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Features

Wiggling through the waves

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What's got metal muscles, wears a Lycra swimsuit, and is designed to hunt down mines for the US Navy? Amy Adams meets the man who knows

SOMETHING strange is wriggling about at the back of Joseph Ayers's lab. Half a metre long from tip to tail, its thin body writhes back and forth in a tank of water. From the way that it wiggles you might think it is a weird kind of eel. But take a closer peek and you'll notice something odd. There are thin metal wires feeding power to its body. And where you might expect to see fishy flesh and scales, there are high-tech metals and plastics.

Based at the Marine Science Center at Northeastern University in Boston, Ayers spends his time building robots. The weird creation in his lab is a synthetic lamprey-a predatory eel-like creature that feeds by sucking the body fluids from other fish. Although it moves like the real thing, Ayers's robot can't yet swim on its own-its head remains tethered to the side of the tank and its writhing body is supported on a sliding cradle. One day soon, Ayers hopes, this robot's heirs will wiggle their way through the sea like their voracious real-life cousins. But they won't dine on fish. Armed with a set of sensitive detectors, these robots will search out a far less palatable prey-mines.

Ayers is designing his lampreys to hunt for mines and booby traps moored in harbours, rivers and estuaries. Anchored to the seabed or the bottom of rivers, these devices float a few metres beneath the surface, ready to catch unwary boats as they pass. And since they are small and difficult to spot, why risk human lives hunting them down when a swarm of tireless robots could offer a faster and safer way to defeat them?

As well as making dangerous forays for the military, teams of robot lampreys could have other roles. Attach video cameras or arrays of chemical sensors to the robots and they could keep an eye on the environment, circling wrecks or oil installations ready to alert us to leaks of chemical nasties. And wiggling their way through the oceans, they could offer marine scientists a cheap and flexible way to collect samples from the seabed or explore the mysteries of the ocean floor.

Building robots may seem an unusual occupation for Ayers, whose background is in neurology. His interest in robots was first stirred in 1991 when he attended a conference on leg locomotion. At that meeting he saw several robot prototypes designed to find mines in shallow water but, he says, none struck him as feasible.

Some ran on wheels or tracks-of limited use on sandy rock-strewn seabeds or beneath waves and pounding surf. "The problem was that nobody had based a robot on an actual underwater animal," he says.

As part of their neurology research, Ayers and his team had spent hours studying the nervous systems and behaviour of creatures such as lobsters and lampreys. Lampreys in particular have evolved for aeons to hunt for prey in shallow water. From his work, Ayers knew that their nervous system was not as complicated as most people had assumed. "These are really very simple animals," he says. And since he'd already worked out the intricacies of the way the creatures move, the next logical step was to build a mine-hunting lamprey of his own.

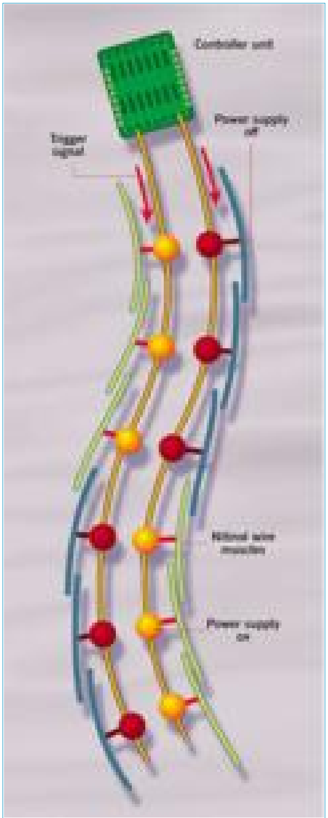
One of the biggest challenges faced by robot designers is getting their creations to walk, waddle or hop about. But an even harder task confronted Ayers. The lamprey's body moves with a wiggling motion much like that of an eel-in a continuous wave that starts with a small movement in the head and ends with a much greater whip-like wave of the tail. Each wiggle pushes diagonally back against the water, giving the lamprey a little forward motion on each flick, with the undulations in the last third of its body producing most of the power. To create this complex swimming motion, lampreys have more than 100 bands of muscle arranged along their bodies. The bands work in sequence one after another, sending waves of contraction first down one side of the lamprey's body, then the other. The lamprey might have a simple nervous system, but how could Ayers hope to recreate these intricate patterns of muscle contraction?

Thanks for the memory

The answer turned out to be surprisingly easy-simply use thin wires of nitinol, a shape memory alloy (SMA) made of nickel and titanium. SMA wires can be imprinted with a shape that they "remember". Take a short length of wire that has been stretched, for instance, and when you heat it above a threshold temperature, it shrinks back to its original length. Let the wire cool, give it a tug and it pops back to its stretched state.

To use this simple effect to re-create the complex motion of a lamprey, Ayers took a flexible plastic backbone and laid four lengths of SMA wire down each side so that every wire overlapped with its neighbours. To "contract" the muscles on one side of the robot, a controller unit sends out a sequence of short pulses. These activate power supplies that pass current through the nitinol wires. The current heats them above their threshold temperature and they shrink, bending the robot's body (see Diagram).

By timing the sequence so that the wires contract one after another, first along one side of the backbone, then along the other, the robot begins to wiggle. Ayers found that when the wires are chilled with cold water, contractions on one side of the robot stretch the wires on the opposite side back to their extended state, readying them for the next contraction. And nitinol can expand and contract at a brisk four times per second, easily fast enough to simulate a lamprey's slithering swim.



How a robot lamprey moves

With his prototype robot already wiggling, Ayers has been awarded a $3.16 million grant from the US Defense Advanced Research Projects Agency (DARPA) to move the robot out of the lab and into the sea. Eventually, Ayers says, it will have a flexible, half-metre long polyurethane backbone running through its body (see Diagram). A joint in the neck will give the head extra flexibility for steering. A small computer chip running a special swimming program will integrate directional signals and information from sensors about the strength of water currents, together with the robot's depth and location. It will then send messages to the "muscles" that control swimming, in much the same way as the nervous system of a real lamprey does. And like all the best-dressed swimmers, it will be wrapped in a fashionable Lycra swimsuit. This should keep dirt and debris out while allowing enough water in to cool the robot's muscles.

How buoys control the robots in their search for mines

Although nitinol works well, the team have a lot to do in implementing these metal muscles. From their prototype they know that the wires must be at least ten centimetres long and a few millimetres thick but they haven't worked out the robot's exact musculature.

The difficulty, says Ayers, lies in controlling the strength of the muscle's contractions-the robot should be able to vary its movements to get a vigorous wiggle in rough conditions or a more gentle undulation in calmer water. To produce this graded response, Ayers and engineer Ranjan Mukherjee at Michigan State University have two plans. One is to stimulate the wires at different locations. Pass a current through half of the wire and only that half will contract, says Ayers.

Well wired

The other plan is to change the amount of current flowing through the wires. With the heat generated by a long pulse of current, the nitinol muscle contracts by about 8 per cent of its original length. Given less heat using a shorter pulse, the wire will contract by only 1 or 2 per cent. Mukherjee is working out the size of wire and strength of current required to get the best response-the current must be kept to a minimum since the lamprey will rely on internal batteries for its power. At the moment, they don't know for sure how many wires they will need-Ayers guesses they might need a total of 12, six along each side.

Exactly where these wires are placed depends on a 3D computer model created by William Vorus at the Department of Naval Architecture and Marine Engineering at the University of New Orleans. This should tell Ayers exactly how the robot's physical properties will affect its swimming behaviour.

With this simulation, Vorus can build a complete model robot with whatever properties he chooses. He can even immerse it in a virtual sea to test its swimming efficiency by measuring the forces it generates on the water. Tweak parameters such as the robot's density, size or the position of its muscles and Vorus can predict how the change will affect the real robot's swimming motion. Put the muscles in the wrong place or make the spine too flexible, for instance, and it might swim backwards or float around aimlessly. "It's one thing to know what we want," says Vorus, "and another thing to get it to work."

Another task for Vorus's software is to test predictions of how lampreys manage to swim right side up. "This problem has been completely overlooked in the literature," says Scott Currie, who worked on the robot project as a graduate student. Although a lamprey has small fins running down its body, these appear to play no role in stabilising the creature: a lamprey without fins has no problem orienting itself. "The question is," says Currie, "if they aren't using the fins, what muscles do they use?"

He believes a lamprey corrects any rotation with a sharp thrust of its head. Should a large wave flip a lamprey upside down, it simply twists its head upright as it begins its next wave of muscle contractions. This rotates the rest of the body behind it, and keeps the lamprey upright. The problem lies in finding which muscles control that initial twitch and discovering exactly how they rotate the head. If the researchers can work this out, Vorus should be able to integrate the movement into the program he will use to control the robot's motion.

At the moment, Ayers suspects that the robots might need two pairs of crossed nitinol wires, one pair on each side of the head, running diagonally from the front of the head to the neck. This should allow the robot to twist its neck up or down, says Ayers, and give the lamprey sufficient control to steer.

This way up

The robot's muscle arrangement will not be the only thing that is borrowed from real life-its nervous system will also mimic the lamprey's. The robot's head cavity will house an array of small gravity sensors to tell it which way is up. But it will need a lot more information besides. In shallow rivers or estuaries, the ebb and flow of currents or the strong wash of waves as they pass will push or tug at the robot as it works. Simply to swim in a straight line, never mind detect mines, the robot must be able to gear its swimming speed according to water conditions. To help it do this, engineers Paul Zavracky and Nick McGruer at Northeastern University have designed tiny hair-like sensors that can measure the water flow across the robot's body. These sensors are tiny mechanical "hairs" that work like miniature computer joysticks. Each sensor is a two millimetre long rod that sticks out from the lamprey's side. Each has a round metal base that sits beneath the lamprey's "skin" and is surrounded by tiny contacts. As water flows across the sensor, the rod tilts and its base presses against a pair of contacts, completing a circuit and generating a signal that is fed to the robot's central processor.

These sensors will line the robot's sides, just like the lateral line organ that helps real fish and lampreys sense water flow. Combining their signals with information from an electronic compass mounted in its head should tell the robot how fast it is moving relative to the seabed, and what the water around it is doing. With this information, the robot can change its swimming movements to match those of the water.

But without some form of external control, there will be little to stop his robots simply swimming off into the murky blue depths. So Ayers is working with Donald Massa, president of Massa Products Corporation, a Massachusetts company that builds sonar equipment, to give each robot a small transducer. This will be used to send and receive commands via sonar pulses.

To clear mines from a particular area, Massa suggests using buoys to mark out the area for the robot. Once positioned, these buoys will give out sonar "bleeps" which the robots can use to orient themselves. In search mode, the robots will swim about randomly in this area with their mine-hunting sensors turned on. The buoys could also relay simple commands to the robots, telling them to report back with their location and that of any mines, or to start or end the search. Exactly how the robots will detect mines-and what they'll do when they find them-is up to the Navy, says Ayers. The robots could carry detonators to plant on each mine they find or signal their discovery to a buoy, producing an accurate record of its position.

If they fulfil their designers' expectations in military service, the robot lampreys could have an exciting time in civilian life too. "We know more about the surface of the moon than we do about the bottom of the ocean," says Ayers, "and marine biologists are struggling to find a way to study it". He believes his robots could step, or wiggle, into the breach. Swap mine-detecting sensors for video cameras or chemical analysers, and develop a way to recharge their batteries underwater and Ayers's robots could explore ocean floors, collect marine samples or monitor the environment. "Getting some cheap device that can go look around on the bottom of the ocean would be great," says Ayers.

One of his latest projects is a robot lobster that will work with the lamprey, scouring the seabed for buried mines. Both robots will be controlled by almost identical programs and use similar muscle and sensor technology. With most of the basic design challenges overcome, Ayers now believes that producing a robotic copy of a salamander or a stingray should be almost trivial. And, he asks, why stop there? "There's a whole aquarium of robots out there waiting to be built."

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