ROBOTS IN EXTREME ENVIRONMENTS

Robots Take the Field

Going where no human dares to go, today's robots are successfully gearing up for exploration in the most dangerous of conditions—but there is much more work to be done.

ASME
SETTING THE STANDARD



Axel, an autonomous NASA/JPL robot, can be combined with another Axel to create DuAxel, allowing one Axel to rappel down steep planetary terrain while the other stays above to anchor the line.

NASA/JPL

Robots have been put to work to take people out of hazardous situations, from inspecting wind turbines to cleaning chemical tanks. But increasingly, they are operating in places that are hazardous to the robot itself.

Robots have worked for years in industry and agriculture, where the ability to stand up to heat, dust, and vibration is critical. But as humans look further and further afield to find resources or conduct research, robots are being sent to the bottom of the ocean, to other planets, and into caves, damaged nuclear reactors, collapsed buildings, and lava fields—extreme environments that bring new and complex engineering challenges.

As one might expect, robotics technologies, from mobility and hardened materials to sensors and perception systems, have advanced significantly in recent years. As a result, it is now possible to "assemble" at least the base of powerful robot platforms, rather than invent them from scratch. For example, the Collaborative SubTerranean Autonomous Robots (CoSTAR) team in the DARPA Subterraneous challenge, designed a robotic team to work in challenging underground environments. This system brings together the Boston Dynamics Spot dog-like robot and NeBula, a modular software system designed by NASA's Jet Propulsion Laboratory (JPL), which enables various types of robots to work together autonomously in extreme environments, from abandoned mines to the surface of the moon.

"In the past, we could talk about a lot of these difficult challenges, but you figured you would need a decade of research to get them done," says Joel Burdick, part of the CoSTAR team, who is a professor of mechanical and civil engineering at Caltech and a scientist at NASA's Jet Propulsion Laboratory. "Now, we are reaching the point where you have a very good chance of succeeding with those crazy missions by properly integrating and extending today's technology."

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ROBOTS ON THEIR OWN

Over the years, engineers have come up with innovative ways to reach and work in extreme environments, with tracked, wheeled, flying, and swimming robots—and robots that move like snakes, dogs, and humans—to traverse complicated terrain. And the search for new approaches appears to be never-ending, as humans continue to expand their activities. In 2021, for example, researchers tested an autonomous, soft-bodied robot that swims like a fish in the Pacific's 35,000-foot-deep Marianas Trench. And NASA is exploring the use of a wind-up clockwork rover that would operate without electronics. Instead, it would use a wind turbine that tightens a spring to power its movement on Venus, where 840° Fahrenheit temperatures and air pressure that is 92 times that of Earth "can turn lead into a puddle and crush a nuclear-powered submarine with ease," according to the agency.

In recent years, increasingly powerful autonomy capabilities have opened up new possibilities for robots in extreme environments. For example, scientists sometimes need to measure the carbon dioxide that's emitted by volcanoes, which can tell them a lot about an eruption's nature and possible future eruptions. This has traditionally been done by sending people wearing protective gear to gather gas samples, which is both dangerous and limited in its effectiveness. More traditional drones provide a logical alternative, but human-operated vehicles often fail in that environment due to sudden updrafts, damage from sulfuric acid, and a lack of visibility due to ash and steam.

At the University of New Mexico, researchers have been working on an alternative—groups of flying robots that work together autonomously to gather gas samples, known collectively as VolCAN (Volcano Co-robot Adaptive Natural algorithms). The VolCAN team designed and built their own quadcopter drones using electric motors (because gasoline engine emissions tend to contaminate samples) that are capable of carrying CO_2 sensors on one-hour flights. Taking measurements often means carrying equipment to remote areas on foot, so these drones can be quickly broken down and carried in backpacks. So too can their lithium ion batteries, in order to comply with airline luggage rules that limit packed batteries to less than 100 milliamp hours of capacity each.



Above: Team CoSTAR, led by NASA's JPL, uses autonomous robots with diverse methods of movement to explore the complex underground environments. One type of CoSTAR robot, NeBula-Spot, walks on four legs to explore hard-to-access locations.

The VolCAN algorithms allow the drones to essentially work as one instrument—"a physically disconnected and therefore reconfigurable sensor," according to Matthew Fricke, an assistant research professor in UNM's Computer Science Department. They map the positions of plumes of the invisible gas coming from the ground and then descend through those plumes to capture physical samples for further analysis—autonomously, operating perhaps half a kilometer from the base station.

The approach is "bio-inspired"—that is, it mimics the strategies of social insects in that not all individual units are expected to survive. "If a drone is lost, the others just adapt to the loss of that drone and keep on going," says Fricke. "The philosophy is to not over-engineer things so they always survive. Instead, make enough of them and make them cheaply so that some can be lost." To that end, the drones were designed to use readily available commodity components and 3D-printed parts, allowing them to be easily repaired or relatively cheap to replace.

The VolCAN software has been successfully tested at a New Mexico volcano that constantly emits CO_2, but it is still "largely theoretical," says Fricke. However, in December 2021, the VolCAN team took their system to a new volcano in the Canary Islands that was in full eruption and had already destroyed more than a thousand buildings. They found themselves working in conditions where winds reached 40 mph, drones had to operate out of sight and without contact with the base, and the team had to abruptly switch launch sites when the first was overrun with lava. In addition, one of the three drones brought along was lost by the airline that flew the team, forcing an adjustment in the search patterns used by the drones.

Nevertheless, the VolCAN robots proved to be a dual success. "We were excited that the drones and the algorithms worked," says Fricke. But the effort was also the first time researchers have been able to collect uncontaminated CO_2 gases in an active eruption. "We were really happy that we were able to get a brand new scientific result as a result of those drones," he says.

EXTREME COMPETITIONS

For years, the Defense Advanced Research Projects Agency (DARPA) has held robotics competitions that have become a focal point for innovation in the field. These have included a series of events in which robots navigated various subterranean environments, where the rigors of the terrain and difficulties in communicating have prompted competitors to turn to autonomous operations.

The most recent of these events was held in 2021 in a limestone cavern beneath Louisville that DARPA modified to resemble tunnel, cave, and underground urban environments. Here, robots had to find their way through narrow, dark passages and large "rooms" to identify and locate objects such as a backpack, a rope, or a mannequin. The winner—created by a team

NASA/JPL-CALTECH

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of universities and companies—was a group of robots called CERBERUS.

CERBERUS consists of various flying drone robots and ANYmal quadruped robots designed to operate in challenging environments. Using multi-modal simultaneous localization and mapping (SLAM), CERBERUS can autonomously navigate, explore, communicate, and search underground spaces. "The robots can know where they are, map the environment, and plan their own routes when they have no prior knowledge of the topology of the environment," says Kostas Alexis, CERBERUS team lead, professor at the Norwegian University of Science and Technology, and head of the Autonomous Robot Lab in Trondheim, Norway.

CERBERUS was designed with unified autonomy functionality, so that a single human operator can easily manage the diverse robotic team. "The operator can just draw a rectangle on his or her screen, without knowing what is in that area, and tell them to go explore on their own," Alexis says. To help the robots stay in touch, he says, "some of the ANYmal robots would drop little communication nodes on the ground, deploying their own network." That helped, but it was not a complete solution. So, after finishing an exploration run, the robots would also move back into communication range to exchange data and commands with the base station.

Alexis says that a key element in CERBERUS's success was its multimodal, multi-robot perception system, which combines LiDAR, camera, and inertial sensor data, from across robots, to enable the robots to plan and execute movements even when visibility is limited. "The ability to fuse sensor information allows the robots to accurately reconstruct their environment and know where they are in real time when there is no GPS and in conditions of perception degradation," he says. That was especially important at one point in the competition, "when DARPA filled a whole section with smoke, and our sensors onboard AnyMALwere able to work with this in our data-fusion algorithm."

A few years before the 2021 competition, the CoSTAR robots—a collaboration of JPL, Caltech, and other universities—won a segment of the DARPA competition that focused on urban underground environments. Overall, says Caltech's Burdick, the DARPA challenges have demonstrated the importance of system resilience in extreme conditions—that is, the ability for the robotic team to recover from problems, rather than try to totally prevent problems up front. "You don't know anything about the environment going in," he says. "You really experience real-world problems in the challenges, and you have to be resilient enough to handle all kinds of unexpected situations."

TRULY ALIEN ENVIRONMENTS

The need for resilience is especially critical for space missions. Here, the challenges include everything from radiation to zero-pressure conditions and temperatures "that range from the cryogenic to oven-like conditions," says William "Red" Whittaker, a robotics pioneer and director of the Field Robotics Center at Carnegie Mellon University. "And the first thing you have to do is survive the launch load. It's hard to describe the violence of the shaking and what it requires for a robot to survive and perform."

Robotic planetary rovers have been working in the extreme environment of space for some time. To survive, these have typically been large, heavy, and radiation-hardened machines that can carry a variety of equipment. The Mars Curiosity rover, for example, weighs 907 kilograms. But Carnegie Mellon and Astrobotic, a spin-off of the university, have been taking a different tack with the development of an autonomous micro-rover—the MoonRanger—which is about the size of a small suitcase and weighs just 18 kg.

Expected to go to the moon in 2024, MoonRanger is designed to search near the moon's south pole for underground ice, which could provide water and oxygen for future astronauts and hydrogen to fuel future deep-space missions. Delivered via a lander that will carry a number of scientific instruments, MoonRanger will be fully autonomous, because it is too small to power and carry the transmission equipment needed to communicate with Earth, so it has to operate without human supervision and control. "MoonRanger pushes the boundaries of miniaturization and autonomy," says Whittaker.

MoonRanger will guide itself from the lander to areas as far as 1 kilometer away to look for ice. As it moves, it will produce 3D maps of the surface and make intelligent navigational decisions based on what it "sees," using visual odometry and stereo cameras during daylight and projected laser lines in the dark to orient itself. At certain intervals, it will drive back within range of the lander to upload data to be relayed to Earth. Power will come from a solar panel that unfolds to a vertical position to catch rays from the sun, which is just a few degrees above the horizon at the pole.

On the moon, night and day each last 14 Earth days—and as darkness falls, temperatures can drop to -387° Fahrenheit. Larger rovers survive such temperatures using their radioisotope heaters, but the MoonRanger is too small for that type of device. Thus, its mission will last just 14 days, ending when night begins. What's more, at one point during that lunar day, the operating area will be in the shadow of a nearby mountain for about 24 hours. To survive, the rover will move very close to the lander to take advantage of the larger vehicle's relative warmth and shut down noncritical systems to free up power for internal heating.

Beating the Heat

MoonRanger, the Carnegie Mellon lunar rover, is dramatically smaller than the typical rover used in space missions, and that has some advantages. Compared to traditional rovers, smaller rovers can be built more quickly and cheaply, and they have more flight options because they can be included with other payloads on the same mission. But their size can also complicate efforts to overcome the stresses of operating in space.

For example, on the moon there is no atmosphere to diffuse sunlight, so lit areas are exceptionally bright, while shadowed areas are completely dark—a problem for cameras trying to assess the landscape. To cope, MoonRanger relies on sophisticated software and hardware—including a powerful graphic processing unit—to process images. That, along with the rover's extensive autonomy capabilities, means that MoonRanger carries a lot of computing resources for its size—about 1.5 teraflops of processing power. Running those computers and moving the rover requires a significant amount of electricity. For example, explains William Whittaker, director of the university's Field Robotics Center, the 1-ton Mars rover generates about 110 watts from its radioisotope thermoelectric generator, while the 18 kg MoonRanger generates 66 watts from its solar panels. "The energy density of this thing is totally unprecedented," he says.

All of this creates cooling challenges in a location where daytime temperatures can reach 260° Fahrenheit. With no atmosphere, convection cooling is not an option, so the rover must rely on passive radiant heat loss, which in the low temperatures of the moon can be efficient enough to cool the rover. MoonRanger uses its active thermal management capability to regulate its internal temperature; it monitors equipment, switches components on and off, and uses resistive heating to "spot heat" specific components as needed. The rover will also adjust its location and speed to control the amount of heat it generates and the sunlight that hits it in order to heat or cool itself. Overall, says Whittaker, "we passively over-cool everything a little bit, and then heat things where it matters most."

Engineers see opportunities to explore underground environments in space, as well as surface regions—which is one of the reasons behind CoSTAR's participation in the DARPA subterranean challenge. "There is quite a bit of interest at JPL and NASA in fielding future missions to Mars and Europa that go into lava tubes and caves, or into crevasses in their ice caps to look for biological material from under-ice oceans that are believed to exist there," says Burdick.

Somewhat closer to home, CoSTAR-type robots could be useful for exploring what appear to be lava tubes on the moon. Some of these tubes have large pit openings with steep sides—and here, scientists and engineers could use a different kind of robot. JPL has created DuAxel, which combines two single-axle autonomous robots (called Axels). The paired robots can travel across rough terrain, and, when they reach the edge of a pit, separate. Then, one Axel rappels down the side, while the other acts as an anchor and feeds a line to it.

As DuAxel rappels down the steep sides of these pits, it takes samples that should expose about a billion years of the moon's geological evolution," says Burdick. "Tests in these pits could also provide insight into the potential for human habitation. "We can tell from satellite data that it's much warmer down in the pit than it is on the surface," he says, "so you wouldn't have to expend as much energy to keep astronauts warm, and the tubes are partially shielded from radiation."

WHAT'S NEXT?

The application of robots in extreme environments has come a long way in recent years, but there are still many areas where there is more work to be done. For example, robots have long used been for search and rescue efforts in collapsed buildings. But while drones can map the surface of a rubble pile effectively, the robots that move down into the rubble run into significant challenges. "They need to get into these very small, narrow, twisty, turning, often high vertical spaces. There may be fire, and there's almost always water from fountains and sewers and the sprinkler system," says Robin Murphy, a professor and director of the Center for Robot Assisted Search and Rescue at Texas A&M University. "There are a lot of different materials, such as metal desks and furniture, carpet, blinds—it's the definition of heterogeneous surface properties."

Murphy was part of a team that pioneered the use of search and rescue robots after the World Trade Center collapse in 2001, and since then she has worked on recovery efforts following Hurricane Katrina, the 2011 earthquake in Japan, and many other disasters. The capabilities of search and rescue robots have certainly advanced over the years, but not as much as one might think. "We haven't made that much progress on this," she says. One reason is lack of an economic incentive for investing in a tool that is used only on rare and unpredictable occasions.

At present, at least, full autonomy is not an especially good fit with search and rescue robots, because humans are better at quickly understanding complex contexts and acting on information rapidly. "A trained responder looks for all these cues and knows things like kids who are terrified will hide under beds or in a closet. It's amazing, the reasoning, analysis, and comprehension they have. We just don't have anything like that with robots right now," Murphy says. And because of communication constraints, autonomous robots would have to return to the surface to download data, which could take 45 minutes to process—when the need to find people quickly is critical.

Typically, Murphy says, rescuers will use tethered robots controlled by humans to search through rubble, viewing camera images in real time as the robot moves. These images can be watched not only by search specialists, but also structural experts who can quickly identify safe routes into the rubble to help people.

With that in mind, Murphy's research is now exploring how rescuers and robots can work together more effectively. Her work shows that when there are problems with search and rescue robots, the root cause is human error 51% of the time. Often, these errors can be traced to design issues, pointing to improvements that can be made to interfaces. In addition, she says, "we've found that operating these robots in these conditions is actually very fatiguing, which increases human error." Such insights are being used to create operating standards for robot teams, such as requiring breaks and rest periods at certain intervals.

Researchers at the University of New Mexico are also looking ahead. They have simulated the use of drone "multi-swarms"—large swarms in which sub-swarms consisting of perhaps five or six drones work together to perform a specific task within a mission. At a volcano, some sub-swarms might triangulate to find the locations of CO_2 plumes; others might flock to plumes to take samples; another sub-swarm might manage the overall swarm to adapt to losses; and so on. "We treat each sub-swarm collection of drones as an agent in itself, and then compose a meta-swarm out of the hierarchies of sub-swarms," says Fricke.

At the Autonomous Robot Lab, Alexis and his engineering colleagues see potential in developing core technologies that can be used to create a generic autonomous stack that can be used across a wide range of applications—the opposite of the traditional robot designed for specialized, specific tasks. For example, the ability to use data from their sensors to alter their own behavior might enable drones to learn how to quickly fly through a complex forest. Or it could enable an underground robot like the CERBERUS system of systems to alter its environment by digging or laying boards over muddy floors—and make decisions about when and how to do that.

At a high level, many engineers are exploring how to "scale these fielded systems in at least two dimensions—being able to cover larger areas in the field and being able to continue to operate autonomously out in the field for longer periods of time," says Caltech's Burdick. "We need to keep getting more clever about how to get to these very extreme environments more efficiently and reliably and with more resilience."

For her part, Murphy expects the robotics world to get there. "We are seeing tremendous advances in control and materials and design," she says, "and it is within the realm of mechanical engineers to really help make the breakthroughs needed for extreme environments."

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