COVER FEATURE

Biomimetic Robots

A wealth of biological data together with advances in low-cost, power-efficient computer systems support the emerging development of robots that mimic insect and sea creature adaptations to environmental niches.

Linda Dailey Paulson

From the ominous Klaatu of *The Day the Earth Stood Still* to the Terminator, we've seen robots typically portrayed on screen as stiff, humanoid machines. But it's not just Hollywood that has locked robots to the human form.

"A lot of conventional thinking pervades the field of robotics," says Morley Stone, a program manager in the US Defense Advanced Research Projects Agency's defense sciences office (www.darpa.mil/dso/). "They still look very much like they are depicted in grainy black-and-white films. You see this humanoid robot that doesn't walk very well. We still haven't improved upon that all that much."

Forget the anthropomorphs. Today, researchers are looking in the cupboards of their local diners and under rocks for biological inspiration to create a new generation of flying, crawling, and swimming automatons known as biomimetic robots. Intrigued by how other species have adapted to a whole world of environmental niches, researchers are working to understand and reverse-engineer the adaptive traits of creatures, including those—like the seemingly indestructible cockroach—we might much rather step on than study.

MIMICKING BIOLOGY

Biomimetics is a general description for engineering a process or system that mimics biology. The term emerged from biochemistry and applies to an infinite range of chemical and mechanical phenomena, from cellular processes to whole-organism functions.

"People have been trying to copy nature for a very long time," says Jerry Pratt, a research scientist at the Institute for Human and Machine Cognition (www.ihmc.us). Leonardo da Vinci made drawings of potential flight contraptions based on detailed anatomical studies of birds, and the Wright brothers based their airplane structure on observations and analysis of bird flight. However, researchers diverge in precisely how they define biomimetics. "'Biomimetic' is often a vague term, much like 'robot,'" says Pratt.

Mark Cutkosky, a professor in Stanford University's Department of Mechanical Engineering, is part of a team working on a family of legged robots based on cockroach locomotion. He says their team defines biomimetics as "extracting principles from biology and applying them to man-made devices—particularly robots."

Cutkosky says two forces are driving the "new wave" of robotics. First, biological research has exposed a huge amount of biological process data that roboticists can apply to their work. Second, advances in low-cost, power-efficient computing systems allow researchers to create robots that work outside laboratories. Cutkosky says that roboticists can "really put some of the lessons we're learning from biology to practice. Ten years ago, even if I had understood exactly what materials and mechanical principles underlie the cockroach's robust dynamic locomotion, I would have been unable to build a robot that embodied them."

Not that current biomimetic robots are dependent on the fastest computing technologies available.

"The interesting thing about the biomimetic work," says Butler Hine, manager of the computing information and communications technology program based at NASA-Ames, "is it uses nature's evolved way of doing things rather than the computationally intensive way." In lieu of algorithmic-intense artificial intelligence, Hine says, some

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researchers are using control loops and 8-bit processors and field-programmable gate arrays (FPGAs) for command control rather than lines and lines of programming.

Biomimetic robots are still relatively new, however, and the possible collaborations among biologists, robotic engineers, and computer scientists have barely begun.

There's more to this process than simply constructing a workable, autonomous robotic device, say scientists. "How birds fly, how fish swim, how dolphins locate objects, and how humans walk might best be discovered and understood by trying to reproduce these activities in a device,"contends IMHC's Pratt. "The knowledge gained might not be immediately useful, but it could some day lead to useful technologies based on, but not necessarily mimicking, these phenomena."

RESEARCH PROJECTS

Most of the current robotic projects sprang from DARPA programs, says Hine. The US is the primary financial underwriter for research through DARPA and other agencies such as NASA, the Office of Naval Research (ONR), and the National Science Foundation (NSF).

Researchers have hopes of creating robots that can detect mines, explore Mars, or search for people trapped beneath an earthquake-damaged building. It is premature to predict which of the many existing projects will be widely deployed first; the variety of concepts and potential applications both alone and in combination with other robotics research is simply still too broad.

Sprawl hexapods

Cutkosky is part of a team at Stanford's Center for Design Research (www-cdr.stanford.edu/biomimetics) that is designing and fabricating six-legged robots that "draw their inspiration from the physical construction and mechanical design principles that are responsible for the robustness of the cockroach." Funded primarily by ONR, the group includes Bob Full, a respected biology researcher from the University of California, Berkeley, whose work on the mechanics of cockroach locomotion underpins the robot design.

Several characteristics of cockroaches intrigue the Stanford team, including the speed and stability with which they can negotiate rough terrain. "They run over obstacles without slowing down or getting knocked off course, and they do this mainly by virtue of having a wonderful tuned mechanical system—sort of like the suspension of a car—that keeps them stable and on course," says Cutkosky. Plus, he notes, "It's hard to damage a cockroach."

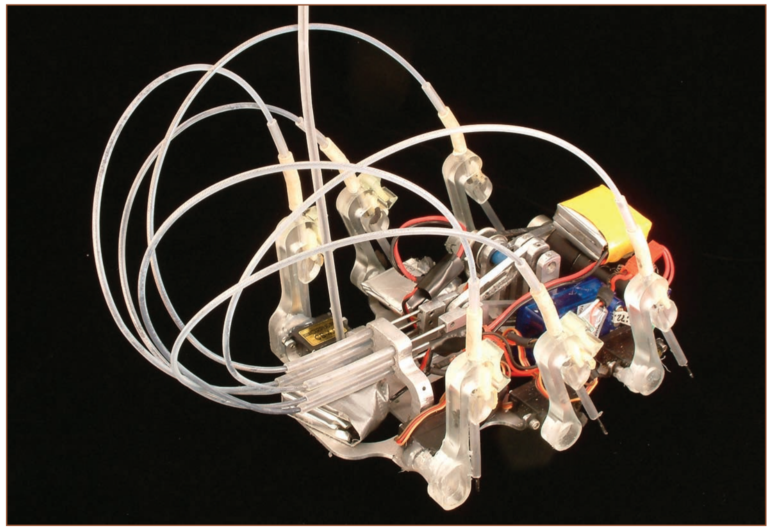

Figure 1. iSprawl robot. The small (115 mm long, 315 grams) cockroach-inspired robot runs autonomously at 15 body lengths per second (photo courtesy of Stanford Center for Design Research).

Figure 1 shows a robot from the Sprawl family. What makes these robots different, says Cutkosky, is their mechanical, rather than computational, properties. "In the past, legged robots were expensive and required fast computation and accurate sensors to achieve rapid locomotion. In contrast, Sprawl robots rely on a tuned, resonant mechanical system."

The system's six legs move in an alternating-tripod gait in a "sprawled" design that mimics the cockroach's biological structure and both supports the robot and allows it to move fast. The system is operated using an open-loop motor pattern driven by a clock associated with the on-board processor. The various sensors, actuators, and microprocessors are embedded in the robot's durable polymer shell, made possible by a complex fabrication process called *shape deposition manufacturing*.

Cutkosky says that government funding is essential because the applications are still a few years away. More work is required to make the robots more robust and to improve fabrication. He would like to make a version using injection-molded plastic parts and subject it to testing in real-world applications, such as military reconnaissance.

Adds Cutkosky, "We are not trying to 'copy a cockroach.' This would be impractical. And besides, who would want one?"

Robotic lobsters

For years now, two independent teams of researchers—one concentrating on sensory-chemical tracking and the other on locomotion—have been working toward creating a chemical-tracking, underwater robot based on lobster biology.

Neuroscientist Frank Grasso, an associate professor of psychology at Brooklyn College, has been

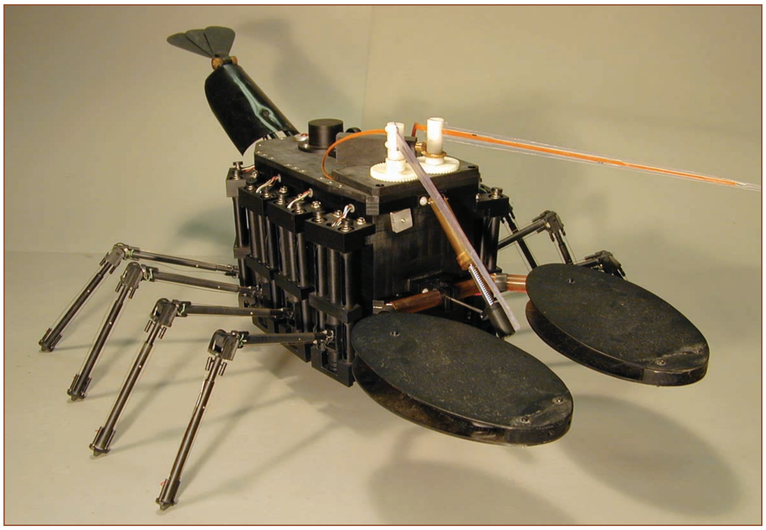

Figure 2. Robotic lobster. This robot prototype uses biomimetic control principles. Its behavior is based on a library of action patterns reverse-engineered from lobster behavior in the target operational environment (photo courtesy of ONR).

part of a research team examining the lobster's acute sense of smell in the turbulent ocean environment. Grasso headed the robotics group that designed and built two generations of autonomous underwater robots, Robolobsters I and II, which match the size as well as the sensing and locomotor capabilities of their biological counterparts. These robots let researchers test hypotheses based on controlled observations of a real lobster's superhuman ability to detect olfactory information and make decisions based on it.

Because Robolobster operates under water, any tether to power interferes with operations, requiring researchers to make it as close to autonomous as possible. Grasso says that Robolobster II is computationally and energetically autonomous for missions up to five hours.

Another team of researchers is working on making the first robot with an elementary nervous system. This project stems from research on lobster and crayfish nervous systems conducted in the 1970s by Joseph Ayers, a biology professor at Northeastern University (www.neurotechnology.neu.edu/). Ayers subsequently used biosonar telemetry to study lobster behavior in the wild.

When DARPA approached him in the 1990s about building a robot, Ayers quips that he was "a card-carrying neurophysiologist." He assembled a group of biologists, naval architects, and electrical and mechanical engineers, several of whom, he says, were "experts on what's impossible." Figure 2 shows a prototype robot currently under development.

In an important evolutionary piece of robotic research, Ayers is collaborating with the University of California, San Diego's Institute for Nonlinear Science to create a locomotion control system that does not use typical motors and finite-state machines as controllers. The team is working to reduce the electronic neurons and synapses to analog VLSI and to generate "motor program-like central pattern generators based on a nonlinear dynamic model of real lobster neurons," Ayers explains. "The artificial neurons generate action potentials that gate power transistors to drive artificial muscle." This eliminates the need for a feedback loop in a motor controller, as many robot controller systems require. Modulation of chaos in these networks will enable more animal-like behaviors in robots, such as a squirming motion.

Eventually, Ayers wants to create an artificial brain by integrating gravity, bump, and flow sensors with the central pattern generators the researchers have already developed, thereby forming an elementary nervous system.

Robotic lobsters have been funded by an alphabet soup of agencies, including DARPA, ONR, and NSF. "The only delay is to really find a mission [for the technology]," says Joel L. Davis, an ONR program officer working on adaptive neural systems. Davis expects one lobster to be available for use by summer 2006.

One military application is minesweeping beachheads, but the robots must have specific knowledge about their mission, says Davis. They must know, for example, if they should detect mines that are on the ocean floor or buried beneath its surface and, when they are working in a swarm, whether to communicate with each other or not. If one lobster detects a mine, it could, for example, signal others in the area to go away before it detonates the mine, taking itself out at the same time.

Entomopter

At Georgia Tech, work continues on Entomopter. This tiny robot is designed to both crawl and fly, but its name stresses its flying ability.

Aerial robots have existed for about two decades, says Robert Michelson, a Georgia Tech professor and principal research engineer, but "they don't necessarily take on biological form." As Figure 3 shows, these robots look more like other machines than winged animals because "the bioinspired things are not as well understood."

When the Entomopter research was initiated in the mid-1990s, the idea was to design a micro-sized air vehicle about the size of a military MRE (meal, ready to eat) and sturdy enough to survive a GI accidentally sitting on it. The dream device could go over a hill or obstacle and "find bad guys ..., but it's unrealistic," says Michelson. Factors such as delicacy and the need for line-of-sight communication made it impractical.

Subsequent research proved "size doesn't matter" for outdoor operations, so Michelson says his group shifted focus to niche indoor operations. His team is working on devices nimble enough to enter a building through a chimney or open window, fly fast, evade detection on camera surveillance, and negotiate tight areas. Such a device would be used for reconnaissance and for missions such as disrupting electrical equipment. And, perhaps, they might even be mistaken for a large moth.

This generation of the Entomopter is designed for operation in two atmospheres: a 50-gram terrestrial version and an aerospace version designed for use in different gravitational environments. Both versions are constructed primarily from carbon composite material. The design feature that intrigues aeronautical engineers is a circulation control process that turns high-speed, hot-gas flow into a lower speed, cooler gas that can, when vented out the wing, cause flow that gives the vehicle seven times more lift and lets it fly at slow speeds. Perfect for exploring Mars.

Michelson expects computer scientists to eventually help create a fully autonomous device, but other problems are more pressing. Once the scientists resolve the flight mechanics, they can work on flight control. Until they know whether the device "turns on a dime or on a quarter … it doesn't make sense to do flight algorithms." Besides, processors and other computing devices will change many times before the Entomopter is deployed, Michelson says.

DARPA has provided much of the funding, and NASA is interested—but it will probably be six or more years before Entomopter is deployed on a Mars mission.

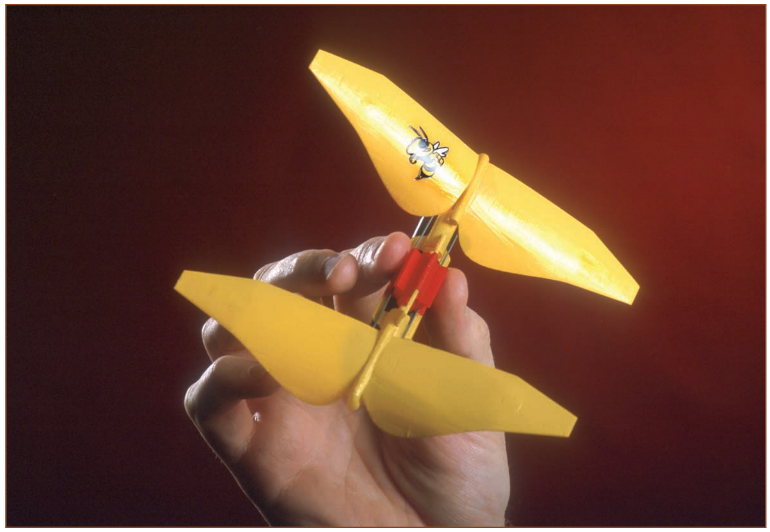

Figure 3. Entomopter. The multimodal design is adapted for indoor flight operations. Its wings beat autonomically from a chemical energy source (photo courtesy of Georgia Tech).

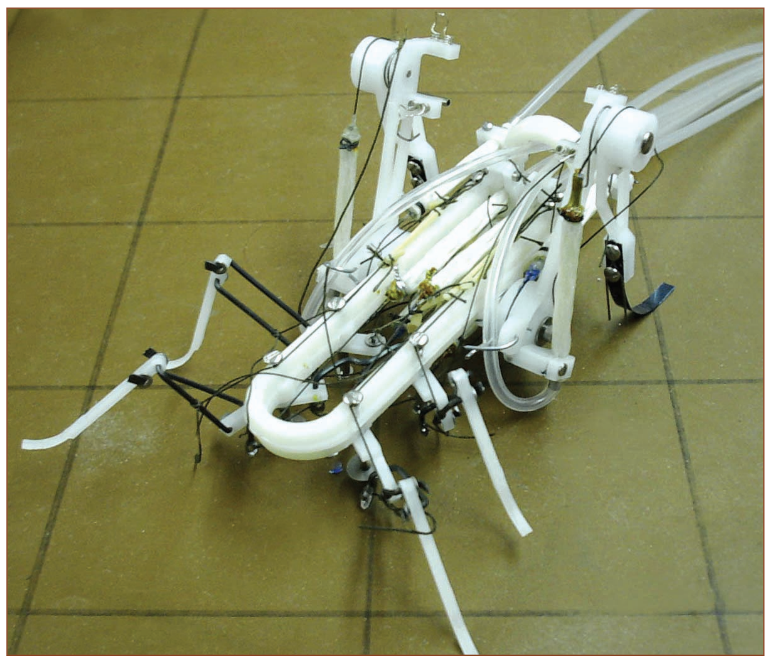

Figure 4. Cricket-inspired robot on a 2-inch grid. The robot can both walk and jump to navigate terrain with features much larger than itself (photo courtesy of Biorobotics Lab/Case Western Reserve).

Bugs and Whegs

Biomimetic research at Case Western Reserve University began in 1987 with insect behavior studies that employed neural networks on biological data. Today, the Biologically Inspired Robotics Lab (http://biorobots.case.edu) creates machines inspired by nature.

Roger D. Quinn, professor of mechanical engineering and the lab's director, says inspiration is a more accurate description of their work since mimicry is neither possible nor desirable. He says robots should not be restricted by an animal model's design as is the case with airplanes, which can fly faster and carry payloads heavier than the birds that inspired their development.

Quinn's team has been working on robots inspired by cockroaches and crickets as well as a hybrid mechanism called Whegs (wheels plus legs). Whegs is the device that is closest to commercial deployment, says Quinn. This fairly simple robot uses one motor and "needs little software in terms of locomotion."

Figure 4 shows a cricket-inspired robot, approximately three inches long, designed for both walking and jumping. Quinn says that one of the most promising projects for this device involved sound tracking in collaboration with Barbara Webb, an expert in artificial intelligence and biology at the University of Edinburgh.

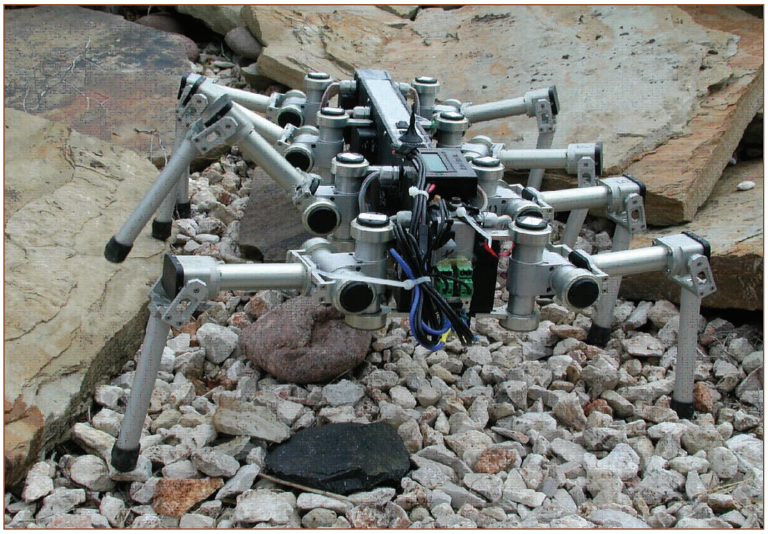

Figure 5. Scorpion robot. The 60-cm, 9.5-kg robot integrates a robust network for navigational and other rules of learning (photo courtesy of Fraunhofer AIS).

Crickets use sound to track potential mates. The team is investigating this phenomenon for robots that could be used in search and rescue efforts. The idea is to deploy small robots in lieu of dog or human search units to safely locate cries for help or detect breathing in a constricted environment such as ruined buildings following an earthquake or explosion. The design places sensing microphones close together like cricket ears so the robot can use the Doppler effect to locate sound.

Quinn's lab has also applied this idea to a full-sized Whegs robot. He says combining the two systems "just makes sense." Applying the idea to mini-Whegs is also a possibility. This three-inch version of the platform can run up to 10 body lengths per second and comes in a jumping version as well.

Like many other programs, Case Western robots have been funded by DARPA and other US military research agencies. Quinn says work on the Whegs platform continues because "the military is going to fund something they can use as soon as possible." A next step is to eliminate radio control in favor of autonomous operation.

Germany's Scorpion

The German-led Scorpion project (www.ais.fraunhofer.de/BAR/SCORPION/) is creating a robot for use in environments where humans either cannot or do not want to go, says Bernhard Klaassen, a researcher on the team from Fraunhofer Institute. The team, led by Bremen academic Frank Kirchner, chose the scorpion to emulate because it is "fast, robust, and in some sense kinematically complex," Klaassen says. One of the more notable physical attributes people remember about a scorpion is the tail, with its venomous stinger. Versions of the robot use the stinger to transport a tiny camera rather than a painful payload.

Figure 5 shows one of these eight-legged robots. Successive Scorpion generations have employed an increasing number of sensors and more sensor data to help them move smoothly. "To read and interpret all these sensor inputs, we used not only a fast processor on board but also a programmable hardware device, an FPGA, to get all sensor inputs prepared within the 100-Hz control loop," Klaassen says. This enables the Scorpion to, for example, increase current to the motor to push away a stone or use a higher swing motion to help its leg clear an obstacle.

"Our latest developments are more concerned with neural control for walking robots," he says. Small, recurrent neural networks and artificial evolution help the robot "learn" simple rules such as how to navigate, including, for example, how to get out of a corner. "The interesting feature of these networks is robustness," says Klaassen. "If you transfer the identical net to a completely different robot that only knows how to change its direction to left or right and how to 'see' a wall, it will react in a similar way if the situation is similar. But you never have to explain what a corner is and what to do then."

Klaassen says Scorpion, funded primarily by DARPA, is still a research platform, but its learning capability is an important part of the autonomy that many military projects require.

RESEARCH DIRECTIONS AND APPLICATIONS

Although the funding has vanished for some promising projects, including Case Western's cricket, Morley Stone expects DARPA's investment in biorobotics to continue, as it is "so important in many aspects of what we do across the Department of Defense." He especially sees the need for missions involving reconnaissance and defusing explosives.

New ideas are still eliciting funds from US military research agencies. For example, an octopus-inspired project is looking at creating soft arms with suckers that can bend in any direction. Grasso's group at Brooklyn College is part of an international team that also includes researchers from Hebrew University, Penn State, and Clemson. Grasso is enthusiastic sbout the work, saying "it's going to keep us going for a few years."

Corporate funding, apart from Japanese companies such as Sony and Fujitsu, has been negligible, say researchers. The lack of commercial activity is partly because the field is very young, but NASA's Hine expects pieces of biomimetic research to be gradually introduced into mass-produced commercial devices by much the same process that resulted in fuzzy logic being used in vacuum cleaners.

It seems that some of this research is destined for use in toys that will appear on the commercial market, not unlike Sony's robot dog Aibo. Toy applications are actually very challenging, says Stanford's Cutkosky. "The companies that are making toy robots have to do extremely clever engineering to achieve entertaining performance at an acceptable cost. I think if you asked iRobot engineers about the challenges associated with Roomba versus their expensive military robots, you'd find there were many," he says.

University research has resulted in some spin-off companies founded by former students. Stanford spawned Iguana Robotics, for example, which is making a cat-inspired robot. Hine says some students who have completed advanced studies in the US have returned to their home countries and opened businesses. Hungary's AnaLogic Computers Ltd., founded by a Berkeley graduate, is one example.

Japan is probably the first nation in which robot assistants will be accepted, but other nations may slowly accept this technology into the mainstream. "If robots are more clever and more helpful in private houses, then of course, the companies will jump on it," says Klaassen. "It would be a sad thing," he adds, "if we had only military robots and not friendly ones."

Computer science is a critical tool for both biologists and roboticists in this enterprise. "If you're a biologist, you start to simulate these things in hardware or software," to gain better understanding, says ONR's Davis. And if you're a roboticist, "Once you get a beating wing, you have to learn how to control it."

The bulk of the research work ahead is concentrated on making robots autonomous, and as this work continues, researchers expect collaboration with computer scientists to increase.

The interdisciplinary nature of the work is intense. Because each creature is so exquisitely made and so vastly different, it can be difficult for teams of biologists, chemists, and engineers to understand it, much less devise a facsimile. While the progress of biomimetic robots from the laboratory to the unpredictable world we live in may seem slow, from the perspective of evolution, it may be on a pace to beat a cockroach. ■

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