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The **Washington Post**

April 17, 2001 Tuesday
Final Edition

SECTION: A SECTION; Pg. A01

LENGTH: 1984 words

HEADLINE: The Animal Mind Inside the Machine;
Scientists Start to Fuse Tissue and Technology in **Robots**

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DATELINE: CHICAGO

BODY:

The cyborg aims for the light and wheels forward. Another light flashes and the cyborg turns. Again and again, like a bull in a ring, the cyborg charges, sometimes veering right, sometimes left, sometimes moving straight ahead, always looking for the light.

The cyborg is no RoboCop, but it is a revolutionary experiment in combining a mechanical device with living tissue. The **robot** is controlled by an immature **lamprey** eel brain that was removed, kept alive in a special solution and attached to the hockey-puck-sized **robot** by wires so it can receive signals from the device's electronic eyes and send commands to move the machine's wheels.

"Until the recent past, people were using biological nervous systems to inspire technology," said physiologist Sandro Mussa-Ivaldi of Northwestern University's Rehabilitation Institute of Chicago. "Now we've gone one step beyond, to tap into the nervous system itself."

Mussa-Ivaldi's lamprey larvae are one of a large number of creatures whose supple sensory resources are being put to work in a new generation of animal/machine hybrids.

Mussa-Ivaldi is testing the lamprey brain's ability to control a robot, but the long-term possibilities could be much more spectacular: learning more about how brains work so electronic microprocessors can be developed to help compensate for damage from strokes and other types of nerve trauma.

A wide variety of other similar experiments are unfolding in labs across the country, where rapid advances in electronics and other fields have enabled scientists to integrate animals and microelectronics. These experiments envision a range of applications -- using bacteria attached to computer chips to map pollutants, insects as part of sensors to detect land mines, chemical weapons and narcotics, and rodent brains to help identify new medicines.

"There's a couple of things making this happen," said electrical engineer Michael Simpson of the Oak Ridge National Laboratory. "Even before the mapping of the human genome was completed, there was an explosion in our understanding of genomics and neural pathways in other animals.

"At the same time, [microelectronic] devices keep getting smaller and denser," Simpson added. "Single chips are beginning to get complex enough so that they can begin to work with biological systems."

In Tennessee, Simpson and colleague Gary Sayler have genetically engineered bacteria to glow in the presence of chemical agents and affixed them to microchips. The Rockville, Md.-based company Dynamac is licensing their "critters on a chip" for applications that could include highlighting the boundaries of toxic waste plumes, monitoring air quality or analyzing body fluids to test for signs of disease.

In Iowa, entomologist Tom Baker has built a device for finding land mines using tiny moth antennae that emit signals to microprocessors, which transform them into different tones. The signals drop in pitch when the antennae encounter the odor of high explosives used in mines or unexploded ordnance.

In Los Angeles, neuroscientist Michel Baudry is using brain slices from mice and rabbits to develop a system for warning soldiers about the presence of chemical or biological weapons. The system creates an electronic blueprint for a normal environment, so that when the balance is upset, an alarm will tell soldiers to don gas masks.

Formidable barriers remain before scientists will fully benefit from critter science. Animals must be trained and maintained. Shelf life of natural tissue is a problem.

And so is size. University of Montana entomologist Jerry Bromenshenk has trained bees to find explosives, and the Agricultural Research Service's Joe Lewis has done the same in Georgia with parasitic wasps, but there is not yet a practical method for tracking such tiny sentinels when they are flying free.

And at Iowa State University in Ames, Baker can read the reactions of his moth antennae on an oscilloscope, but he doesn't yet have the electronics that a soldier needs to discriminate between the signal he wants and other odor sources.

Using animals to serve humankind is as old as training falcons to hunt and dogs to fetch. The impulse is always to take advantage of animals' superior qualities, and if scientists couldn't use the animals themselves, they have tried -- and often failed -- to make devices that mimic their expertise.

Harold Hawkins, head of the Office of Naval Research's bioacoustics program, notes that a dolphin can map the sea bottom in its mind's eye with "one, or two, or three" pings from its echo-location system, while the world's fanciest side-scan sonar needs dozens of slow passes to build the same picture.

Other animals are just as sophisticated, but science is catching up: "We are getting the engineering tools that allow us to plug into living systems," said Alan Rudolph of the federal government's Defense Advanced Research Projects Agency, which has funded a number of critter projects. "We are asking the question, 'Can we make machines with living components and make them work?' "

Mussa-Ivaldi's experiments in "biology as technology" brought him and colleague Simon Alford to the lamprey because it is a well-studied creature with very large nerve cells and a brain stem that can survive for several days in an oxygenated and refrigerated salt solution.

Using a microscope, Mussa-Ivaldi or his colleagues extract brain stems from the squiggly, pencil-thin, 6-inch-long lamprey larvae under anesthetic. They put the half-inch-long brain stem on a stand, connect electrodes to both sides of it, and run wires to each side of the robot, an off-the-shelf miniature from Switzerland called a Khepera. The robot is placed in the center of a circular arena about 3 1/2 feet in diameter -- like a tiny bull ring.

As lights mounted at 45-degree intervals flash on and off around the pit's rim, the robot's light sensors send signals to microprocessors that transform them into impulses the lamprey brain can interpret. The brain sends signals back through another set of microprocessors, which produce the electric impulses that drive the wheels. When the lights don't flash, the robot doesn't move.

The lamprey ordinarily uses this mechanism for balance -- to keep itself centered and upright in the water. As a result, the animal's brain will seek equilibrium, and, indeed, in most cases the robot will turn to the light and run toward it.

But if assistant Karen Fleming masks one of the eyes, the robot will first travel in circles, since only one side of the brain receives signals -- "but we hope it will compensate," and straighten out. It usually does, after a few practice runs.

The effect is eerie, for it is clear that the brain senses the light. In darkness, an oscilloscope picture is stationary, but when a light flashes, the display spikes dramatically and the robot's wheels begin to turn.

"As you see it here," said Mussa-Ivaldi, watching the robot scoot across the pit, "the lamprey brain is the only thing that makes it move." While the team appears to have established that the brain can learn, Mussa-Ivaldi said, it has not yet been able to keep brain function stable long enough to test its memory. Mussa-Ivaldi is optimistic that whatever he learns will eventually help researchers develop high-tech prostheses for stroke victims and others who suffer nerve damage.

Training unusual animals to serve human ends has proved surprisingly easy, in part because of the extensive research that scientists have done simply to find out why they do what they do.

In Tifton, Ga., the Department of Agriculture's Lewis and several colleagues had studied parasitic wasps for 30 years as a way to kill caterpillars in farm crops before Rudolph's DARPA funded him to see if he could transform his charges into sensors.

Lewis knew the wasp responded to smells it identified with food and with reproduction. By feeding the wasps sugar water as he exposed them to the odor of di-nitro toluene, an explosive akin to dynamite, he was able to teach the insects to seek di-nitro toluene in the field. In Montana, Bromenshenk has done the same thing with bees, also a DARPA project.

But having trained his "miniature bloodhounds," Bromenshenk had to be able to track them electronically. Radio transmitters were too heavy, and although scientists had had some success gluing microchips on the bees, the process took too long. Bromenshenk is waiting for someone to produce a "spray-on" chip.

In Georgia, Lewis has patented a hand-held "biosensor," and puts his wasps -- much smaller than the bees -- inside. When the insects smell an odor, they duck their heads to receive the reward, tripping an electric eye. Lewis said such a device could work well searching for explosives at airports, cocaine at the border, or even traces of disease in odors from the human body.

Baker's experiment with moth antennae, also funded by DARPA, may offer a solution to the size dilemma, for it uses only tissue from the insect, rather than the whole animal, and mounts the detector in a vehicle.

Moths use their antennae to detect different odors. Baker attaches electrodes to the base of the antennae to try to develop an olfactory "signature" for any odor he seeks, including high explosives. The eventual goal is to put the antennae in a mobile cyborg that can both sense a land mine and flag the target.

The system now works with a remote-controlled vehicle, Baker said, but a trained researcher has to walk beside it to listen for the tonal patterns that signal "hits," and find their source by assessing the wind direction.

In the insect experiments, researchers are trying to pick one odor from a barrage of competing signals, but in Los Angeles, the University of Southern California's Baudry has reversed the approach by modeling hundreds of thousands of signals that describe a normal environment. When something doesn't fit -- a biological agent or a toxic pesticide -- a warning alarm sounds.

Baudry does this using slices from the hippocampus of a rabbit or mouse, a section of the brain that forms new, long-term memory -- in humans, for example, it links a face with a name.

The sophistication of the mammalian brain, coupled with modern computer capacity, has given this research almost unlimited potential, for once scientists assemble a library of responses, they can screen for practically anything, including testing thousands of chemicals to see if one might produce a novel medicine.

One barrier to the practical exploitation of critter devices is the need to increase their life span. Baudry said his team has "almost, but not quite," developed a way to suspend the slice in a gelatinized nutrient that can be activated with heat -- extending the shelf life to several weeks or months.

In simpler organisms, this hurdle can be lower. Oak Ridge's Simpson and Sayler, a University of Tennessee microbiologist, were able to freeze-dry and encapsulate bacteria so that they would activate when water was added to the chip.

The Simpson-Sayler "critter on a chip," being marketed by Dynamac as an environmental biosensor, grew out of Sayler's ability to transplant a luminescent gene from a marine bacterium into another bacterium that degrades pollutants.

When the second bacterium ate the pollutant, it glowed, demonstrating that it was doing its job. If the researchers pasted a bunch of bacteria on a chip, the microcircuitry could detect the luminescence and send a signal to a remote display.

By salting a site with bacteria, scientists might map the extent of a toxic plume. Installed sensors could monitor pollutants at water purification plants, check air quality on spacecraft or warn of chemical or biological warfare attacks.

"We're turning the bacteria into microelectronic components to detect different substances," said Sayler. "You can engineer the organisms to eat almost anything."

LOAD-DATE: April 20, 2001