Shape Shifters Tread a Daunting Path Toward Reality

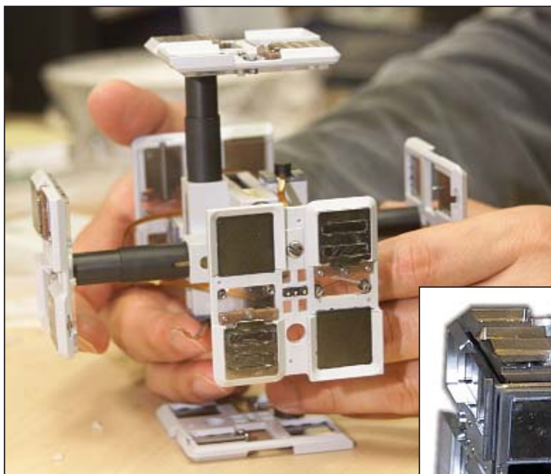
New designs of robots built from cell-like modules are learning to walk, slither, roll, flow, and reinvent themselves on the fly

From *Star Trek* to *Star Wars* to *Terminator*, science-fiction movies and TV series teem with morphing robots. If that vision is indeed a sneak preview of things to come, then the future of robotics is lying face down on a table in Mark Yim's laboratory at the Palo Alto Research Center (PARC) in California. Or rather, *was* lying face down, because now it's trying to stand up.

First, the 30-centimeter-long, vaguely humanoid robot pushes itself up on all fours into a head-down, yogalike pose. Next, because the motors in its waist aren't strong enough to lift its torso from that position, it places its head on the table. This frees the arms, which swing back behind the legs, giving it a more favorable mass distribution. Finally, the torso straightens up, and "Terminator 0.001" is ready for action.

At the moment, standing up is about all the action this particular robot can handle. Unlike its cinematic kin, PARC's Terminator cannot shoot people, take over the world, or (as one wag has suggested) run for governor of California. But what it does share with movie robots is the potential to change form. It is composed of 15 identical palm-sized modules, called PolyBots, versions of which are learning to reassemble themselves into sundry snake, insect, and wheel configurations and—most important—move around.

Yim's group at PARC, which consists of six full-time researchers and an ever-changing cadre of college and even high school interns, is one of several teams in North America, Europe, and Japan trying to build modular, self-reconfigurable robots. Like living organisms, these machines would be constructed out of many "cells" of a few basic types. They would be able to change their body plans and detach or attach extra modules without outside assistance. In theory, they would be more versatile, more robust, and cheaper than special-purpose robots (assuming that the modules could be mass-produced). In practice, modular robots have yet to reach most of these goals, to say nothing of the more far-fetched capabilities of their fictional counterparts. Nevertheless, the field has moved ahead rapidly since 1989, when Toshio Fukuda of Nagoya University in Japan built the first prototypes. Modular robots may soon get their first chance to prove themselves in the real world.



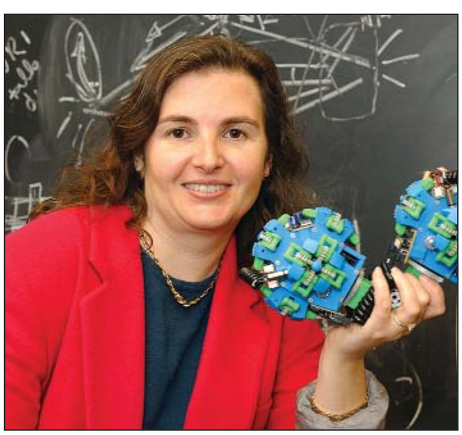
From one cell ... Mark Yim's "Telecube" robots are made of modules that can double in size by extending the sides outward.

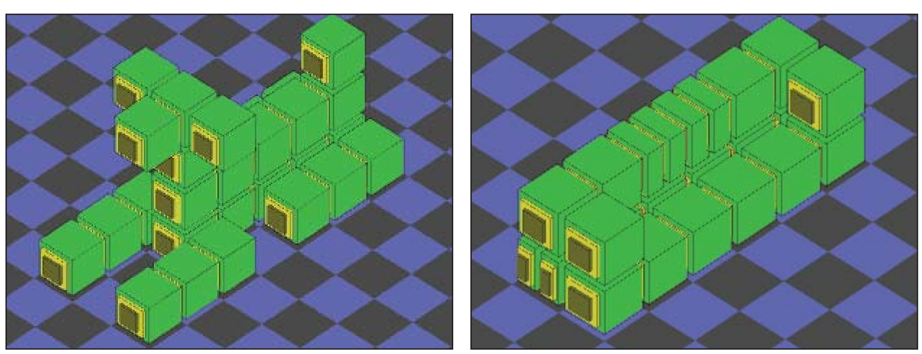
Dockers and sliders

At this point, there are more designs for reconfigurable robots than labs working on them, each with its own strengths and weaknesses. Lattice robots, such as Yim's "Telecube" and the "Crystal" robots built by Daniela Rus of Dartmouth College in Hanover, New Hampshire, offer perhaps the ultimate in morphing ability. The robots are stacks of cubical modules. By extending or retracting their faces (see figure), the modules can move through the stack like the squares in a two-dimensional sliding-tile puzzle. Yim's group has proven that, given enough modules, lattice robots can reconfigure themselves from any shape to any other. In computer simulations, the sequence of moves looks baroque yet eerily systematic. Finding the quickest sequence still poses a formidable mathematical challenge (see sidebar, p. 756).

Lattice robots offer one other important advantage: Whereas most modular robots must monitor all their cells continuously to keep different parts from smacking into one another, in a lattice robot each module has to watch out only for its neighbors. Because the modules can occupy positions only in a grid, they must touch each other and "introduce themselves" before they compete for the same space. Their decentralized architecture lets lattice robots move in a free-form, spontaneous way, which Rus compares to the flowing of water.

Another popular robot design is the chain





... To many. Daniela Rus pioneered the expanding-cube design for a lattice robot. Computer simulations by her lab show how stacks of lattice modules can reshuffle themselves into a nearly limitless variety of shapes.

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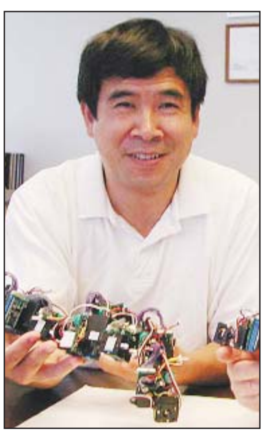
Arachnifying. Through a series of gyrations, PARC's PolyBots can autonomously switch from a basic slithering-snake configuration (*top*) to a four-legged walking spider (*bottom*).

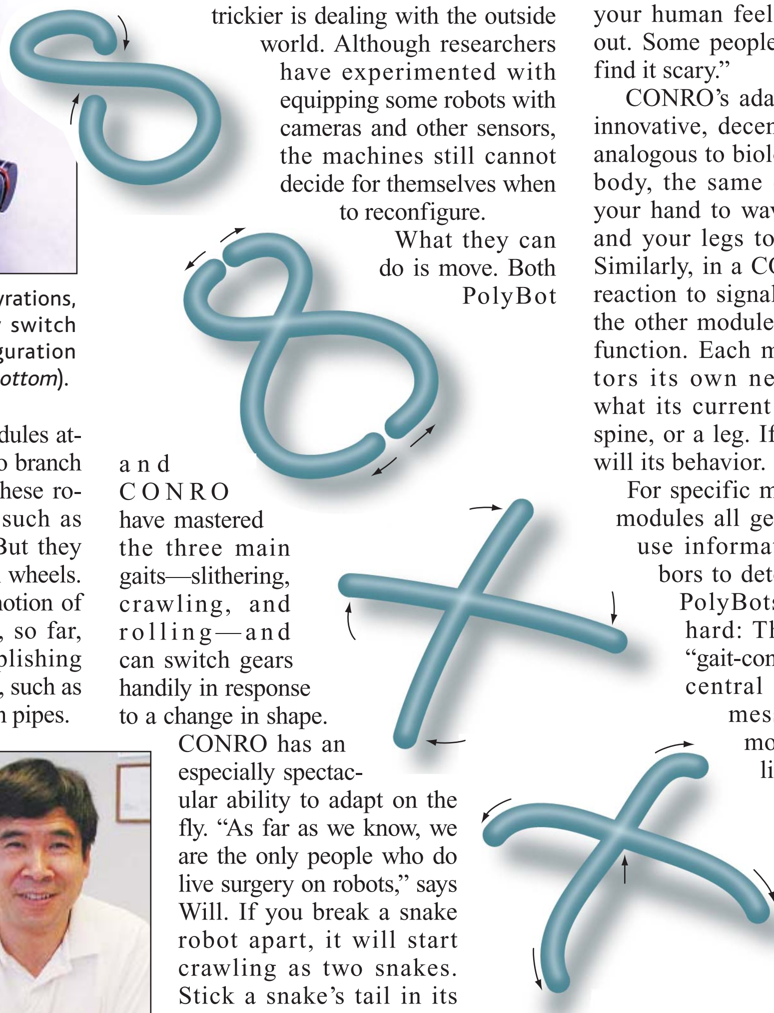
or branched chain, in which the modules attach mostly in sequence but can also branch off if desired. The locomotion of these robots inspires animal metaphors, such as snakes, spiders, and centipedes. But they can also attach end to end and form wheels. More structured than the flowing motion of lattice robots, these "gaits" have, so far, proved more suitable for accomplishing tasks that might have practical value, such as climbing fences or tunneling through pipes.

The most advanced chain robots at present are Yim's PolyBots and the CONRO robots built by Wei-Min Shen and Peter Will of the University of Southern California in Los Angeles. PolyBot and CONRO are comparable in many ways. Mechanically, they are basically hinges: PolyBot modules can bend in one direction, like an elbow, whereas CONRO modules can bend in two. Each module carries its own computer chips and can attach to as many as four neighbors. Both robots have physical latches for "docking" modules together. In a PolyBot the connection is also electronic, whereas CONRO modules communicate via infrared light.

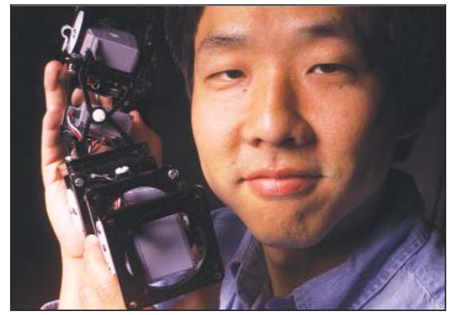


Rapid response. Wei-Min Shen's CONRO robots can adapt on the fly to changes in shape.

Chain robots aren't about to win Olympic medals for speed or agility. Simply attaching two modules—something any 3-year-old could do with ease—takes PolyBot 30 seconds. "Getting them to touch and dock blindly is hard," Yim says. "When you have a chain of several modules together, the positional error for each module builds up as you go down the chain." For that reason, whenever two PolyBot or CONRO modules dock, they have to shine infrared beams at each other for guidance—"flying down the beam," Will calls it. Even trickier is dealing with the outside world. Although researchers have experimented with equipping some robots with cameras and other sensors, the machines still cannot decide for themselves when to reconfigure.



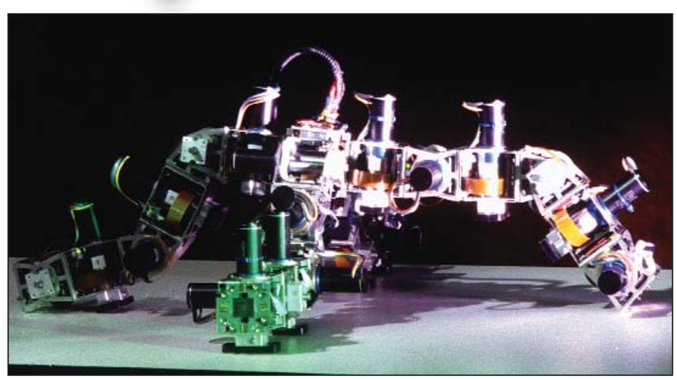
What they can do is move. Both PolyBot and CONRO have mastered the three main gaits—slithering, crawling, and rolling—and can switch gears handily in response to a change in shape. CONRO has an especially spectacular ability to adapt on the fly. "As far as we know, we are the only people who do live surgery on robots," says Will. If you break a snake robot apart, it will start crawling as two snakes. Stick a snake's tail in its mouth, and it will figure out what happened and roll like a tank tread. Finally, if you attach snakes to the sides of a snake, they will realize that they are now legs and change gait accordingly. "The surprise in people's eyes when they see this is amazing," Will says. "When the thing gets up and walks, all your human feelings about robots come out. Some people cheer for it, and others find it scary."



Daredevil 'bots. Yim hopes to send modular robots into a hazardous environment.

CONRO's adaptability comes from an innovative, decentralized control system, analogous to biological hormones. "In the body, the same chemical signal causes your hand to wave, your mouth to open, and your legs to move," explains Shen. Similarly, in a CONRO robot, a module's reaction to signals (or "hormones") from the other modules depends on its current function. Each module constantly monitors its own neighbors to determine what its current role is—say, a head, a spine, or a leg. If its position changes, so will its behavior.

For specific marching orders, CONRO modules all get the same message and use information about their neighbors to determine how to act on it. PolyBots don't have to think as hard: Their modules consult a "gait-control table," usually with a central control, to get unique messages tailored for each module. To slither forward like a snake, for example, the robot's "brain" might tell one module after another to bend to the left, straighten, and then bend to the right, sending a wave of motion down the snake's body. A different cycle



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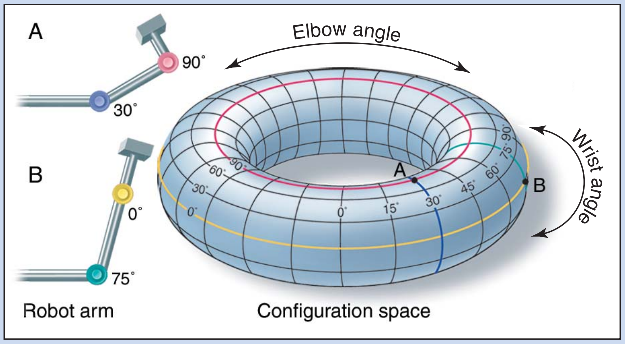
Topologists and Roboticists Explore an 'Inchoate World'

Last month, in a workshop at the Swiss Federal Institute of Technology in Zürich, researchers explored the common ground between the very concrete subject of robotics and the very abstract world of topology; from all reports, they found a lot to talk about. "The conference … was perhaps the most exciting I have ever attended," says Steven LaValle, a roboticist at the University of Illinois, Urbana-Champaign (UIUC).

Topology is involved even in an elementary robotic device, such as an arm with two pivots (see figure). At any time, the configuration of the robot arm can be described by two angles. These run from 0° to 360°, with every different pair of angles corresponding to a different configuration. (However, 0° and 360° are considered to be the same angle.) The angles can be thought of as "latitudes" and "longitudes" on a torus—the topologist's favorite surface. Any movement of the arm corresponds to a path from one place to another in the torus. "What you can achieve is determined by topology," says Daniel Koditschek, an electrical engineer at the University of Michigan, Ann Arbor.



Go configure. Topologists translate movements of a robot's arm (left) into paths through a "configuration space" (right).

Modular robots, of course, contain many more than two moving parts. Every part adds at least one dimension to the "configuration space." Thus, for example, each pose of Mark Yim's 15-module humanoid PolyBot, built at the Palo Alto Research Center in California, corresponds to a point in a 15-dimensional space. Although 15 dimensions might be baffling to most people, they pose no difficulty for topologists, who are used to spaces with many dimensions.

In Zürich, topologists Robert Ghrist of UIUC and Aaron Abrams of the University of Georgia in Athens showed how the topology of configuration spaces might simplify the movement of lattice robots, whose movements can be described by discrete translations. (Their work does not apply to robots with continuous motions, such as Yim's PolyBots.)

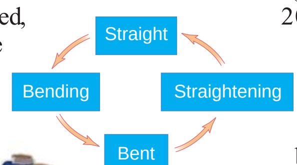
If you want a lattice robot to morph from, say, a wheel to a centipede, your best bet now is a sort of blind flailing around through configuration space that takes you from wheel-like shapes to centipede-like shapes. But Ghrist and Abrams have devised a path-shortening algorithm that shrinks the random stagger down to the shortest possible path. Their idea exploits the possibility of moving cubes simultaneously whenever they don't interfere with each other. It also uses a deep theorem by French topologist Mikhael Gromov—proved in a completely different context—to show that you never get hung up on an intermediate path that appears shortest but isn't. In their algorithm, says Ghrist, "there's no deity instructing every module where to go. You just optimize the path locally, and then you pull out this abstract theorem that gives you the global result—bam!" According to Gregory Chirikjian, a roboticist at Johns Hopkins University in Baltimore, "until now, the people who worked on modular self-reconfigurable robots have established their own algorithms, whereas the Ghrist and Abrams approach is more of a blanket approach that has potential to be applied to any of these [lattice] systems."

"That's where mathematicians can really contribute something," Ghrist says. "The mind frame of roboticists is to work only on the system they have in the lab." But mathematicians have the luxury of looking for a broader theory. So far, the details of such a theory are sketchy. "Reconfigurable systems are still an inchoate world," says Koditschek. But if the work of Ghrist and Abrams provides any clue, some of the answers for navigating that world may already be lurking in topology books. **–D.M.**

of bending and straightening makes the tank-tread configuration roll (see figure below).

Stepping out

So far, no modular robot has stepped, rolled, or slithered out of the laboratory to prove its mettle in the real world. But that may change soon. Recently, Yim's group was included in a 5-year grant from NASA to explore an abandoned mine where biologists have found bacteria thriving in ultra-acidic water (*Science*, 10 March 2000, p. 1731). For humans, the site varies from hazardous to completely inaccessible. "Some parts would require being completely submerged," Yim says. "It's not clear if swimming, floating, or crawling on the bottom would be best. It is likely that different gaits would be required." In other words, it's a perfect job for a reconfigurable robot.



Treading lightly. In "wheel" configuration, Yim's PolyBots move by consulting a gait-control table that cycles each module through four different states.

If the PolyBots succeed in bringing back microbe samples, biologists could learn more about one of the most bizarre ecosystems on Earth. In the future, modular robots may also be used to build power stations in space (a project the CONRO team is working on) or to conduct search-and-rescue operations. Eventually, Yim would like to see one in every garage. "Our ultimate vision is what we call a 'bucket of stuff,' " Yim says. "It will take decades, but hopefully not centuries. You go up to this bucket of stuff and say, 'Do the dishes. Change the oil in my car.' It climbs out and puts itself together in the appropriate shape. It's easy to command, it understands the environment, and it does the dishes, too."

–DANA MACKENZIE

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More information about modular robots, along with photographs and video clips, can be found at the research teams' Web pages: Modular Robotics at PARC, www2.parc.com/spl/projects/modrobots; Dartmouth Robotics Lab, www.cs.dartmouth.edu/~robotlab; and the USC Polymorphic Robots Lab, www.isi.edu/robots.