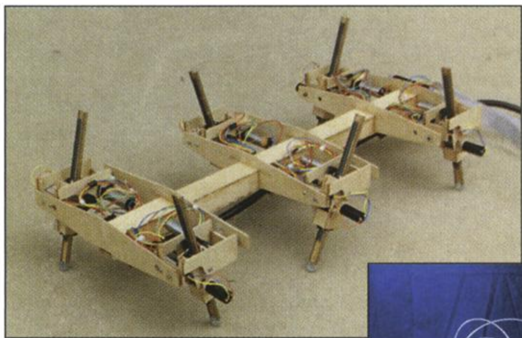
NEWS

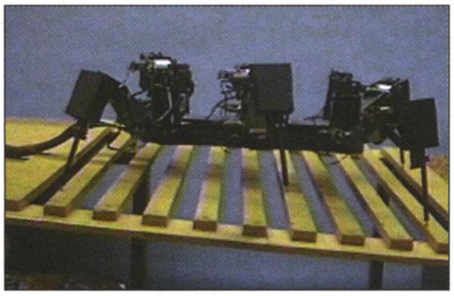
Biologists and Engineers Create a New Generation of Robots That Imitate Life

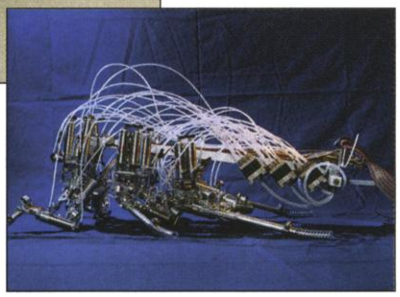
As they learn to walk, crawl, and fly, biologically inspired robots advance both robotics and scientists' understanding of how animals move

The robots developed at Case Western Reserve University in Cleveland may have unimaginative names—Robot One, Robot Two, and Robot Three—but they make up for it in looks. "All three so far are six legged," explains Roger Quinn, the mechanical engineer who built them, "but they get more and more like an insect."

To be specific, they get more and more like a cockroach. The legs of Robot One, for instance, emerge from directly beneath its balsa-wood body and are distributed in the simplest possible hexagon. Robot Two adopts a sprawl posture, with the legs, cockroach-like, on the outside of the body. The legs of Robot Three are specialized to look and act like cockroach legs—small, mobile front legs for grooming and exploring the environment; medium-sized middle legs; and big, powerful rear legs for running and jumping.







Marching onward. Robot cockroaches One, Two, and Three (counterclockwise from top) get progressively more lifelike.

This biological mimicry gives Robot Three the general gestalt of the urban dweller's worst nightmare: a 14-kilogram, bread-box–sized creation that not only looks like a cockroach but promises to walk, run, and jump like a cockroach. The only feature that's obviously not inspired by biology is the tether that supplies power to the pneumatic air compressors which serve as muscles. This tether means Robot Three cannot move about on its own. But Robot Four—which will also be modeled after a cockroach, says Quinn, "only more so"—will carry its power supply with it. It "will be able to run around the campus," no doubt to the delight of Case Western students and faculty.

The Case Western robots are among the vanguard of a new army of biologically inspired robots emerging from laboratories throughout the world. Indeed, a revolution seems to be going on in robotics, fueled by new insights and generous financial support from the Defense Department—in particular, from the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR), which together are pumping tens of millions of dollars into the field.

This largesse is promoting a union between engineers and biologists, and is spawning a new generation of swimming, flying, and crawling robotic offspring. Alan Rudolph, manager of DARPA's 2-year-old controlled biological and biomimetic systems program, says his goal is to create robots that can go where humans either can't go or where it's not safe to send them, such as the surfaces of other planets, the bowels of a burning building, or the risky confines of a minefield or a battlefield. The idea, he says, is to take inspiration from the natural world, rather than build on existing machines. Why use two legs or four wheels to maneuver when a six-legged insect will do the job better? If you want a vehicle that moves sideways and diagonally as effortlessly as back and forth, why not find your inspiration in an eight-legged spider that can do just that? To put it simply, why not let evolution do your thinking for you?

For biologists, the lure is to create a moving, three-dimensional model to test their theories of how animals function. "The experiments you do on the robots tell you what you ought to be looking for within the animal," explains Joseph Ayers, a neurophysiologist at Northeastern University in Boston, who is now working on a robot lobster (see sidebar on p. 82). "To say it works both ways is an understatement."

Gil Pratt, for instance, an electrical engineer and computer scientist who runs the Leg Lab at the Massachusetts Institute of Technology (MIT), describes his motivation as twofold: to build a robot to do housework for him—"I'm a lazy person by nature," he explains—and to understand the mechanisms of control, balance, and locomotion in animals and insects. "It's very easy to theorize about how biological systems work. What's great about building robots is you can actually test the theories."

"The art in this is what you take from biology," adds Michael Dickinson, a neurobiologist at the University of California, Berkeley, who is working on a robot fly with DARPA support. "If you really want to make a useful robot, you don't want to just copy nature. You want to extract principles at the right level"—even if the resulting robot doesn't look much like the organism that inspired it (see sidebar on p. 81).

From animals to robots

Robot-building collaborations are often sprawling and involve unlikely partners: computer scientists, mathematicians, electrical and mechanical engineers, as well as biologists and zoologists. At Case Western, for instance, the program started with Randall Beer, a computer scientist who was frustrated by the slow progress in artificial intelligence and thought guidance might be found in the nervous systems of simple insects. Beer began collaborating with Case Western biologists Roy Ritzman and Hillel Chiel, and created a computer simulation of a walking insect. They then recruited Quinn, the engineer, to build hardware models to test the software simulation in the real world. Robots One, Two, and Three were born.

As each robot has progressively captured more of the mechanical and control complexity found in the animal, says Quinn, the robots have become increasing-

CREDIT: ROGER QUINN/CASE WESTERN RESERVE UNIVERSITY

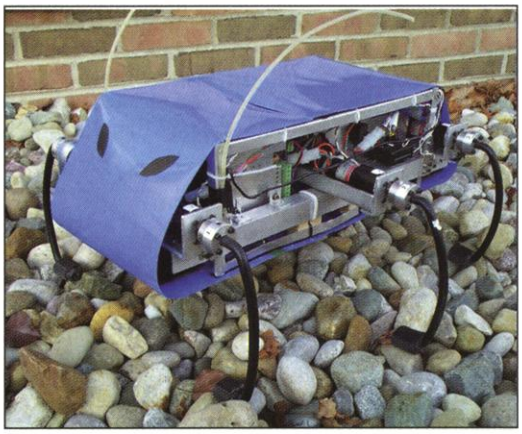
Better Than Nature Made It

As poets are inclined to point out, the ways in which inspiration can be taken from nature are wondrous, infinite, and varied. In the pursuit of bio-inspired robotics, inspiration doesn't always mean simply copying nature. Instead, many roboticists believe in distilling the fundamental principles at work in organisms and then incorporating those principles in robots, creating a machine that may look nothing like the organisms that inspired it. "We think blind copying is exactly what you don't want to do," says Robert Full, a biologist at the University of California, Berkeley. "You will fail miserably, because nature is way too complex."

Full has studied the locomotion of organisms with two, four, six, eight, and 44 legs—the latter being centipedes—and has concluded that their locomotion is all based on the same basic model, known as a spring-mass system. In effect, they all bounce as they run, like a mass on top of a spring, using alternating sets of legs. "To put it simply," he says, "they act like a pogo stick. And all these legs are bouncing along with the same patterns. The easy way to think about it is that one of your legs works like two legs of a trotting dog or three legs of an insect or four legs of an eight-legged crab and so on."

As to why insects have sprawled postures with their legs on the outside of the body, while humans, dogs, and cats do not, that can be boiled down to a second general principle, says Full. Working with Princeton University mathematician Phil Holmes and others, Full showed that the sprawled posture serves as a self-stabilizing system. As the organism runs along on uneven ground or is buffeted by a predator or a gust of wind, the sprawled legs can absorb the sideways motion and keep the organism's center of mass over its legs where it belongs. "A leg sticking out can act as both springs and shock absorbers," says Full. "Bend it to one side, and it just tosses you back."

Full believes these two observations are general principles of effective locomotion and that any robot that employs them will display the benefits. As supporting evidence, he offers up Robot Hexapod, or RHex. RHex was designed to utilize pogo stick legs and sprawled posture to get by in the world, no matter how rough the terrain. Built by a collaboration of researchers led by engineers Dan Koditschek of the University of Michigan, Ann Arbor, and Martin Buehler of McGill University in Montreal, RHex is roughly the size of a shoe box and weighs 7 kilograms. It has a six-legged sprawled posture and C-shaped plastic legs that provide the necessary springiness and self-stabilization. The legs are mounted on hip joints that rotate a full 360 degrees, taking the legs around with them. RHex doesn't look much like an insect until you see it walking across rough terrain, which it does effortlessly, with neither eyes to see nor nerves to feel, at a speed of a meter a second.



Roughing it. RHex can travel swiftly over uneven ground.

"It's the fastest running legged platform I know of," says Alan Rudolph, who manages the controlled biological and biomimetic systems program at the Defense Advanced Research Projects Agency. "And it's pretty simple but quite stable." Or as Full puts it, "RHex demonstrates the point that you don't need to copy things to make a better robot." **–G.T.**

ly capable. Robot Two, for instance, can walk over rough terrain, whereas Robot One cannot. Robot Three can climb. And having a larger-than-life-sized cockroach to manipulate has taught the biologists a lot, adds Ritzman. For example, to get the robots moving fluidly, the researchers needed to incorporate input from strain gauges in the body into the computer that controls the robots, suggesting that the actual animal relies on organic structures that do the same thing, he says. "These insights have led us to propose many more experiments in the future" on the cockroaches themselves.

Flapper. The robot Hawk moth emits smoke as it flaps its half-meter wings.

CREDITS: (TOP TO BOTTOM) M. BUEHLER/MCGILL UNIVERSITY; ELLINGTON *ET AL, NATURE* 384, P. 6610 (1996)

Beer eventually returned to the world of software simulations, while Ritzman—who spent 20 years studying the instinctive mechanism the cockroach uses to flee predators or an approaching rolled-up newspaper—has continued to work with Quinn on robots. "We started getting a lot of money from DARPA to build robots based on how cockroaches walk. I started getting less money for cockroach escape, so I took the hint," he says. "I thought I was getting into a hobby, and it took over my career."

Other biologists tell similar tales. Ayers, for example, spent much of his early career studying how the lobster's nervous system controls its behavior and locomotion. Now he leads his own team of engineers working on a robot lobster, after he realized that the firing pattern the lobster's nervous system uses to move the animal's limbs would work well for almost any six-legged creature, including a robot one. He had his epiphany when DARPA asked him if it was possible to put sonar on live lobsters, apparently for use as unobtrusive underwater espionage agents. "I naïvely said it would be easier to build a lobster robot," says Ayers. "Now I appear to be a card-carrying roboticist, but it's very clear to me that my training in neurophysiology is expert training for a roboticist and much better at the control end than anything a mechanical engineer gets."

For other researchers, robotics offered a new avenue of research when studies of live animals hit a dead end. Dickinson and Charlie Ellington of Cambridge University, for instance, both started off studying how real insects fly. Ellington's lab gets credit for the observation that the flapping of insect wings seems to generate two to three times more lift than can be explained by conventional aerodynamics. (This led to the misconceived suggestion that science can't explain why the bumblebee flies.) "We took our studies of real insects about as far as we could," says Ellington, "and we wanted them to do things that they couldn't, so we had to build our own."

Specifically, Ellington concluded in the early 1990s that his research would benefit mightily from an insect that could release smoke from its wings on command, something real insects resolutely refused to do. So he and his colleagues built "the flapper," a mechanical, computer-controlled, scaled-up model of a Hawk moth that emits smoke as it flaps its mechanical wings, allowing Ellington and his colleagues to visualize the air flow around and over the wings. A similar line of thought led Dickinson and Berkeley engineer Ron Fearing to build a scaled-up model of a robotic fly. To create a robot big enough to work with, they had to scale up not just the fly's body but the size and relative strength of the forces on it—the viscosity of air matters considerably more to a fly, for example, than it does to a pigeon. The researchers adjusted the forces to mimic those acting on a real fly by playing with variables such as the speed of the wings and the medium around them; they ended up with a robotic fly with a half-meter wingspan slowly flapping its wings in 2 tons of mineral oil. That robot allowed them to directly measure the forces generated by the wings.

In the last few years, Ellington's and Dickinson's labs together finally managed to explain the lift generated by insect wings. As published in a handful of papers, insect flight is the result of decidedly unconventional aerodynamics—a threesome of phenomena, involving the creation of a spiral leading-edge vortex (also known as a delayed stall), rotational lift, and wake capture. All three phenomena had been identified years ago and had been suspected of providing the necessary lift to insects, but the robots allowed researchers to measure the actual forces involved and provide the requisite experimental verification.

Now both groups are designing small flying robots for DARPA. Ellington says his recent wind-tunnel studies suggest that insect wings mounted on rotors, like a helicopter, generate as much lift as flapping insect wings and that a rotor design may be much more practical for a working robot. "My own aim," he says, "has always been to be able to build my own insect and fly it around the room under remote control. If you can do that, then you really understand how they're flying." That goal, however, is still years away.

Learning from robotuna

A similar desire to understand how animals manage their feats of locomotion led Michael Triantafyllou, an MIT oceanographic engineer, to probe the secrets of fish propulsion. Triantafyllou decided to build a robot tuna to study underwater vortices, in particular the vortices that propel fish forward rather than dragging them back. Real tuna are champion long-distance swimmers, and so presumably their physiques are highly evolved to manipulate the forces around them as they swim. Triantafyllou and his collaborators used a taxidermist's cast of a bluefin, then built an internal musculature of six "links," each of which can be swiveled back and forth by its own motor. The links are covered by plastic and aluminum ribs supporting a skin of padded foam and the same Lycra of which swimsuits are made. The 2-meter-long robotuna is only "a lab robot," says Triantafyllou, because it lives in its own water tank, the undersea version of a wind tunnel, and is attached to an overhead carriage through a thin strut that holds it in place and transmits commands and electricity to the motors. By using a robot tuna in lieu of the real thing, Triantafyllou and his colleagues can precisely control its motion and the amount of energy it expends to swim. They can then compare that energy to the propulsive force the robot exerts, while studying the flow of water over its body.

Triantafyllou and his colleagues realized that as the tuna swims, swishing its vertical tail fin from side to side, it minimizes the amount of energy needed to form the propulsion vortices while also controlling the flow around its body to reduce drag and turbulence. "Both mechanisms are hard at work," he says.

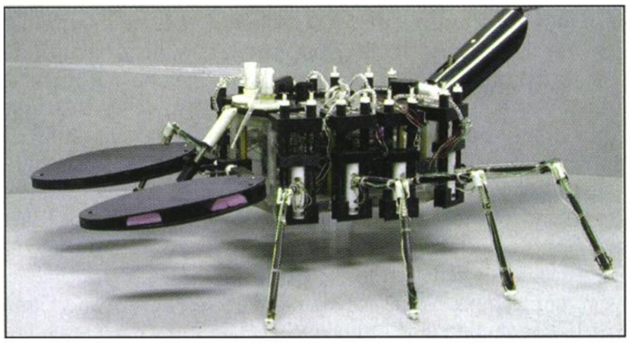
The MIT researchers then proceeded to build a robot pike. Their creation is about 1.3 meters long and composed of three links plus a tail. "This was primarily constructed to

Making a Robot Lobster Dance

It's one thing to make a robot walk, quite another to make it engage in all the complex behavior that a biological organism might demonstrate. But that's what neurophysiologist Joseph Ayers of Northeastern University in Boston is trying to achieve with his robot lobster, which has been designed to function as an underwater, remote-sensing autonomous vehicle.

Ayers has created the robot's control system by taking films of lobsters in motion, breaking them down into specific movements and postures—sideways crawling with claws extended, for instance—and then turning that into a matrix tying the 21 basic lobster movements and postures to the commands that put the robot in motion. For instance, rotating to the left can be done by telling the lobster's four right legs to move forward while simultaneously instructing the four left legs to move backward. This control matrix, says Ayers, "plays like a player piano. You would be amazed at how accurately it describes the behavior. It flabbergasted me the first time I got it working."

The control system may be the easy part, however, compared to the engineering. Rather than using motors to move the robot around—using them as "actuators," in roboticists' lingo—Ayers has opted for "muscle wire," a technology brought to his attention by his brother-in-law, an amateur inventor. Muscle wire contracts when heated, which can be done by sending a current through it, but it has to be cooled again to get it to relax. "We have had to learn how to train this stuff," says Ayers. "There's just a lot of basic engineering that has slowed us down."



Made for walking. The robot lobster can already walk and turn, and may one day be able to sniff out mines.

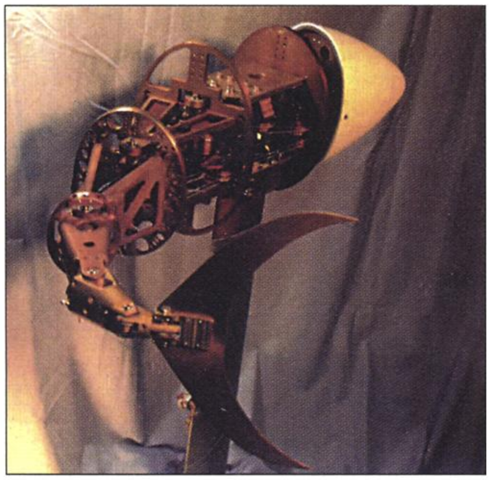
CREDIT: J. AYERS AND J. WITTING/NORTHEASTERN UNIVERSITY

At the moment, the movements of the robot lobster are limited to walking and turning. But eventually Ayers expects his creations to do everything real lobsters do and maybe do them better. The robot lobsters will have sonar to navigate and to receive instructions, and they should be able to crawl across the ocean floor, avoid obstacles, and demonstrate "investigative behavior." Eventually, the goal is to use the lobster to sniff around curious or suspicious objects like potential undersea mines.

Ayers realizes he has a long way to go, but he's optimistic if not downright impressed with what he's wrought. "When you see this robot on the Web page,"* he says, "it will blow your mind." –G.T.

* Robot lobster can be seen at www.dac.neu.edu/msc/burp.html

study acceleration," says Triantafyllou, as the pike is a "a very aggressive and agile fish, a master at fast starting and turning." The robopike is autonomous, meaning it needs no strut for support, has onboard batteries for power, and receives commands via a wireless modem in its nose. "You can put it in water and it starts swimming," says Triantafyllou.



Turning tail. The robotuna's "muscles" allow it to turn like the real thing.

By manipulating the robopike to precisely follow commands as real fish never would, Triantafyllou and colleagues learned how fish maneuver—"an exercise in vorticity control," says Triantafyllou. In order to turn, the fish has to push hard on the water to get going, and that requires, in effect, creating a temporary jet of water on one side. "The way they do it is by bending their body, which begins the formation of two very large vortices, and then the tail spins the one closest to the tail and then [the tail] spins the other vortex, closest to the head, to generate the two-vortex pair, which shoots out and generates the force needed for fast starting or turning."

Now, with support from ONR and DARPA, Triantafyllou and his colleagues are embarked on a pair of collaborations to build autonomous underwater vehicles (AUVs) that are more agile and maneuverable than existing miniature submarines. "If you compare a dolphin, for instance, with an AUV," says Triantafyllou, "the most striking difference is the ability of the dolphin to turn on a dime. So if you need to operate in areas that are cluttered, shallow, or with lots of waves, or if you want to do dangerous kinds of work, you want these very dexterous robots that can move quickly, position themselves in currents, and pack a lot of power."

The end result of all these collaborations is likely to be a world of new bio-inspired robots to help humans, although so far few robots have successfully made the leap out of the controlled environment of the lab into the unpredictable territory of the real world. Advocates argue that there's another reason for pursuing this line of work: The technology developed will likely yield tremendous unforeseen benefits later—what Dickinson calls "the moon shot" rationale. "The amount of technology that needs to be developed to build something like an autonomously flying insect is extraordinary," he says. "Fifty years from now, people will be talking about the technology that came off these projects in the same way they now talk about the technology that came out of the space program. There's nowhere near the same amount of money going into it, but we're going to reap similar rewards in terms of the technology."

–GARY TAUBES

NEWS

In Nature, Animals That Stop and Start Win the Race

Researchers studying how animals move in the wild find that intermittent locomotion offers a surprising array of advantages over keeping a steady pace

In 1995, marine physiologist Terrie Williams was stumped. After studying the oxygen requirements of diving dolphins, she had carefully calculated that dives to 200 meters required 28% more oxygen than the animal could possibly inhale or have in reserve. Deep, prolonged dives might well be fatal. Yet in field experiments, somehow her study subjects—trained bottlenose dolphins—easily plummeted to depths well below 200 meters and returned safely, with ample reserves of oxygen. Now after 5 years of arduous field experiments—strapping videos to the backs of dolphins, seals, and whales, in both the Pacific and Antarctic oceans—Williams and her colleagues at the University of California, Santa Cruz, have finally discovered the diving dolphins' secret.

As she reports on page 133, rather than swimming—and consuming oxygen—all the way down, dolphins take a few strokes and then glide as long as possible, a trick biomechanicists call intermittent locomotion. By doing less work, the animals use less oxygen, and so can dive deeper and longer. This was quite a surprise, for dolphins and whales have been intensely studied for years and no one had any inkling that this diving behavior existed. "Only by going back and looking at the behavior [in the field] could we find this out," Williams notes.

Different strokes. A custom-fitted housing carries a video camera to record whether diving dolphins stroke or glide.

For decades researchers have emphasized steady-state locomotion, bringing organisms into the laboratory and watching them move at a steady pace. Besides studying dolphins and fish in flow tanks, for example, they used wind tunnels for birds and treadmills for creatures from mice to kangaroos. But Williams's finding is just one of a stream of recent results indicating that that focus was only a first step. The new work shows that animals from aquatic invertebrates to humans move like window shoppers, stopping and starting as they seek out food, mates, or shelter.

The findings have "really begun to cast doubt on the way we have looked at locomotion in animals in the past," says Frank Fish, a functional morphologist at West Chester University in West Chester, Pennsylvania. "A whole new area is opening up in the way we perceive energetics in organisms." Probing the fitful nature of locomotion is helping researchers understand how various organisms'

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