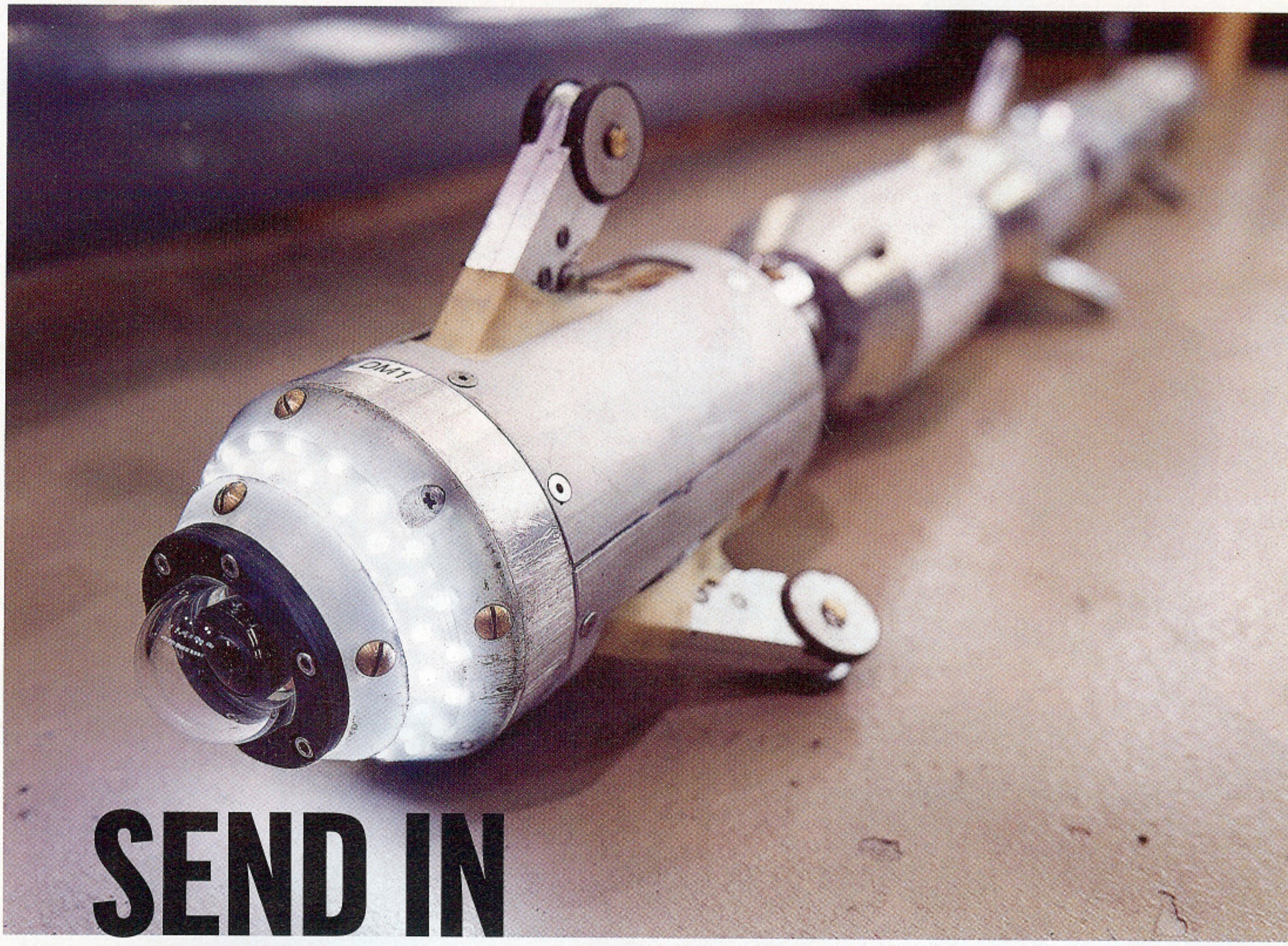


SEND IN THE ROBOTS!

A new generation of industrial robots can strip paint off ship hulls, inspect buried gas mains, cross trackless deserts, and even mow the grass at your local golf course. By Stuart F. Brown

Explorer, a pipe-crawling robot, is built to snake its way through gas pipelines looking for leaks.

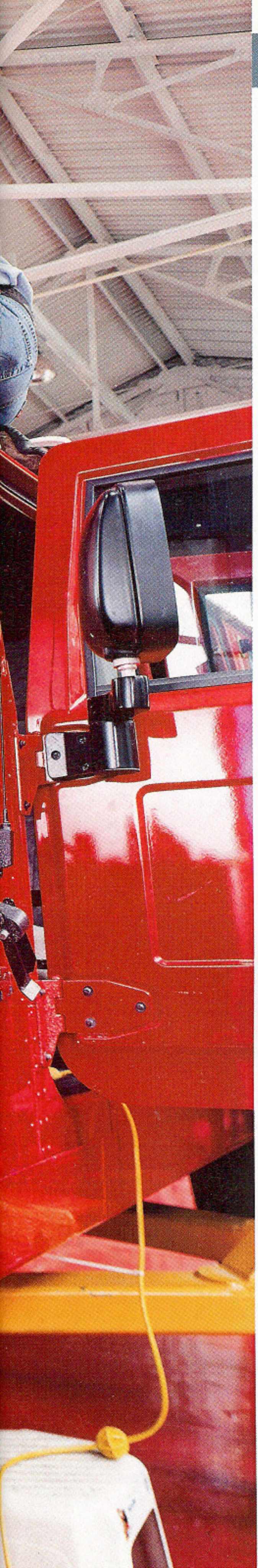
THE FIRST GREAT WAVE OF INDUSTRIAL robots began appearing in factories in the 1980s. Most of them were stationary armlike machines assigned to the "three D's"—dull, dirty, or dangerous jobs, such as stuffing chips into circuitboards, spray painting, or spot welding. Workers who labor alongside these gizmos have gradually come to think of them as machine tools rather than automatons that can, at least in a limited way, act for themselves.

But the robot world is changing fast. Helped by the tumbling price of computing power and by navigation technologies such as the global positioning system (GPS), today's industrial robots can move

PHOTOGRAPHS BY BERND AUERS

around in the world. Instead of working on tasks presented to them by moving conveyors, mobile robots are going where the work needs doing.

Consumers are already warming to robots that vacuum floors and mow lawns. Meanwhile university researchers are developing industrial robots that go beyond the three D's to jobs that require significant ability to make independent decisions. They include inspecting an underground pipeline as natural gas flows though it, navigating rugged desert terrain without a driver, and even walking on water while testing for pollutants. For a glimpse at what's coming in mobile robotics, FORTUNE visited a place that's always hopping with wild ideas: the Robotics Institute at Carnegie Mellon University in Pittsburgh.



OFFROAD WARRIOR

Red Whittaker, the founder of CMU's Field Robotics Center, is a hyperkinetic, success-oriented guy who's been building mobile robots that work in unpredictable environments since 1984. Whittaker's attention is currently focused on "driverless desert racing." His Red Team is making an all-out effort to win the Pentagon's second Grand Challenge, a robot vehicle race across the Mojave Desert sponsored by the Defense Advanced Research Projects Agency (DARPA).

Last March the Red Team entered a robotized, 1986-vintage military Humvee, nicknamed Sandstorm, in the first DARPA challenge race. Sandstorm managed to cross only 7.4 miles of dusty desert before it lost traction and got stuck in rough terrain. Although the Red Team made it farther than any of the other dozen competitors, DARPA's $1 million prize went unclaimed.

Whittaker is taking no chances this time. On Oct. 8 the Red Team will run two robot Hummers in the second Grand Challenge: Sandstorm and a brand-new civilian Hummer called Highlander. Each truck carries a stack of computers, sensors, laser scanners, and other equipment that enables them to navigate desert terrain without human guidance of any kind. A new ultrastable sensor platform allows Highlander to navigate bumpy terrain like a cheetah that can keep its head still while bounding across the savannah in pursuit of prey.

The two vehicles present very different engineering challenges. "If you're going to automate an old-style Hummer, you'd better be into actuators that push on pedals and linkages, because the way you control it is going to be mechanical," explains Whittaker. "The new model has electronic controls for the engine, transmission, and brakes. That lets us just tap into the software to control the vehicle."

Carnegie Mellon University's robotic Hummer flipped in road trials before the first DARPA race.

DARPA has increased the prize this time to $2 million, which is expected to attract a lot of inventive talent. And the U.S. military badly wants driverless vehicles. If the Grand Challenge produces a viable robotic truck, DARPA will see an amazing return on its investment.

A few days before the event, the 20 teams selected to run in this year's race will be given a starting point in the southwestern U.S. The actual 175-mile route will be disclosed just hours before start time. In order to win, a robot vehicle must cover the ground in less than ten hours.

Whittaker excels at recruiting student volunteers, who have been kept busy in recent months compiling digital maps of large desert areas in California, Nevada, and New Mexico. They are using aerial data from public and commercial sources, along with imagery that they collect themselves by driving cars through the desert. "This is one of our secret weapons for 2005," Whittaker says. "We've compiled tens of terabytes of geographic data, so we're no longer planning at the level of MapQuest."

Carnegie Mellon's Red Whittaker (center) on a newly robotized Humvee designed to compete in the next trans-Mojave race.

The robot paint stripper's spinning nozzle shoots water at pressures as high as 50,000 pounds per square inch.

WET WORK

The traditional way to remove old paint from a ship's hull involves erecting a scaffold from which a bunch of guys blast garnet grit propelled by compressed air. It's a filthy, dangerous task: Workers risk falling off the scaffolding, and the process spews toxic dust downwind.

Seeking a cleaner way to get the job done, Ultrastrip Systems in Stuart, Fla., developed a high-pressure waterjet nozzle equipped with a vacuum hose that carried away the paint dust and water for filtering and disposal. But the system was a tough sell because it worked only half as fast as grit blasting.

To reduce the labor involved, Ultrastrip decided to automate the process by building a self-propelled stripping head. Roboticists at Carnegie Mellon helped the company develop the M3500 stripping robot, which moves on steerable rubber wheels and features powerful permanent magnets that cling to the ship's hull.

Efforts to equip the robot with a vision system to make it autonomous proved overly complicated in practice, so the device is run by a joystick-wielding worker. The spinning waterjet nozzle shoots water at pressures as high as 50,000 pounds per square inch. (A pair of cables secure the robot as a safety backup while it's working on a ship.) The nozzle can be raised or lowered to navigate past welds and other obstacles. Water hits the hull hard enough to warm its surface, which dries quickly after the robot passes by.

"Each robot replaces about ten men, and the quality of the stripped surface is actually superior to what you get with grit blasting," claims Ultrastrip CEO Stephen Johnson.

Ultrastrip has sold seven of the $800,000 systems, Johnson says. Ultrastrip robots keep Carnival Cruise Lines ships looking spiffy. And another robot stripper was used to work on the guided-missile destroyer USS *Cole* after it was damaged in a terrorist attack in Aden, Yemen, in 2000.

Ultrastrip's robot (next to the worker on the left) strips a hull. Attached hoses supply water and remove waste.

ULTRASTRIP

A robotized version of the Toro Groundsmaster 3500D grass mower. Among the challenges it must face: staying oriented when golf course trees block signals for its GPS system.

MOWING ALONE

Let's say you've got an inkling that customers will eventually want your products to work without a human being in charge. The folks at Toro Co., a maker of landscape-maintenance equipment, anticipate future demand for robotic lawn mowers.

"With the way technology is advancing, we know that one of these days robots will be mowing golf courses," says CEO Kendrick Melrose. "We run our research and development with a ten- or 20-year view of what we think our industry is going to be like, and it's clear that customers are looking for lower labor costs."

Toro noodles future ideas at its Center for Advanced Turf Technology, directed by mechanical engineer Dana Lonn. Several years ago Lonn asked scientists at CMU, including associate research professor Sanjiv Singh, to help develop an autonomous mower with advanced vision and navigation capabilities. The machine they selected to robotize was a Toro Groundsmaster 3500D, a heavy-duty mower used on golf courses and playing fields.

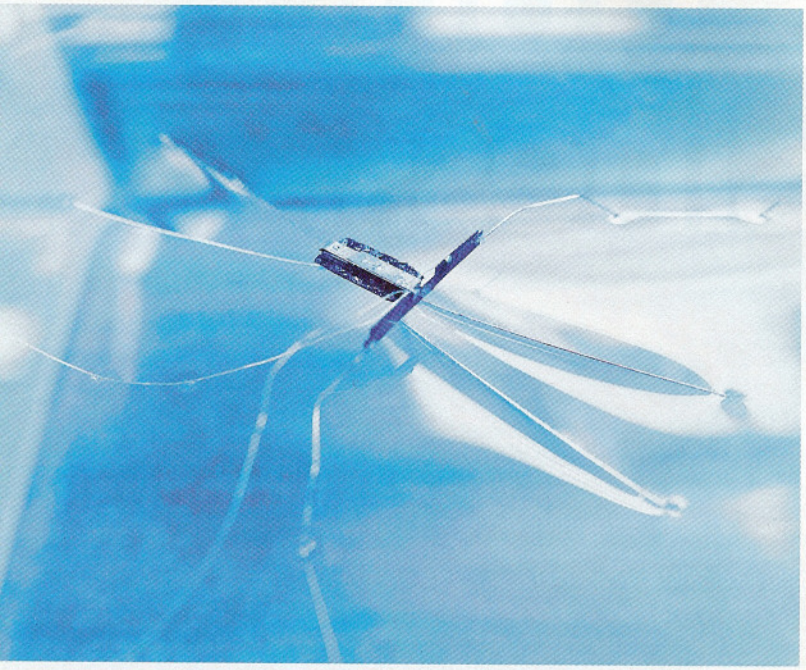
Robotic lawn mowers face two fundamental challenges, says Lonn: precise positioning (knowing where you are) and obstacle detection (so that you don't run into things.) Affordable GPS receivers allow Toro's prototype mower to navigate quite well on open greens and fields. But the machine can't always receive signals from GPS satellites when it passes beneath overhanging tree limbs and other obstacles.

In these situations the mower needs a backup navigation aid to stay on course. One possibility is an inertial navigation system, or INS, which uses multiple gyroscopes as sensors to determine location. Many airplanes currently feature high-priced INS systems, but the booming field of silicon micro-electromechanical systems, or MEMS, holds more promise for engineers on a beer budget. Tiny, cheap MEMS gyroscopes are widely used in automobile stability-control systems. GPS manufacturers are already working on building them into low-cost INS products.

Another possibility is to equip the mower with a laser that bounces light off reflectors located in the work area. Through mathematical triangulation—the same method GPS systems use—the laser system could take over navigation chores when the mower's GPS antenna can't see the sky. One way or the other, Lonn thinks it won't be long before his navigation problems are solved.

Designing reliable video vision systems is a whole different challenge. The basic principle? Green is good. "We were working from the idea that if things are good in front of the machine, they are generally green," says Lonn. "And if an object isn't green, we need to look at it more closely." But green comes in many shades and textures: You don't want your mower to chow that herbaceous border next to the fairway or try to mow the Astroturf on the clubhouse deck.

Toro's mower also needs to see objects as small as a golf ball. But the cameras struggled with certain sun angles and with effects such as light glinting from dewdrops. So the researchers tried an industrial laser scanner mounted on a platform that sweeps it left and right like a searchlight. Laser scanners are expensive but do a good job of recognizing obstacles at slow speeds. And given that human labor cost drives the current demand for fast mowers, speed may not be an issue for robot mowers. "The economics of the machine change when it's unmanned," says Lonn. "Going slower could be fine."



LEARNING FROM LIZARDS

Geckos and their amazingly sticky feet are all the rage in biomimetics, the science of emulating successful adaptations from the world of plants and animals. That explains why a New Caledonian gecko, named Pinotto, is ensconced in a glass terrarium in Metin Sitti's office at the Robotics Institute.

Sitti was born in Turkey and educated in Japan. The 33-year-old assistant professor and his students are trying to mold synthetic gecko-foot material that could give small robots the "dry adhesion" needed to climb around on smooth surfaces.

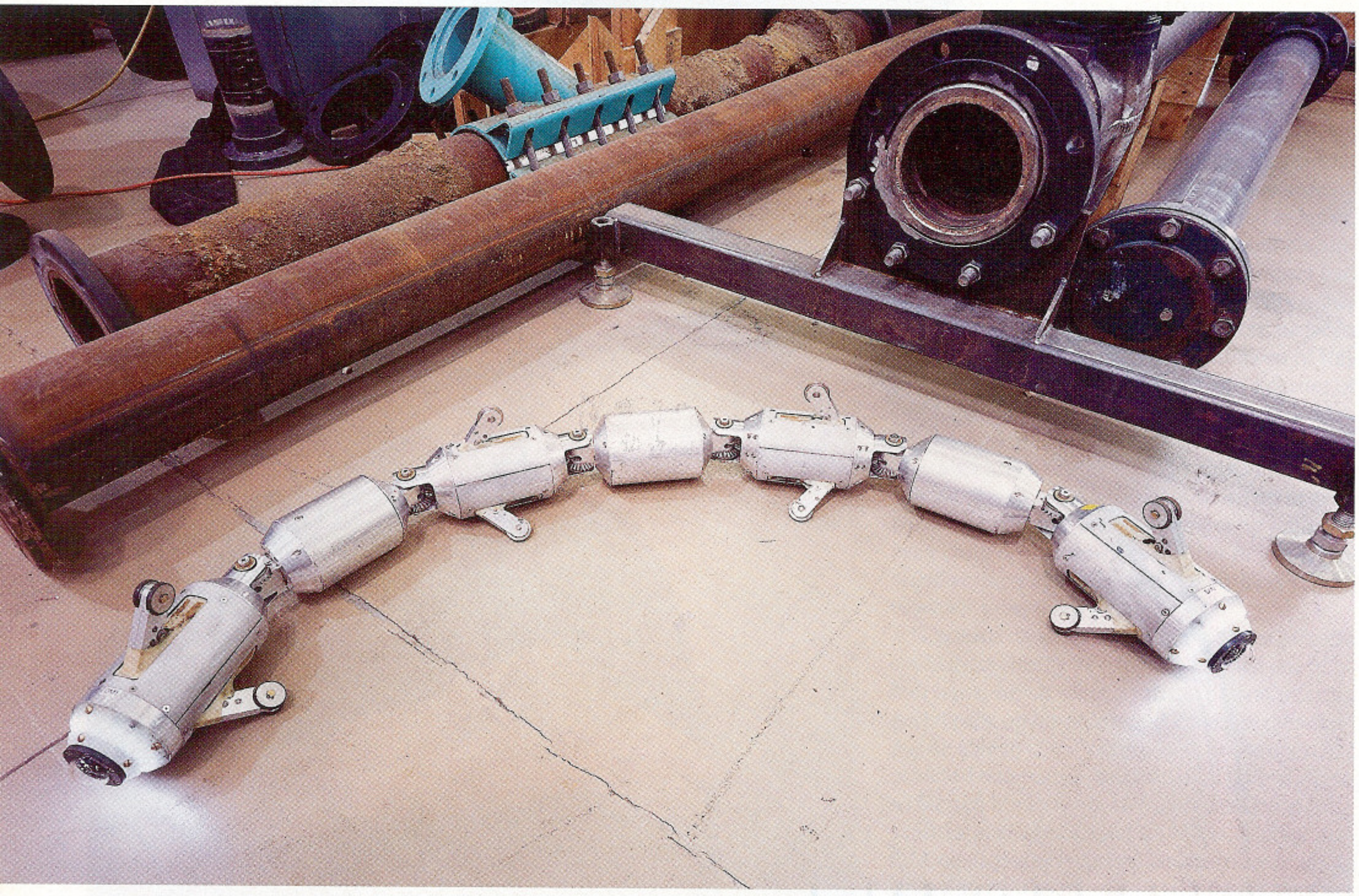
Geckos' toes are covered with millions of tiny hairs. The end of each hair splits into a cluster of even finer hairs, rather like a microscopic broom. The sum of all these hairs is a tremendous surface area that allows geckos to exploit so-called van der Waals attractive forces between materials at the molecular level to scamper up walls and even cling upside down to a sheet of glass. Researchers have identified only one surface, Teflon, to which geckos can't cling.

Scientists have calculated that a gecko's weight could theoretically be supported by just one of its foot hairs, which suggests that a person wearing gecko pads on his palms and knees might someday be able to clamber up a wall. Sitti's team has achieved one-tenth the adhesion of the real thing so far and hopes for better performance soon.

Sitti is also interested in repulsion, another useful force that allows certain insects to scoot across calm water without breaking the liquid's surface tension. Sitti has fabricated a tiny robotic water strider whose six wire legs are coated with a water-repelling plastic. Three piezoelectric actuators propel its center legs in an elliptical motion, like a rowboat's oars.

Sitti's water-striding robot weighs less than a gram and draws power from ultrathin electrical wires. Thin-film polymer batteries will let the next-generation strider run on its own. Sitti predicts that robotic water insects equipped with miniature biochemical sensors could someday work as environmental monitors.

Top: Metin Sitti with a gecko, the lizard whose adhesive feet he is trying to emulate for climbing robots. Left: Sitti's robotic water strider can walk on calm water.



Explorer has wide-angle videocameras on both ends. It rolls on flipperlike legs that press against the inner walls of a gas pipe.

INNER SPACE

As America's buried-pipe infrastructure ages, utility companies face the challenge of locating and fixing a growing number of underground leaks. Pinpointing a leak can be surprisingly difficult, which is why utilities must frequently dig multiple holes in search of a single problem.

"Traditionally the gas companies have waited for you to call and say, 'I smell gas.' Then they come out and check for a leak," says Hagen Schempf, a principal systems scientist at CMU. Suppliers of natural gas in the Northeast concluded that their maintenance dollars would stretch further if they did more preventive maintenance and less emergency response. That's the idea behind Explorer, a segmented pipe-inspecting robot that looks like a string of metal sausages.

Explorer was developed by a CMU engineering team led by Schempf. Funding for the project comes from the Northeast Gas Consortium, NASA, and the Department of Energy. "The idea is to prevent leaks by inspecting gas mains before they have problems," says Schempf, who predicts that utilities will hire specialized service companies to investigate buried mains using production versions of his robotic pipe crawler. (The service contractors are likely to charge by the foot, he says.)

Thanks to its multiple joints, the 45-pound Explorer has the impressive ability to make 90-degree turns in the six- and eight-inch gas mains through which it crawls. The battery-powered robot has wide-angle videocameras at both ends. It propels itself using motorized rollers attached to flipper-like legs that push against the inner walls of a pipe.

In a field test last summer in Yonkers, N.Y., Con Edison successfully ran Explorer down several hundred feet of cast-iron gas main dating to the 1890s. As the robot crawled through the pipe at a speed of about four inches per second, an operator in a nearby van watched video imagery of the pipe's interior that was wirelessly transmitted from Explorer's cameras.

Future versions of the automaton will feature a sophisticated evaluation sensor to detect corrosion or cracks that might not be apparent in video images. F

Future versions of Explorer will be equipped with a sensor that can detect corrosion or cracks in a gas main that might not be apparent in video images.

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