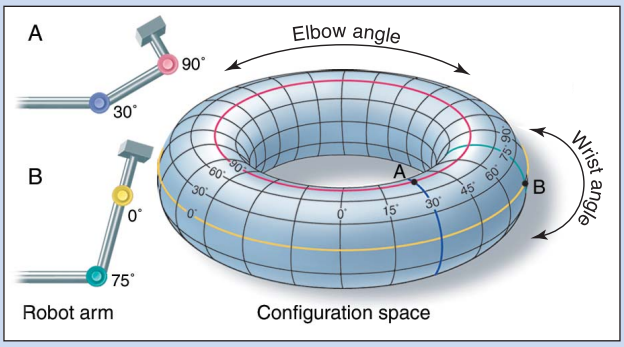
Topologists and Roboticists Explore an 'Inchoate World'

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."

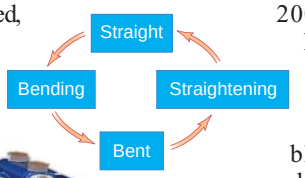
"That's where mathematicians can really contribute something," Ghrist says. "The mind frame of roboticists is to work only on the system they have in the lab." But mathematicians have the luxury of looking for a broader theory. So far, the details of such a theory are sketchy. "Reconfigurable systems 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."

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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.

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