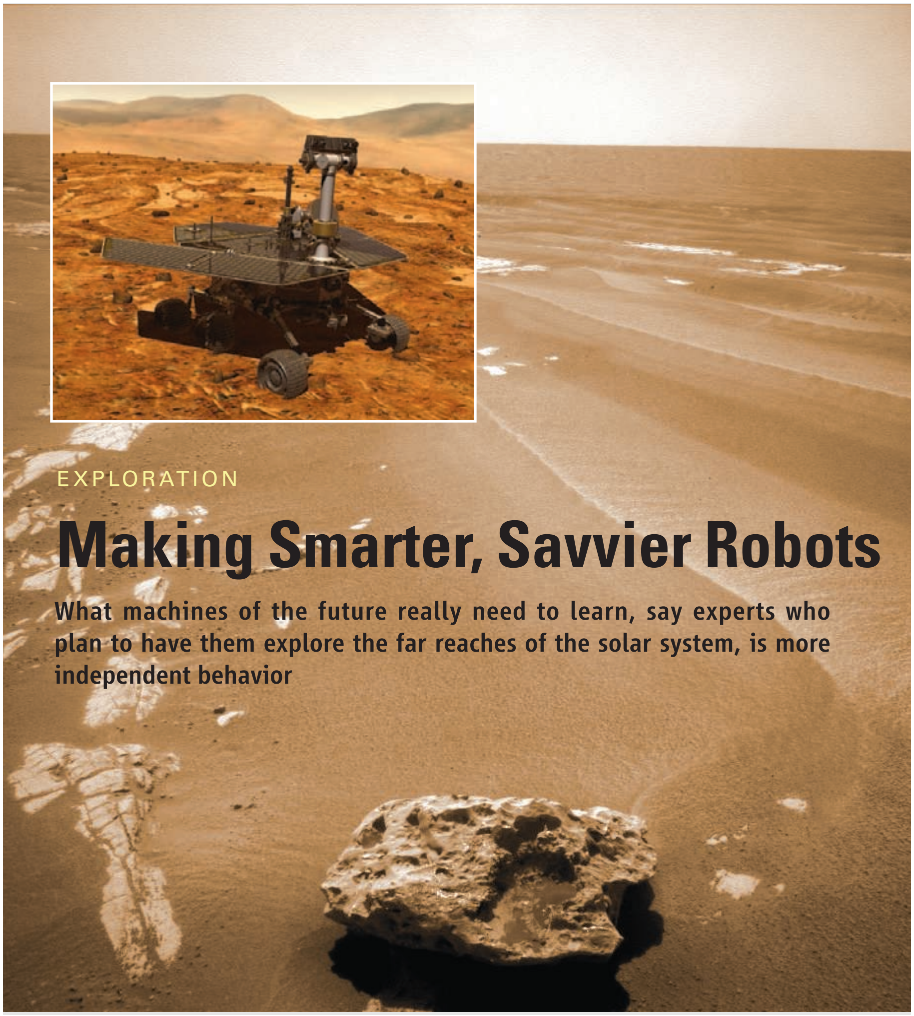

Which rock? On Mars, the robot Opportunity needed some human help to spot this meteorite.

EXPLORATION

Making Smarter, Savvier Robots

What machines of the future really need to learn, say experts who plan to have them explore the far reaches of the solar system, is more independent behavior

On 18 July 2009, the Mars rover Opportunity was scooting toward a distant martian crater when it spied an anomaly amid the ripples of red soil: a bruise-colored rock the size of a watermelon. It looked like a meteorite—potential evidence that the ancient atmosphere of Mars, like today's, was thin enough for such rocks to pass through without exploding.

The strange rock was exactly the kind of thing NASA sent Opportunity to find. But because Mars and Earth are millions of kilometers apart and rotate out of sync, NASA scientists didn't see it until Opportunity had driven 200 meters beyond it. They hit reverse but had to wait three full days for Opportunity to backtrack to the spot.

The researchers got their meteorite. But the near miss—and the frustrating delay—underscored a defect of current exploration technology: Basically, robots are pretty dumb. Now scientists across the world are striving to change that by developing intelligent robots that can circumvent danger and spot enticing features on their own.

Hundreds of scientists, mostly at NASA and at universities, are working on improving robot explorers. But only a few dozen specialize in developing robots with true, high-level independence. The main NASA lab, at the Jet Propulsion Laboratory (JPL) in Pasadena, California, has a dozen people and a budget of about $4 million—a lower figure than in the past. But scientists there see promising signs. For one, NASA chief technologist Robert Braun has begun a new, general Space Technology Program that lists "machine intelligence" as one thrust.

"There are compelling reasons to send humans into deep space," says Steve Chien, who develops autonomous space systems for JPL. "A smart scientist can do much better experiments. But it's very expensive. By making the spacecraft much smarter, we can reduce the gap between human exploration and robotic exploration."

Where to go

Robots with an IQ boost will be essential for fully exploring some locations in the solar system—including hostile spots. On Venus, for example, 450°C surface temperatures and pressures comparable to those a kilometer deep in the ocean will destroy the onboard computers of any lander within 5 hours, tops. To get anything done, the lander will need to perform experiments, such as sampling soil, without human input.

Rendezvous missions with comets or asteroids and landings on distant moons would also benefit from more autonomous robots, researchers say. On Saturn's moon Titan, radio waves carrying scientists' instructions take 90 minutes to arrive from Earth. Yet a probe flying through Titan's atmosphere would have to negotiate hazards in real time, notes Wolfgang Fink, a computer scientist working at the California Institute of Technology and the University of Arizona. "If it's about to fly into a mountain range, it can't say, 'I'm flying into a mountain range. Please advise,' and wait 1½ hours."

Scientists also hope that greater intelligence will make robots more efficient, improving their "energy storage, memory, computational throughput, communication downlink bandwidth, and heating and cooling capability," says Larry Matthies, a computer scientist at JPL. Opportunity (and its companion on Mars, Spirit) travel at such pokey paces—28 kilometers total in 6 years—partly because they rely on humans to spot dangerously loose sand or steep slopes. A smarter robot could zip around obstacles by itself and travel up to 10 times as far each day, Matthies estimates. And the more work the rover can do alone, the more time it will have to collect good samples.

Recipes for "eureka"

In December and January, NASA took the first steps toward making a spacecraft autonomous when it uploaded four pieces of software to Opportunity. Tara Estlin, a senior engineer at JPL, explains that, with the new software, "scientists can give us a single property or combination of properties—the largest rock you can find, or the darkest rock," and Opportunity will zero in on them. In March, the software passed its first test by discovering, all on its own, an angular, football-size rock—ejected from a nearby impact crater—in a field of rounder boulders. (Paradoxically, though, Estlin's team still has to tell the rover a day in advance when to be autonomous and when not to.)

Earth-based systems have already demonstrated significant independence, within limits. Chien works on the Earth Observing

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Sensorweb, a group of half a dozen NASA satellites that monitor Earth's atmosphere. Some scan large sections of Earth's surface and pick out a flood or a volcanic plume from space. They beam the data to ground-based computers, which in turn direct higher-resolution satellites to focus on the event—all without human input. Chien hopes to expand the work to other planets. But the instruments can spot only a short list of predefined events; they cannot find anything interesting or new on their own. Asked whether the system could shift its attention on its own between the two most notable geological events of the past few months, the Eyjafjallajökull volcano eruption in March and the BP oil slick in the Gulf of Mexico in April, Chien groans: "I wish, I wish."

To solve problems of data filtering and interpretation, some researchers are working to cultivate a robot's taste for the unusual. Sometimes scientists want to study the most representative feature around, but more often they are intrigued by anomalies. "If the whole desert is smooth and one area is rough, that's interesting," says Chien. "If the whole desert is rough and one area is smooth, that's interesting. If you really don't know about the environment, you have to fall back on something like outliers."

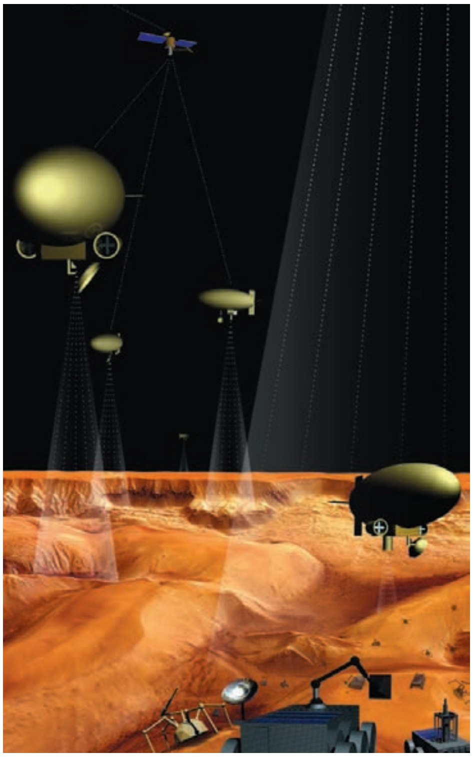
Patrick McGuire, a computer scientist and geologist at the University of Chicago in Illinois, has developed a simple setup that can detect novel features in a landscape. A netbook laptop hooked up to a cell phone with a camera snaps a picture and compares its colors, textures, and shapes with other pictures in its memory. The computer then compresses the image with an algorithm. If the compression process is very similar to that of an earlier image, the computer concludes that the new image doesn't contain much novel information and throws it out.

McGuire has tested this system at rock outcrops in Utah and Spain that resemble the barren landscape a probe might encounter on a distant planet. He reported late last year that the software performed equally well in both locations. In one case, the software immediately recognized a patch of lichen as novel—and then, with the next picture, threw out an image of lichen on another rock as too similar to bother remembering, demonstrating that it is a quick study.

Curious future

Some scientists, including Fink, say better programming alone won't turn robots into independent explorers. "In planetary exploration, you're in for surprises," Fink argues, "and you will not always have a rule" on how to proceed. He dreams of robots that can experiment with their own "neural networks"—their internal architectures for taking inputs, processing information, and producing outputs—and can, like humans, form their own rules for exploring.

McGuire says certain architectures have advantages in different applications. With a so-called Hopfield neural network, for example, a computer can recognize an entire picture stored in memory after seeing only a fraction. Many robots come equipped with multiple lenses and cameras that take pictures on different scales, so the capability to tag small snippets as familiar would help make the robot more efficient in selecting which scenes to shoot or not shoot.



Mechanized teamwork. Caltech's Wolfgang Fink foresees robots exploring in tiered ranks.

CREDIT: DR. WOLFGANG FINK AND WAYNE WALLER, VISUAL AND AUTONOMOUS EXPLORATION SYSTEMS RESEARCH LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY

Even more ambitiously, Fink is developing systems to give robots freedom to change their logical architecture—essentially to "rewire" their brains. A robot might make a rule more complicated or simpler by adding or cutting steps, or combining the binary code of two rules and trying out their "offspring." If the new rules worked well, it adds them to its problem-solving repertoire.

Fink published a paper last year on a self-configuring neural network to sort odd numbers from even numbers. Working with numbers 24 bits long—in the tens of millions in decimal notation—the network hit upon the solution (look at the final digit) with no guidance. And by focusing on one bit, the computer freed 23 other bits for different tasks. In other contexts, such self-configuring networks have helped scientists design circuits and new drugs.

Ultimately, Fink says, he hopes to instill something like curiosity in robots. That kind of programming would go far beyond algorithms his team has developed to help robots calculate the best angle to stretch out an arm to grasp an object or scoop soil. "We're after the *intent* to deploy the arm. How does the spacecraft know where it wants to dig? This is of interest to me."

The first test?

Smart, curious robot explorers wouldn't have to work alone. Fink envisions a multitier scheme of robots with satellites, blimps or balloons, and platoons of ground rovers. An intelligent satellite would direct the blimps to canvass certain areas. The blimps, in turn, would direct surface rovers to scout hydrothermal vents or rappel down cliff faces with a cable. Based on feedback between each tier, the satellite would decide which sites to concentrate on and how best to deploy the other machines. It would judge when to risk sending rovers into dangerous areas like active volcanoes, and when to stop collecting data, Fink says. "A spacecraft could even leave a place and tell you, 'There's nothing interesting here. I'll go somewhere else and I'll tell you when I get there.' " Fink and his team have started building a test site in Arizona with rovers, boats, and blimps for field experiments with rudimentary versions of such robotic expeditions.

Chien imagines a different sort of teamwork: human explorers with fast-learning robot assistants. A group led by David Akin at the University of Maryland, College Park, is testing a golf cart–size three-wheeled rover, named Raven, to help astronauts explore planets. On tricky terrain such as loose soil or slopes, Akin says, the astronaut can simply say, "Follow my path," and the robot will.

President Barack Obama's stated goals of sending humans to an asteroid in the 2020s and to Mars in the 2030s could help foster such partnerships. Chien says human-and-robot teams could do a better job together than either could alone. Humans would make plans and be in charge, while robots slogged through the important but routine technician work. "It's the classic apprentice thing," Chien says. "You want the biggest brainpower worrying about the biggest problems."

–SAM KEAN

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