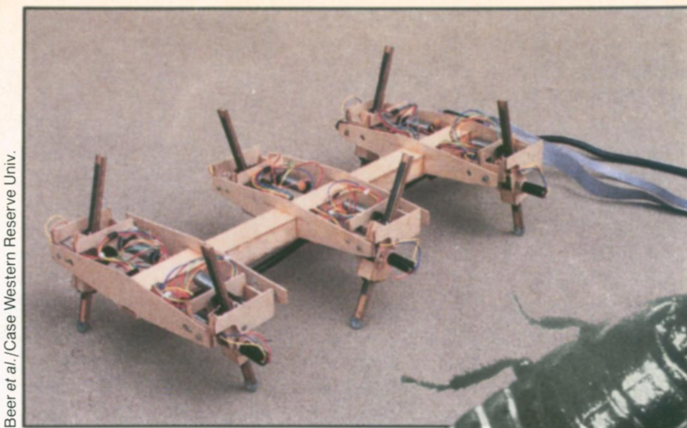
Robots Go Buggy

Engineers eye biology for better robot designs

By ELIZABETH PENNISI



Beer et al./Case Western Reserve Univ.

A roach approach to robots: This 50-centimeter-long robot exhibits the same gaits as a real cockroach because its builders used circuitry based on a computer model of insect locomotion.

C.F. Herreid/SUNY Buffalo

This fall, the U.S. Office of Naval Research (ONR) spent thousands of dollars trying to encourage university scientists to do what high school senior Christopher P. Stone did with less than $50: Blend biology with robotics. Intractable problems in biological research and in technology—the unfathomable complexity of the nervous system and the rather primitive state of autonomous robot locomotion compared with even simple animals — warrant such a blending, says Thomas McKenna, a neurobiologist with ONR in Arlington, Va.

At an ONR-sponsored workshop in September, titled "Locomotion Control in Legged Invertebrates," about 15 biologists and 10 computer scientists and engineers gathered in Woods Hole, Mass., to discuss their progress in studying how animals and machines move. ONR wants these scientists to share ideas, learn from one another and ultimately make faster progress in understanding locomotion and building better robots.

However, the workshop participants tend to view locomotion from quite different perspectives. Some care about making robots mobile. Some try to express movement as equations, which are then incorporated into computer simulations of locomotion. Others want to observe and understand a living creature. These differences mean that the investigators sometimes don't agree on what research they need to do, what questions need answering or even how to go about answering those questions. Moreover, they tend not to exchange ideas very often.

But Stone, a 17-year-old tinkerer from Bloomington, Ind., combines all these perspectives in his approach to research. As a high school freshman, he built an insect robot, in part by scavenging syringes for pistons and removing voltage converters from old computer printers for use in his robot. Last year, he got interested in how crayfish walk and began probing their nervous systems. For his junior year science project he pinpointed crayfish nerve cells involved in walking and connected them to his computer via very thin copper wires. He then modified the computer program that coordinated the robot's legs. With this new version, he stimulated a living crayfish by sending very tiny voltages down the copper wires. The voltages made the animal amble across a table.

At the International Science and Engineering Fair last May, the crayfish project earned him an award from the scientific society Sigma Xi for the best use of scientific integration. It also won him an invitation to attend ONR's September robotics workshop.

"I want to help make [paralyzed] people walk, and for quadriplegics to sign their names," says Stone about his long-term goals.

Though his experiments may seem simplistic and his ideas a bit futuristic, Stone's desire to couple biological and technological knowledge may prove quite insightful. Several researchers — and ONR — think biology may provide strategies for making faster and more versatile robots, McKenna says. At the same time, biologists find they need engineering and computing tools for their work, he says.

Although many types of walking machines exist, engineers have not yet figured out the best way to make these machines handle unfamiliar situations. Even artificial intelligence, in which computers supposedly reason the way humans do, so far has proved inadequate. "Even the simplest animals are much more versatile than the most sophisticated artificial intelligence machine," says Randall D. Beer, a computer scientist at Case Western Reserve University in Cleveland.

Yet NASA needs agile robots that can work in space or roam planetary surfaces to collect samples; the military wants robots that can maneuver along the ocean bottom or scour battlefields for mines. And to make robots do that, researchers need to develop more adaptable machines with better coordination.

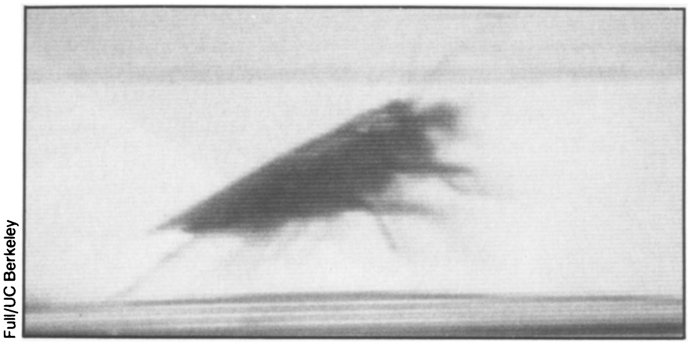
Animals are adept at avoiding obstacles, escaping predators and finding food. To understand how they do this, neurobiologists usually monitor nerve impulses and try to trace the pathways of nerve signals from the eye or other sensory organ, through the brain and down to the muscle that actually moves the wing, fin or foot. Other researchers investigate biomechanics — how joints and muscles move and keep an animal balanced.

But biological experimentation and observation alone have proved inadequate for figuring out all the intricate ingredients of animal movement. So in the past few years, some scientists have begun modeling these phenomena on computers. Their simulations help them make sense of experimental results.

A few have teamed up with other researchers to make artificial "insects" based on these computer models or to create realistic environments that simulate on a computer what animals encounter in real life. "We're trying to understand how real critters organize their behavior," says David Zeltzer, a computer scientist at the Massachusetts Institute of Technology in Cambridge.

In doing so, researchers have given birth to a field called computational neuroethology, in which computer and engineering experts create programs that try to do what animals do the way animals do it. "It allows you to get new insights into a system," Beer says.

ONR wants to nudge the evolution of this discipline yet another step. It hopes that engineers interested primarily in building robots will link up with computational neuroethologists to learn how to propel robotics out of its primitive state locomotion-wise, says McKenna.



Full/UC Berkeley

This picture from a high-speed video demonstrates that some cockroaches lean back and zoom along on two legs, reaching top speeds of 1.5 meters per second.

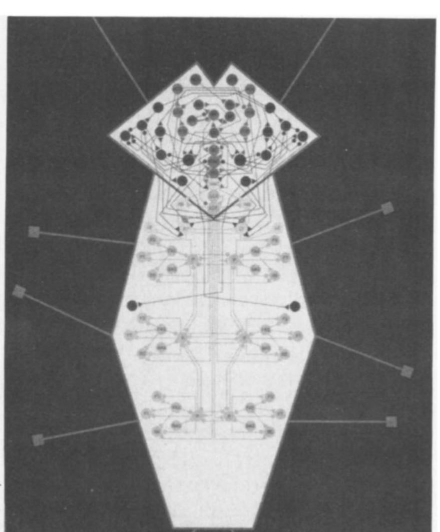
Unfortunately, the world of the engineer does not meld easily with the realm of biology. "The engineer wants to ignore as much of the biology as possible," says Beer, whereas "most biologists think every detail is important." The tension between these two perspectives can stimulate – or, more often, inhibit – collaboration, and it certainly makes life more complicated for everyone involved.

"Most engineers think neurons are on-off switches," says Allen Selverston, a neurobiologist at the University of California, San Diego. But neurons vary in their shape, their membrane composition and the type of connections they form with other nerve cells – and all of these factors affect their responses. "All that detail is very important," Selverston notes, commenting that he spends a lot of time trying to change engineers' perspectives.

But would-be robot inventors prefer not to be constrained by all this detail, and in many cases they lack the technical know-how to replicate the complexities and subtleties of living systems.

Given these differences, it's no surprise that during most of the ONR workshop, talks divided along disciplinary lines. Neurobiologists described biological experiments; computer experts talked about their neat simulation programs; roboticists showed off their machines.

But exceptions did emerge, and McKenna thinks some collaborations may soon develop.



Elyse Carter/AMERICAN SCIENTIST

Circuitry diagram shows the 78 neurons (circles) of Case Western Reserve's simulated insect.

Four years ago, scientists at Case Western Reserve began to build a bridge between these very different worlds. Beer, then a graduate student in computer science, and neurobiologist Hillel J. Chiel decided to create *Periplaneta computatrix* – a make-believe cockroach with walking capabilities inspired by what neurobiologists knew about locomotion in *Periplaneta americana*, a real cockroach commonly found outdoors in the United States.

On the computer, Beer and Chiel drew *P. computatrix* with a head, a mouth, two antennas and a body with six legs. Each leg can move up or down, support the body, or push off to move or turn the insect. The limbs also can swing in midair. The mouth opens and closes and contains tactile and chemical sensors for detecting food. The tips of the antennas relay a message when they tap an object or bend. Beer programmed energy use into the simulated critter, as well as a way for it to tell when it needed to eat.

So that their computers could handle the computational load required for simulations, the researchers adapted and incorporated a commonly used model that simplifies neuron activity. In the model, the simulated nerve cell fires depending on the cumulative effect of signals from all the neurons that connect with it. Some nerve cells send stimulating signals and others send inhibitory signals. Collectively, the signals cause the model neuron to fire when they add up to a certain level of activity.

Beer then had to decide how many nerve cells the computer cockroach needed and how they would connect. These cells would form a locomotion controller, which would get the legs moving in a coordinated fashion. In a live cockroach, small groups of nerve cells – some of which fire rhythmically – make up a pattern generator, which controls leg movements. Other nerve cells monitor the position and load on each leg. Nerve cells in one leg can inhibit those in adjacent legs, keeping any two legs from swinging at once. For the simulated cockroach, the scientists made a neural network: For each leg they put in three motor neurons, two sensory neurons and a pacemaker neuron – one that generates signals regularly. A command neuron connected all six groups of nerve cells and moderated the overall activity level.

Once they completed the computer model, the researchers discovered they could make their insect walk in different ways at different speeds. To their surprise, it exhibited the range of gaits used by real insects, even though the researchers had not set up a centralized command center to coordinate the legs. It also continued to walk even when the scientists made the computer disconnect parts of the circuitry. "If we hadn't taken the time [to look at the biology], we still would have made a locomotion controller," says Beer, "but I don't think it would have had these interesting properties."

From these studies, Beer and Chiel concluded that gaits develop as a result of interaction between the intrinsic rhythms and feedback from sensors that detect leg positions. Their results draw attention to the potential of biology for helping roboticists. "They've shown that these biologically realistic networks, at least in simulations, replicate the kinds of gaits that insects have," McKenna says.

The scientists went on to add more nerve circuitry to their computer creation so that it used its antennas to stay close to an edge as it walked around in its simulated world. They even made the computer insect seek out and eat food. Even with these bare-bones faculties – 78 neurons with 156 connections – the insect did what its real counterpart tends to do, Beer says.

Two years into the project, they decided to bring the simulated insect into the real world. Such an effort tests both the experimenters' models and the realism of the simulation. "It's one thing to say, 'I understand how something works,' but the proof is in the implementation," says McKenna. "The thing has to physically walk and not fall down."

Beer and Chiel asked Roger Quinn, a mechanical engineer at Case Western Reserve, to breathe life into their creation by building a robot that incorporated the simulation's neural network to control its locomotion. "I said, 'It will never work,'" Quinn recalls. Nonetheless, he decided to give it a try.

Quinn and Kenneth S. Espenschied designed a six-legged, 1-kilogram machine in which each leg could move up or down and backward or forward. They then constructed the insect using model aircraft plywood. "The system didn't work perfectly at first," Quinn says. For example, the researchers discovered that the robot's electrical and mechanical devices slowed the signals, sometimes unevenly, and that the delays could make it walk inefficiently. "But we did not tune the network; we had to tune our implementation," Quinn adds. And in the end, the robotic insect proved itself capable of walking as well as the computer-simulated insect.

Now Beer and Chiel want to make an even more realistic simulation, one that will reenact a complex behavior called the startle or escape response.

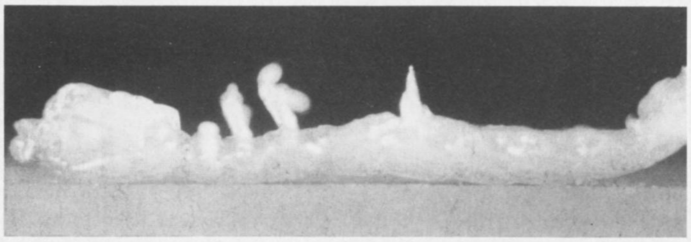
When a cockroach detects a puff of wind, as might occur when a predator lunges toward it, the insect quickly turns and runs. In less than 60 milliseconds, it determines the wind direction and then acts. Beer would like the simulated cockroach to do the same when it encounters a simulated predator. "We're trying to make the simulated insect much more physiological," says Roy E. Ritzmann, a Case Western Reserve neurobiologist who studies startle response and works with Beer on this project.

But programming realism into the simulation is proving no easy task. "Just to build a model requires a tremendous amount of nagging; it requires day-to-day interaction," says Beer. "We need a lot of data."

Often, neither he nor Ritzmann realizes what biological details they lack until they get stumped designing the model. And sometimes, the biologist has no answer. "For nine out of 10 questions, he just throws up his hands and says, 'It will take me a decade to find that out,'" says Beer. Then, together, they work out a solution. In this way, he and Ritzmann are learning about the startle response and what neurobiological experiments need to be done, they say.

In addition, they think their work can aid robot builders. It appears that neural networks, such as those Quinn used, are more flexible and require less computing power than other types of control systems. And while neither Beer nor Ritzmann thinks robots need to be just like cockroaches to work, they do believe that "biology suggests different ways of designing control systems", says Beer. "The [systems] are more likely to be more versatile and robust." □

Scoot, scramble and roll



Invertebrate biologists have good reason to think their data could inspire even the best engineer. Real-life walking, sliding, inching and somersaulting creatures showcase quite a few possibilities for robot locomotion.

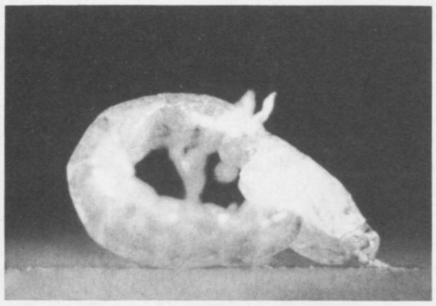
"Nowhere is there greater diversity in locomotor designs than in arthropods," says Robert J. Full, a comparative physiologist at the University of California, Berkeley. These critters – crabs that scoot sideways just out of reach of waves, centipedes that scramble up tall walls, stomatopods that curl up and roll away backwards – make their way through environments that would immobilize the most sophisticated machines.

"[Conventionally designed] robots never move in a way that's similar to animals," says Full.

To understand how arthropods scoot, scramble and roll, he and others have begun breaking these movements down into their simplest mechanical components. They find, however, that deriving general principles for use in robot design requires a bit of ingenuity.

To get a better handle on crab-scooting and cockroach-running, for example, Full constructed a force plate – a platform with sensors underneath that connect to a computer. The sensors detect when a leg pushes down. As the crab or cockroach runs across the plate, Full films it with a high-speed video camera and then analyzes leg positions frame by frame, correlating the movements with force plate measurements.

These and other studies show that no animal, not even a tumbling stomatopod, moves as a wheel does. Instead, animals' legs act like pendulums during slow walks and like springs when the animal speeds up. Full has found that animals with two, four, six and even eight legs all produce similar patterns on force plates, indicating that "the body is being propelled alternately by two sets of legs," he says. "The differences come when you look at individual legs." Thus, three legs of an insect, two legs of a poodle and four legs of a crab act as units equivalent to one leg of a human. But in each animal, the role of each leg varies. "I believe the legs are positioned and develop forces to minimize the torque at all the joints," Full explains.



R. Caldwell/UC Berkeley

Ready, set, roll: To move, a stomatopod curls up and somersaults backwards.

He found another parallel between animals with different numbers of legs when he examined the relationship between speed and stride. Trotting four-legged animals, for example, speed up by switching to a gallop: They take longer strides rather than move their legs faster to accelerate. Full discovered that a crab and a mouse of equal weight will switch gaits at the same speed – about 1 meter per second – and the same stride frequency, or number of times all the legs cycle per second.

"That suggests that there are general principles that can be applied to animals with tremendous differences in body form," he says. "Those same concepts can be transferred to nonbiological systems."

Such close examination has yielded other surprises about the versatility of moving arthropods. Scientists once thought that cockroaches always kept three legs on the ground and so remained stable all the time as they moved. This static stability contrasts with the dynamic stability of running humans, who would fall over if stopped in midstride but who stay upright because all the forces balance out as they move through each stride cycle.

Full's videos, however, show that cockroaches can reach speeds of 1.5 meters per second – more than 3 miles per hour. As the roach accelerates, it leans farther back, first depending on the back four legs and then, at top speeds, zooming along on just two. "This rejects the notion that arthropods require static stability," says Full. It also shows that an animal or robot can be capable of both dynamic and static stability, he says.

"The key is not to exactly mimic the biological system but to take the concepts and see if they can be transferred to a design to make it better," says Full, who has provided MIT engineers with data about leg length and position for possible use in the design of new robots. He also sees himself as benefiting from such collaboration: "We can provide biological inspiration for them, and the questions they ask us will help us define how we need to quantify these systems in the animal world." – *E. Pennisi*