary fly's wing muscles. Our second breakthrough came when we successfully converted the actuator movements to biomimetic wing motions, using a four-bar linkage. Only after we made the transmission did we discover, to our great satisfaction, that its mechanism is remarkably similar to a dipteran fly's thorax driving its wing movements.

Our latest version weighs 60 milligrams, about the same as certain dipteran flies, and can generate nearly twice its weight in thrust. That's almost on par with a real fly, which typically can attain lift forces three to five times its weight. Our immediate goal is to get the fly to hover, which is key for maneuvering in constricted environments. A hovering vehicle can turn itself in place and does not require forward motion to remain aloft.

To achieve stable, untethered flight, we will need to miniaturize and install three more things: sensors, controls, and a power source. A number of laboratories and companies are developing a promising suite of sensors, inspired by biological sensory systems, to enable the robot to stabilize its own flight and to control simple behaviors. My former advisor Ron Fearing's work at the Biomimetic Millisystems Lab, at Berkeley, has demonstrated bio-inspired gyroscopes and sensors capable of detecting the horizon. Centeye, in Washington, D.C., has built vision sensors weighing less than a gram to help flying robots navigate.

Control remains a challenge. A real fly can make rapid turns, called saccades, because it has a specialized neural system that allows for speedy responses. In a fly, neural impulses from internal feedback sensors directly modulate the flight muscles—without processing from the central nervous system—to counter disturbances. We are studying practical ways to emulate this system by using inputs from a number of attitude sensors that figure out the orientation of the fly and directly manipulate the actuators.

Then there's the question of getting a power source onto the fly. A battery small enough to fit aboard



a robotic fly will have a much higher surface-area-to-volume ratio than its macroscale counterpart, so a greater percentage of its mass will be the packaging. We expect that scaled-down versions of today's best lithium-polymer batteries will weigh about 50 mg, accounting for half the fly's weight, and will provide 5 to 10 minutes of flight. For more flight time we will have to increase the battery's energy density, make the propulsion more efficient, or develop energy-harvesting techniques, perhaps by mounting tiny solar panels on the insect's back or converting the fly's vibrations into electric current.

We're now turning our attention to the robot's low-power, decentralized control algorithms. Again, we begin with nature. Social insects use simple local rules and minimal direct communication, yet they achieve tasks of astounding complexity. For example, termites can produce a structure millions of times their own size, even though no one termite has a blueprint for it. We believe that our robots can eventually be used as tools to study such insect behaviors; what we learn could then help us to design algorithms to enable swarms of simple robots to accomplish complex tasks.

Even with basic control algorithms, however, we expect microrobots to be able to perform useful roles as ad hoc mobile sensor networks. Search-and-rescue operations, hazardous environment exploration and monitoring, planetary exploration, and building inspections are just a few of the potential applications for highly agile, insect-scale rescue robots. Smart sensors on wings are not a distant dream: we predict that a fully autonomous robotic insect will be flying in laboratory conditions within five years. Five years beyond that, we could begin seeing these devices in our daily lives. ❑

TO PROBE FURTHER For a video of Robert Wood's microrobotic fly and more on robotic-insect research, see http://www.spectrum.ieee.org/mar08/morefly.

NEXT-GEN UFOS?

Insectlike robots have reached new milestones on the path to full autonomy, and the public has become more aware of them, as well. This past October, protestors in Washington, D.C., claimed they saw strange-looking, larger-than-life dragonflies hovering above the crowd. Were they actually flying robots? Probably not. But the mystery of their sightings hasn't been resolved, and it has spooked the public enough to raise concerns about new frontiers in domestic spying. Indeed, a robotic insect would make the perfect spy, but there are other, benevolent uses. Swarms of small, agile robots could be great for all kinds of exploration, such as investigating other planets, penetrating hazardous environments, and monitoring traffic. What's more, they would make great toys! —*R.W.*

CLOCKWISE FROM TOP RIGHT: CARLYE D. LA POINTE/U.S. AIR FORCE; TIM MCCAIG; NASA