Michel M. Maharbiz is an associate professor of electrical engineering and computer sciences at the University of California, Berkeley. His lab has harnessed nature's ability to grow and power tiny flying machines, a.k.a. beetles, and melded it with computer command systems that allow researchers to direct the insects' flight.

Hirotaka Sato received his B.S. and Ph.D. in chemistry from Waseda University in Tokyo for his work on electrochemistry-based nanofabrication processes. He started his postdoctoral work on cyborg beetles in 2007 at the University of Michigan at Ann Arbor and in 2008 at Berkeley.

ROBOTICS

Cyborg Beetles

Tiny flying robots that are part machine and part insect may one day save lives in wars and disasters

By Michel M. Maharbiz and Hirotaka Sato

THE COMMON HOUSEFLY IS A MARVEL OF AERONAUTICAL engineering. One reason the fly is a master at evading the handheld swatter is that its wings beat remarkably fast—about 200 times a second. To achieve this amazing speed, the fly makes use of complex biomechanics. Its wings are not directly attached to the muscles of the thorax. Rather the fly tenses and relaxes the muscles in rhythmic cycles that cause the thorax itself to change shape. That deformation in turn sets the wings to oscillating, much the way a tuning fork vibrates after having been struck. In this way, the fly manages to convert a tiny bit of energy into a whole lot of motion with very little effort.

Engineers, spurred by the miniaturization of computer circuits and micromanufacturing techniques, have done their best to build tiny flying machines that imitate this locomotive ability. The DelFly Micro, unveiled in 2008 by researchers at the Delft University of Technology in the Netherlands, weighs only three grams, has a wingspan of 100 millimeters and can carry a tiny video camera. The synthetic flier produced at the Harvard Microrobotics Laboratory is even smaller—it weighs in at a mere 0.06 gram (still more than four times heavier than a fly)—though once set in motion, the flier's flight cannot be controlled. The real Achilles' heel of these mechanical insects, however, is the amount of power they consume: no one has yet figured out how to pack enough energy into miniature batteries to

IN BRIEF

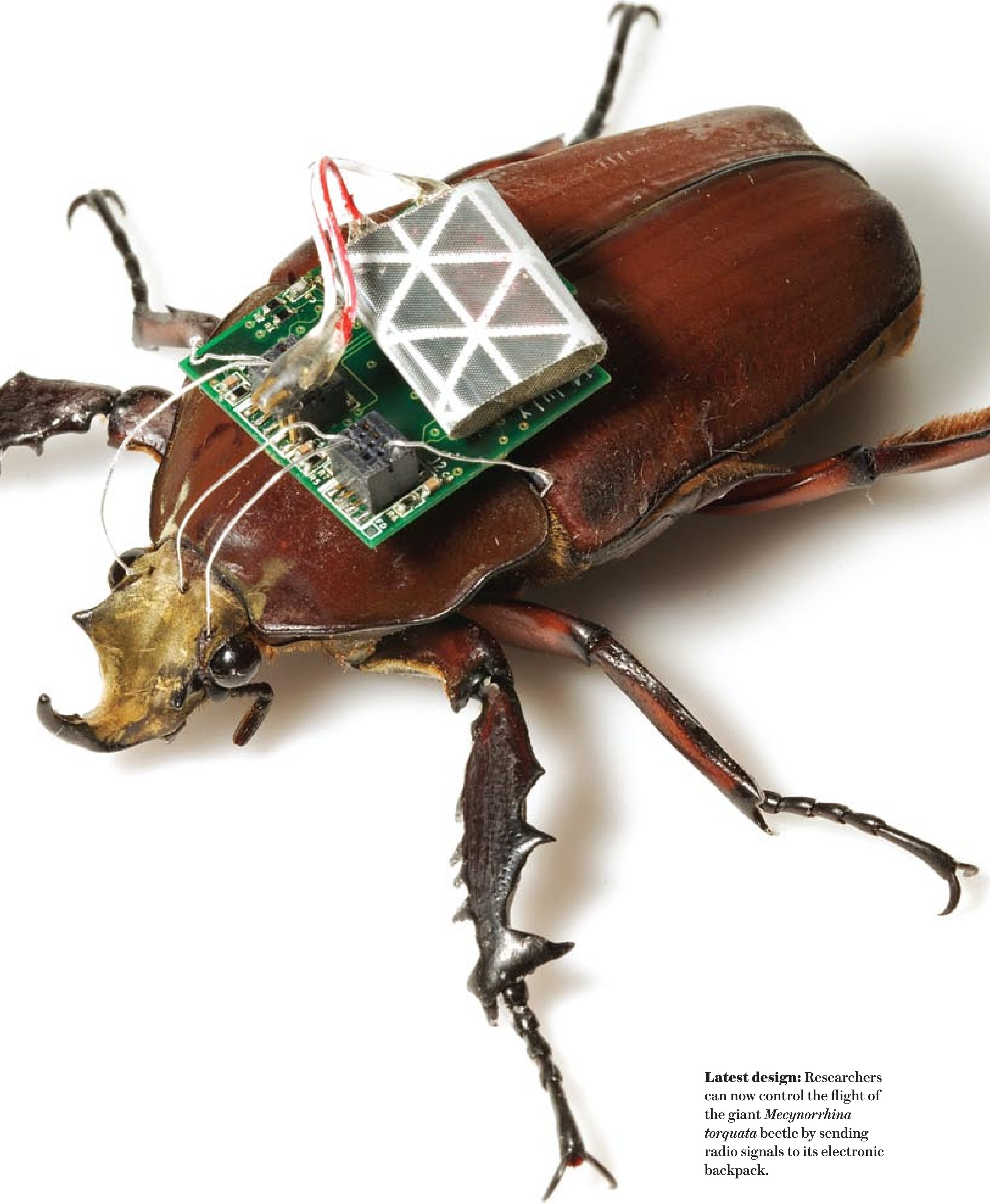
Martial need: The military would like to develop tiny robots that can fly inside caves and barricaded rooms to send back real-time intelligence about the people and weapons inside.

Technical hitch: Current fully synthetic micromechanical fliers require too much energy to be powered by today's miniature batteries for longer than a few minutes of free flight.

Potential solution: Attach a camera and other equipment onto the backs of insects, which are already incredibly energy-efficient fliers, to control where and how they fly.

Progress so far: Researchers at Berkeley, M.I.T. and Cornell have shown that they can wirelessly control a giant beetle's ability to start and stop flying, turn left or right, and fly in rough circles.

Photograph by David Liittschwager



Latest design: Researchers can now control the flight of the giant *Mecynorrhina torquata* beetle by sending radio signals to its electronic backpack.

supply the fliers with juice for more than a few minutes of flight.

In the past few years we have hit on a way around these technical limitations. Rather than building a robotic insect from scratch, we use the insects themselves as flying machines. In that way, we dispense with the heavy batteries and the micromanufacturing techniques and focus just on the man-made control systems, which intervene as necessary in the animals' flight. In other words, the insect flies itself, but circuitry embedded into its nervous system transmits commands—turn left or right, up or down—from remote human operators. In effect, we make cyborg fliers—part insect, part machine.

We got the idea five years ago, when one of us (Maharbiz) attended a workshop about cyborg fliers organized by the Defense Advanced Research Projects Agency (DARPA). (I was an expert in microtechnology, but I did not know much about insects.) At the workshop, participants reviewed some of the technology that allows biologists to receive and record electrical signals from individual muscles of free-flying insects. Amit Lal, the DARPA program manager who organized the conference, thought that the time was right to build on these advances by determining if we could also transmit electrical signals to those muscles via implanted microcircuits that would make them move the way we wanted them to move.

Our goal was to show that we could remotely induce an insect to fly, control its turns and speed when required, then stop it when the insect reached a set location—all done repeatedly and reliably.

Cyborg insects would potentially have many military uses, including the ability to tell how many people are inside a building or a cave and identify who they are before deciding whether to commit soldiers to clear the location. Silicon-carbon hybrids could also lead to civilian innovations, such as creating insectoid robots that can find survivors in the rubble of an earthquake.

WHY BEETLES?

BEFORE THE DARPA CONFERENCE, many of the best studies describing insect flight had been done in locusts, moths and flies. By piggybacking my endeavors on that work, I thought I could reduce the number of false starts that always accompany a new field of inquiry. Moths and locusts are large, but they cannot carry much weight, so they were out. That left flies.

Flies have many advantages. For one thing, biologists know a fair amount about them. Michael H. Dickinson of the California Institute of Technology and others have worked out in great detail which muscles twitch where and when to generate lift and turns in flies. Moreover, flies are incredibly efficient users of energy, which allows them to beat and steer their wings at fantastic speeds. From an engineering standpoint, however, flies are hard to work with. They are so small that you practically have to be a nanosurgeon to implant the necessary wires and circuits in them, and I'm no nanosurgeon. I started thinking about alternatives. Dragonflies were big enough and amazing fliers, but they are very fragile. Cockroaches were possibilities.

That is when I picked up a copy of *The Biology of the Coleoptera,* a classic guide to the world of beetles written by R. A. Crowson in 1981. It turns out that beetles fly much the way flies do. The flight muscles of a beetle's thorax deform its shell so that the wings oscillate like a tuning fork. The types of muscles and their positions on the beetle also seemed similar to the fly. A few elegant studies of beetles from the 1950s offered ideas on where to begin. But perhaps most important of all: beetles are large—ranging from one millimeter to more than 10 centimeters. Beetles also account for one fifth of all known species. So in theory, there was ready access. But here I encountered a new problem: few people in the U.S. raised beetles large enough for my purposes. In the end, it took years for my laboratory to develop a fairly stable supply of beetles, which we now import from breeders in Europe and Asia.

At this point in the research, the other of us (Sato), a chemist with expertise in nanofabrication, joined as a postdoctoral fellow. Our goal was to show that we could remotely induce an insect to fly, control its turns and speed when required, then stop it when the insect reached a set location. As engineers, we wanted these functions to be repeatable and reliable, with little or no damage to the insect.

We first had to decide on a minimum set of behaviors that we needed to control to produce a rudimentary cyborg flier. Because we wanted to control insects in free flight, we did not want to use tethers to maneuver their behavior as others had done—the lines would get long and tangled up. We settled on using radio control, in much the way hobbyists remotely control miniature cars, planes and helicopters. We wanted to start and stop the wingbeat on demand, increase or decrease the insect's lift in flight, and produce left and right turns. We explicitly did not want to control every aspect of the insect's flight, because the beetles are already good at leveling to the horizon and adjusting their speed and trajectories to wind and obstacles.

At the same time, we wanted to be sure we could deliver signals directly into the insect's own neuromuscular circuitry, so that even if the insect attempted to do something else, we could provide a countercommand. Any insect that could ignore our commands would make for a crummy robot.

We weren't exactly flying blind. Most of the beetles we chose to work with can each carry a load that weighs between 20 and 30 percent of its body weight. Thus, the size of the insect determines the maximum size of our control equipment. Because we knew which muscles on the beetle make the wings oscillate, it seemed reasonable to suppose that delivering electrical charges of varying frequencies to the muscles on either side of the body would allow us to change the insect's trajectory by changing the way the insect was flapping its wings.

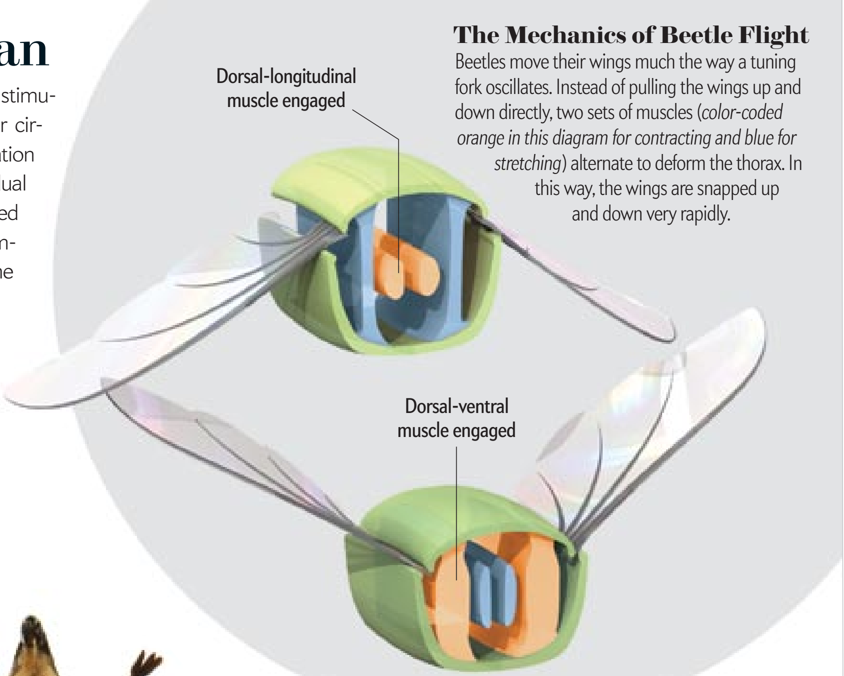
We also knew that these insects use visual cues extensively during flight. Just as in humans, light entering the insects' eyes trigger light-sensitive neurons. The signals generated by these neurons travel down the optic lobes into the midbrain and ganglia, where they are processed and provide the insect with visual information during locomotion. We also knew that the amount of light mattered in a broad sense. If, for example, we abruptly turned off the lights in a room, our beetles immediately stopped flying—implying that the insects required some sensory input from the eyes to continue oscillating their wings. We reasoned that stimulation of the optic lobes or the areas near the base of the optic lobes might elicit strong locomotion responses. Because directly implanting the eye or the optic lobe itself would impair the insect's ability to maneuver, we focused our stimula-

Flight-Control Plan

The authors use carefully timed electrical pulses to stimulate relatively large areas of insect neuromuscular circuitry to direct their beetle's flight. Had the stimulation scheme depended on the triggering of an individual neuron, the results could not have been replicated across many insects. The attachment point of the implant would have shifted in midflight, rendering the insects uncontrollable.

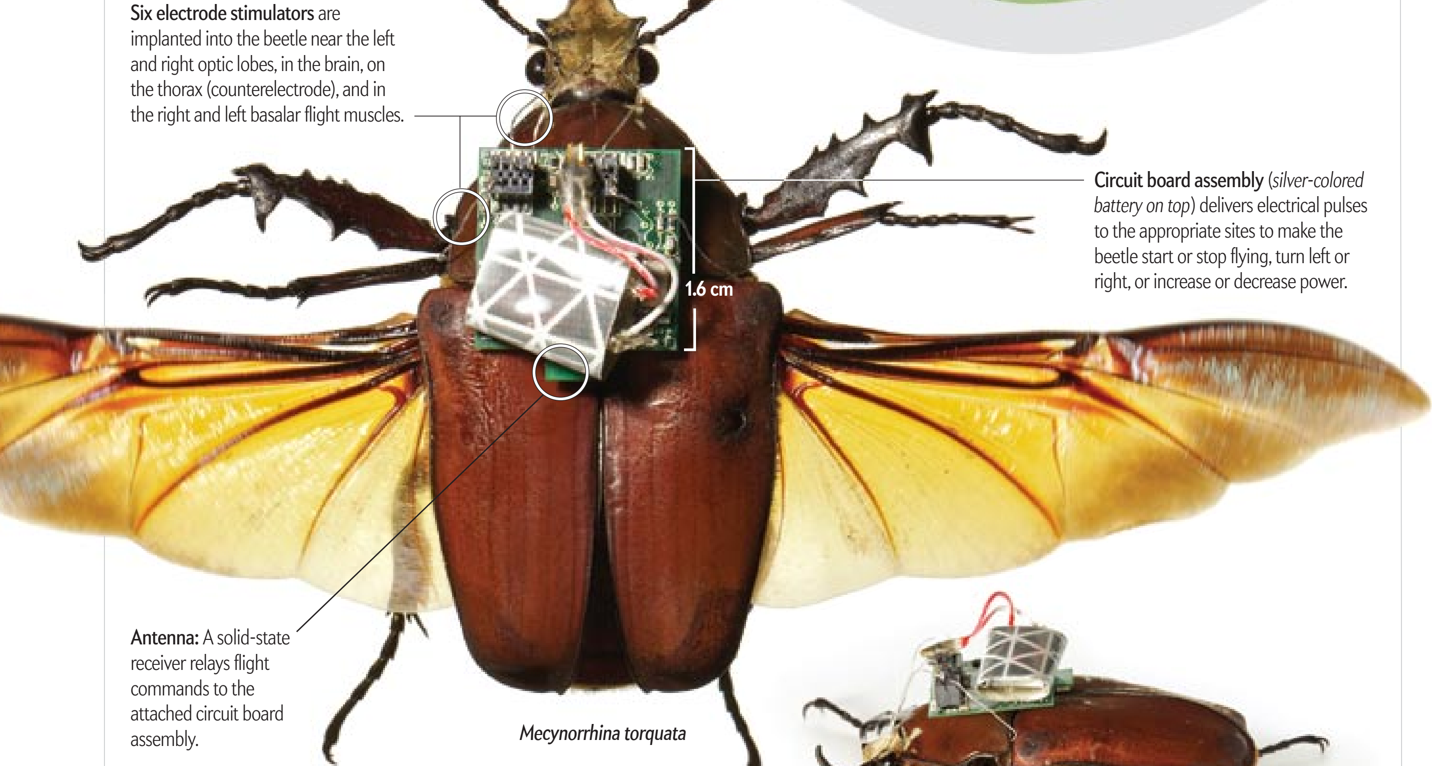
The Mechanics of Beetle Flight

Beetles move their wings much the way a tuning fork oscillates. Instead of pulling the wings up and down directly, two sets of muscles (*color-coded orange in this diagram for contracting and blue for stretching*) alternate to deform the thorax. In this way, the wings are snapped up and down very rapidly.



Wireless Flight Control

In much the same way hobbyists remotely maneuver miniature cars, planes and helicopters, the researchers developed a system for sending radio commands to beetles in free flight.

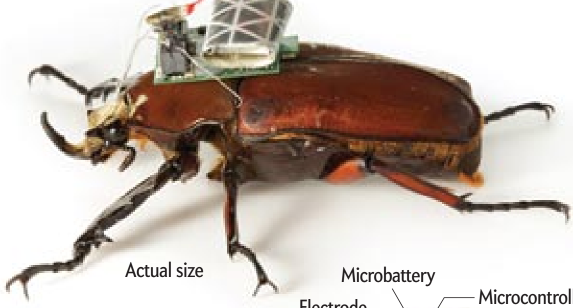


Six electrode stimulators are implanted into the beetle near the left and right optic lobes, in the brain, on the thorax (counterelectrode), and in the right and left basalar flight muscles.

Circuit board assembly (*silver-colored battery on top*) delivers electrical pulses to the appropriate sites to make the beetle start or stop flying, turn left or right, or increase or decrease power.

Antenna: A solid-state receiver relays flight commands to the attached circuit board assembly.

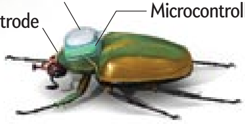
Mecynorrhina torquata



Actual size

Early Experiments

Preliminary work with Texas Green June Beetles established that wing oscillations could be controlled. For this early model, flight commands were preloaded into the microcontroller. But for wireless control, a radio needed to be added to the payload—too much weight for the two-centimeter-long beetles to handle.



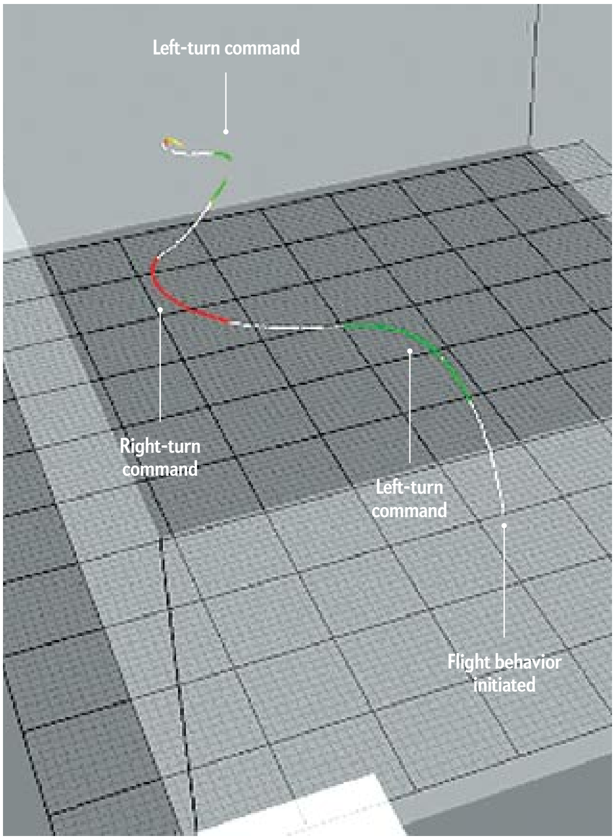
Cotinis texana (actual size)

Illustration by Bryan Christie; photographs by David Liittschwager

CONTROLLED FLIGHT

Trajectory of a Cyborg

Investigators at Maharbiz's lab put cyborg beetles through their paces in a specially equipped test room (*below; Sato is standing*). The flight path depicted at the right began (*bottom right, white line*) by stimulating the beetle's optic lobes, which triggers flight behavior. Electrical pulses delivered to the right basalar muscle prompt the insect to turn to the left, and stimulating the left basalar muscle results in right turns. The flight ended (*top left*) after the optic lobes received a second pulse longer than the first one.



SOURCE FOR TELEMETRY DATA: SVETOSLAV KOLEV AND NIMBUS GOEHAUSEN *University of California, Berkeley*

tion instead on the areas at the base of the lobes. We did not have to stimulate individual neurons. Rather if we delivered the correct electric pulse near the base of the optic lobes, the beetle's own circuitry took care of the rest, and the beetle took flight.

IF AT FIRST YOU DON'T SUCCEED

WE HAD MANY FALSE STARTS before making our first successful flight. Initially we worked for six months with *Zophobas morio* beetles (1.5 centimeters long and weighing one gram), also known as darkling beetles. These insects are available at pet stores because their larvae are used to feed pet geckos and other small reptiles. Unfortunately, we never could figure out how to get them to fly. We threw them in the air hundreds of times, and they simply refused to open their wings. Apparently *Zophobas* just does not seem to like to fly much. (We certainly learned a lot of insect anatomy from *Zophobas,* though.) Eventually we switched to the Texas Green June beetle, *Cotinis texana* (two centimeters long, weighing one to 1.5 grams), which is common in the southeastern U.S. and is popularly referred to as a June bug.

We did not want to repeat our experience with *Zophobas,* so we looked for a beetle that flies, and *Cotinis* is a well-known flier—as well as a pest to fruit farmers. In fact, for a couple of years we collected thousands of these from farmers who could not believe we were paying them five dollars per beetle to get rid of their pests.

Based on these early experiments with *Zophobas* and *Cotinis,* we figured out exactly how to hold the beetles without hurting them and where to glue the microwires on the back near the wing muscles and at the base of the head. (We used beeswax.) We designed and custom-built tiny circuit boards that could receive radio instructions and apply the types of electrical signals with which we were experimenting. (For examples of beetles outfitted with both an early version of the technology and our latest—as of April—iteration, see the box on the preceding page.) Nowadays the basic system consists of the following components: a microcontroller with a built-in radio (to receive instructions), a battery (to deliver electric charges), and several thin (125-micron diameter) silver wires implanted into the brain and the flight muscles.

Because the Texas beetles could at most carry between 200 to 450 milligrams of payload, the initial system was not equipped with a radio. To test the control, we would preload flight commands into the microcontroller and then observe the beetle

Photograph by David Liittschwager

whether it was free-flying, tied to a string or suspended inside of a gimbal. (Attaching a beetle to a gimbal allows us to watch it fly in place.)

Our first success with *Cotinis* took two months to achieve. After several experiments, we found a relatively large section of neurons that, when electrically stimulated, could produce repeatable and predictable modulations of flight. We determined that stimulating an area of the insect brain that lies just between the left and right optic lobes with fast electrical pulses (around 10 milliseconds long, or 100 hertz) causes the insect to start beating its wings and adopt a correct flight posture almost every time (97 percent of the time, to be exact). Equally exciting, one longer pulse to the same area stopped the wing oscillation completely. In other words, we could toggle the insect on and off—applying a pulse to start its wings going and another pulse to get it to stop.

We believe this longer pulse effectively overloads the neurons at the base of the optic lobe and prevents any electrical signals from propagating. This activity, in turn, disrupts the trigger signal that maintains wing oscillation [see "More to Explore" on this page for video links of this and other behaviors]. We found that our electrical impulses worked, over and over, regardless of what the insect happened to be doing at the time. If a beetle was walking along a table when we started the 10-millisecond electrical pulses, its wings started beating and it flew off. If we placed it on its back on the table and gave it a pulse, it would beat its wings upside down. If it was already in flight and we gave it an additional pulse, its wings would stop and it would fall—and then continue crawling.

There was no indication that we were damaging the insects—even when they fell to the floor. Implanted beetles lived for just as long as nonimplanted beetles (a few months). They flew, ate and mated just like regular beetles. We further found that when applying "on" and "off" signals repeatedly and in quick succession while the insect was flying, we could modulate the wing oscillations. That is, once the insect was flying, if we quickly issued the on and off commands one after the other, the oscillation of the wings would not cease but would merely dampen slightly. This had the effect of changing the insect's thrust and of allowing us to reliably control the power the beetles used to fly, much the way pilots use a throttle to control their planes.

To make the beetles turn, we implanted microwires on the right and left basalar muscles. By applying 10-millsecond pulses to the right muscle, the insect would produce more power on the right side, causing it to veer left (movies are available online at www.eecs.berkeley.edu/~maharbiz/Cyborg.html and at www.frontiersin.org/integrative_neuroscience/10.3389/neuro.07/024.2009/abstract). Eventually we started using *Mecynorrhina torquata* beetles, which at eight grams are ideal for carrying both the radio and the payloads that we have developed.

NEXT STEPS

AS EYE-CATCHING AS some of these results are, we need to do more. Although we have shown that we can make a beetle turn left and right and fly in rough circles, we ultimately want to be able to guide a beetle's flight through complex three-dimensional patterns so that they can fly around obstacles—down chimneys and up pipes, for example. To do this, we have added to the payload tiny microphones that record the wingbeats of the beetle in flight. When the sound reaches a certain level—broadly indicating whether the wing is up or down in its beat—we can apply precise stimulation pulses to the steering muscles of the beetle.

The hardware is now working pretty well, but we would like some help with the computer code that controls our beetles. We have reached out to some of our colleagues who have more experience with programming the software for fully synthetic fliers. Based on his work with autonomous helicopters, Pieter Abbeel of the University of California, Berkeley, along with his students Svetoslav Kolev and Nimbus Goehausen, is developing a control system for insects that breaks down complex commands (such as "change heading by 20 degrees") to their component parts (such as "apply 10-millsecond pulses to the left basalar muscle for so many seconds"). A user would then only have to enter certain course corrections, and the microcontroller would handle the specific stimuli needed to make the beetle fly in that direction. To figure out what that series of stimuli needs to be, we are using magnetic resonance imaging scans, extensive anatomical investigations and high-speed recordings of flying beetles to map out the three-dimensional configuration and function of some of the other muscles responsible for steering each wing. From these data, we are now targeting different muscles so that we might control yaw and roll more independently in free flight.

SHOULD WE MAKE CYBORG BEETLES?

WHETHER OR NOT remotely controlled insects will be useful as robots is an open question, but our hunch is that they will be. Smaller and lower-power microcontrollers and radios will continue to appear on the market, allowing us to develop better and finer control of our cyborg beetles. As long as it remains difficult to develop miniature power sources that pack a huge wallop or engineer highly energy-efficient mechanical wings, our beetles and their superefficient muscles will enjoy a distinct advantage over entirely synthetic fliers.

Of all the implications our work might have, we believe this to be the most fundamental: as our computational technology gets smaller and our knowledge of the biological systems advances, we will be increasingly tempted to introduce synthetic interfaces and control loops into existing biological systems. Working out the details in insects first will help us avoid mistakes and false starts in higher organisms, such as rats, mice and ultimately people. And it allows us to postpone many of the deeper ethical questions about free will, among other things, that would become more pressing if this work took place on vertebrates. Developing cyborg beetles will not replace the fundamental pursuit of building synthetic robots (given that humans often build better machines than nature does), but the discipline of seamlessly merging the organic with the synthetic is only beginning.

MORE TO EXPLORE

A Radiotelemetric 2-Channel Unit for Transmission of Muscle Potentials during Free Flight of the Desert Locust, *Schistocerca gregaria*. H. Fischer, H. Kautz and W. Kutsch in *Journal of Neuroscience Methods*, Vol. 64, No. 1, pages 39–45; January 1996.

Wing Rotation and the Aerodynamic Basis of Insect Flight. Michael H. Dickinson, Fritz-Olaf Lehmann and Sanjay P. Sane in *Science,* Vol. 284, pages 1954–960; June 18, 1999.

A Dual-Channel FM Transmitter for Acquisition of Flight Muscle Activities from the Freely Flying Hawkmoth, *Agrius convolvuli.* N. Ando, I. Shimoyama and R. Kanzaki in *Journal of Neuroscience Methods,* Vol. 115, No. 2, pages 181–187; April 2002.

Remote Radio Control of Insect Flight. H. Sato, C. W. Berry, Y. Peeri, E. Baghoomian, B. E. Casey, G. Lavella, J. M. VandenBrooks, J. F. Harrison and M. M. Maharbiz in *Frontiers in Integrative Neuroscience,* Vol. 3, Article 24; October 5, 2009.

SEE CYBORG BEETLES FLY **www.ScientificAmerican.com/dec2010/cyborg_video**