Artist's concept of EELS (Exobiology Extant Life Surveyor) at work on Enceladus.
Credit: NASA/JPL-Caltech

roving distant worlds

a new generation of rovers will be exploration's best friends

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The future of planetary exploration does not lie soley with the 2,000-pound (907.2-kilogram) flagship rovers we've seen traversing Mars, loaded with a menagerie of instruments. Nor does it lie only with people cracking rocks with hammers, which we hope for in the next decade. The near-term future of otherworldly discoveries lies with small all-terrain robotics, able to scale and search environments currently beyond the reach of human explorers. Developed in all shapes, sizes, and intended scopes, these rovers will make extraordinary discoveries on our celestial neighbors.

DUAxel

The innovative DuAxel turns extraterrestrial four-wheeling on its head in its quest to explore routes down precipitous slopes. Its two conjoined single-axled robots have the capability to separate so that one can rappel down steep grades or cliffs while the other anchors it in place up top. The two halves are connected by a tether which not only keeps the descending half from falling into oblivion, but also provides all of the power and communications to the anchored robot, essentially acting as a third robot in itself.

DuAxel, whose concept dates back two decades, is an evolution of a rover system coined Axel, whose design centers around minimal complexity. The basic Axel rover uses a symmetrical shape with only three actuators to control its wheels and a trailing link. The link serves several purposes: it provides a reaction lever arm against wheel thrust, adjusts the rover's pitch for pointing its stereo cameras, and provides redundancy if one of the wheel actuators fails.

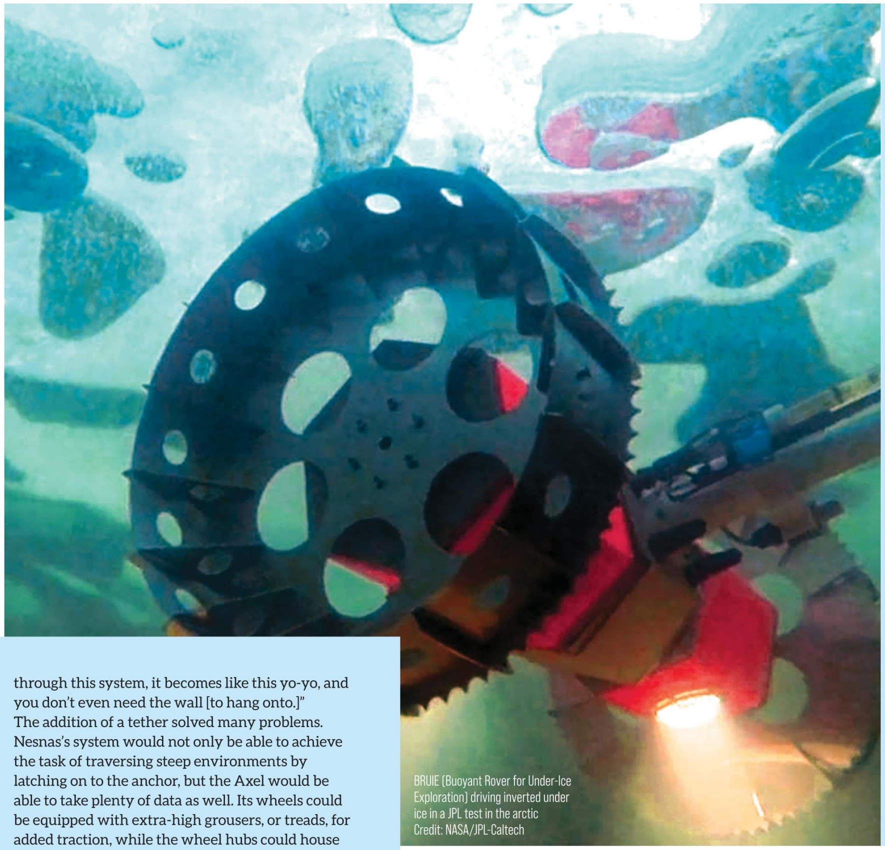
Using only three actuators, the rover is capable of following complex paths, turning in place, and operating upside-down or right-side-up as required. Axel can readily support different wheel types and sizes ranging from large foldable wheels to inflatables. This gives the robot the ability to traverse steep, rocky terrains and tolerate strong impacts during landing or driving. Additionally, Axel is designed with co-location of its sensors, actuators, electronics, power, and payload inside the central cylinder. This configuration provides compactness for launch and robustness against environmental extremes in planetary missions.

"[Conventional rovers and landers] are a really easy mission to understand," said Patrick McGarey, a Robotics Technologist at NASA's Jet Propulsion Laboratory (JPL). "You drive the rover off the lander and do stuff. DuAxel is really a system of three robots. [It allows] two of the robots together to drive as one." While the original plan was for a train of connecting rovers, in the mid-2000s, plans were developed to investigate previously unexplored terrains of Mars, such as crater walls and ridges, and the design of rovers changed with the revised goals.

Satellite imaging had discovered what appeared to be seasonal outflows of liquid water—dark features known as recurring slope lineae. This heightened interest in using robots to take samples. Researchers wanted to know whether gullies and recurring slope lineae were caused by water flows or just dry sand.

The sticking point, however, was exactly how to see the walls up close. Curiosity and the then-in-progress Perseverance rovers could only descend inclines of up to 30 degrees. It was too hair-raising to consider possibly flipping a multi-billion dollar rover while descending a severe slope. These targets demanded something new.

"We started discovering something was going on with crater walls," explained Issa Nesnas, a principal technologist and the supervisor of the Robotic Mobility group at JPL. "There were changes going on with crater walls on very steep terrains. I was asked if there was any way we could begin exploring these areas and here I had this two-wheeler. I thought if I could run a tether



BRUIE (Buoyant Rover for Under-Ice Exploration) driving inverted under ice in a JPL test in the arctic
Credit: NASA/JPL-Caltech

through this system, it becomes like this yo-yo, and you don't even need the wall [to hang onto.]"
The addition of a tether solved many problems. Nesnas's system would not only be able to achieve the task of traversing steep environments by latching on to the anchor, but the Axel would be able to take plenty of data as well. Its wheels could be equipped with extra-high grousers, or treads, for added traction, while the wheel hubs could house microscopes, drills, sample-collection scoops, and other instrumentation to study the terrain.
"If you can rappel down these [steep areas], then you can start doing scientific investigations that could potentially bring interesting possibilities," says Nesnas. "The whole idea of being able to rappel just gives you access to places that you couldn't access otherwise."

EELS

Finding a path to liquid water is the goal of any mission seeking extant life. It's possible that the Cassini Saturn probe did just that in 2005, when it discovered over 100 jets of water vapor emitting from the south pole of Saturn's sixth-largest satellite, Enceladus. To know for sure, however, a rover is needed to explore the emission points of these vapors to provide a definite answer.

The Exobiology Extant Life Surveyor (EELS) was created for just this purpose, descending crevasses in ice sheets where the plumes are emitted, looking for living organisms. Evidence has also shown water plumes on Jupiter's moon, Europa. To explore these crevasses and to determine if there might be life in the areas surrounding these plumes, a rover was needed that could not only explore the recesses of the chasm but also navigate the frigid waters when it reached them. "We're really trying to get to the place where you can see extant life, that's the exobiology," says Kalind Carpenter, principal investigator for the project and robotics specialist. "We're really interested in life not from Earth, and we're looking for life that's still alive ... and if there is life out there, you could probably find it in hydrothermic vents."

A PUFFER prototype being tested in JPL's Mars Yard. Above it is a wheel from the Curiosity rover
Credit: NASA/JPL-Caltech

The snake-like rover is the first of its kind, consisting of an Archimedes screw-like propulsion system that acts as its wheels and its tracking and gripping mechanisms all at once, and gives the rover the ability to propel itself under water by working as propellers. These screws enable the robot to traverse its way to the plume from the lander and then proceed into the crevasse. After entering the open space, its instruments allow the robot to gather information from the area before it heads down into deeper unknown areas.

The twisting screw propulsion allows the robot to lower itself into the crevasse in a circular motion, pressing against the sidewalls, and when needed, permits it to go vertical. Once EELS hits the water below, its screws send it submarining through the sea below the ice.

"The idea came from a string of beads which can twist and turn its way around various obstacles," said Carpenter. "To propel it, the robot has this active skin with these rotating screws which can help in all kinds of environments. For snow, they're a really good way to get around and for water, they can act as propellers."

Once EELS swims, it will see if it swims alone.

PUFFER

Probably the only rover to have been inspired by the art of Japanese paper folding, the designers of the foldable Pop-Up Flat Folding Explorer Robot (PUFFER) used origami as inspiration for their mini-rover. The first prototype was little more than rolling origami, but it quickly grew more complex. The rover's lightweight design can flatten itself, some down to the size of a smartphone, tucking in its wheels and crawling into places other rovers simply can't. Its sturdy construction features flexible fabric mats with electronics impregnated into them, allowing them to fold in ways that metal and plastics simply cannot match.

Working on a two-wheeled system, the shoe-box-sized robot is unique in its ability to fold itself relative to the terrain and can gain access to hard-to-reach craters and narrow caves out of reach for your everyday Toyota-sized rover. The versatile PUFFER is meant to be the hardy assistant to a larger robot companion, increasing the amount of scientific research done in a day.

PUFFER was designed with an attribute called a "skittering walk." This motion allows it to progress forward slowly one wheel at a time without slipping, meaning the robot can amble up steep ascents even on surfaces that don't provide great footing. The two-wheeled rover also features a tail for extra stability and solar panels on its underside, allowing it to flip over when it needs a recharge. On flat ground the rover can currently travel around 2,050 feet (625 meters) on a single charge. The tiny rover is already outfitted with a micro-imager that allows it to see objects just 10 microns in size, but the PUFFER team hopes to kit it out with scientific instruments such as a spectrometer to study chemistry, or technologies to test water for organic material. The future could also see PUFFER becoming autonomous and operating in self-guiding swarms.

PUFFER's small stature could allow several to be packed onto a flagship rover, allowing for greater exploration capacity the larger rovers possess. They can be dropped in any orientation and quickly right themselves upon unfolding, ready to carry out their exploration duties.

"If Curiosity had a stack of PUFFERs on board, each of them could go to separate spots, and the rover would just go to the most interesting one," commented Carpenter.

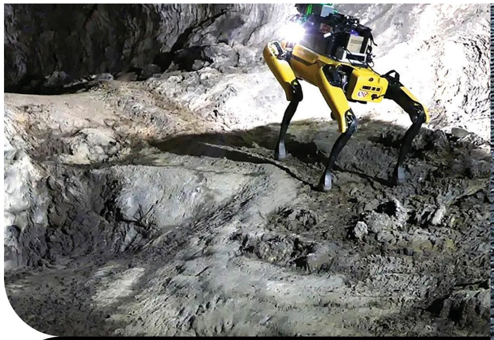
One of its biggest attractions to NASA is the pint-sized rover's low-cost, high-value potential. The development approach of PUFFER took advantage of commercial off-the-shelf electronics and electronics manufacturing capabilities to assure budget-friendly production of multiple sturdy mini rovers.

"NASA is looking for these payloads that they can bring to the Moon, small, low cost, cheap. PUFFER is kind of the perfect thing for that," says McGarey. "Not only can a puffer drive off the lander and survive, but it can also potentially drive into a winter pit and survive."

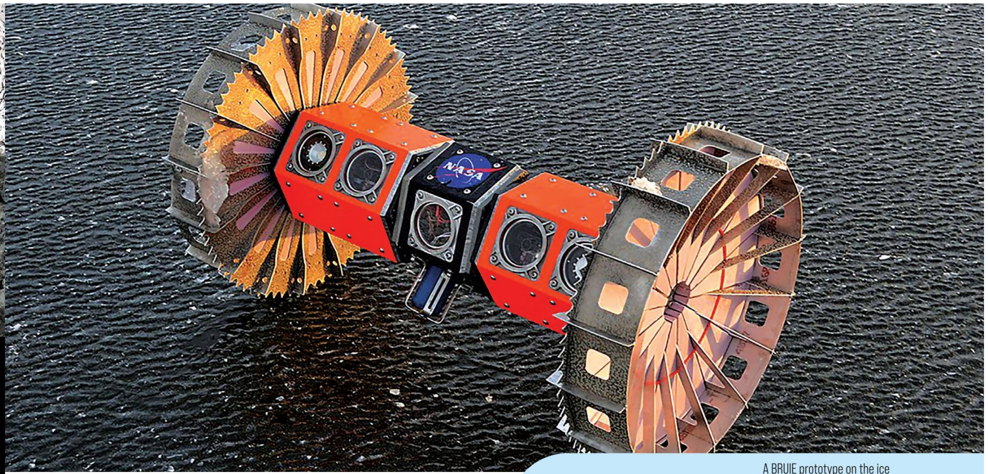
PUFFER already includes many Mars-compatible materials in its construction, including heritage technology from the Viking lander, the various Mars rovers, and the Phoenix lander missions. As an example, the rover's body is wrapped in Nomex, a strong textile used in the airbags that cushioned the Mars Exploration Rovers Spirit and Opportunity when they touched down on the Red Planet. Nomex also repels heat, meaning PUFFER could survive punishing high temperatures.

Besides desert conditions, PUFFER has been outfitted for snow. Carpenter designed bigger wheels and a flat fishtail to help it traverse wintry terrain. So far, it's been tested at a ski resort in Grand Junction, Colorado; Big Bear, California; and on Mt. Erebus, an active volcano in Antarctica.

"Small robotic explorers like Puffer could change the way we do science on Mars," said Jaakko Karras, PUFFER's project manager at JPL. "We think it's an exciting advance in robotic design."



NeBula-SPOT (Networked Belief-aware Perceptual Autonomy robot) undergoing testing inside a cave
Credit: NASA/JPL-Caltech



A BRUIE prototype on the ice
Credit: NASA/JPL-Caltech

NeBula-SPOT

The Networked Belief-aware Perceptual Autonomy (NeBula-SPOT) robot—also called the Mars Dog for its resemblance to our faithful canine companions—won the urban circuit of the 2020 DARPA Subterranean Challenge, the world's most competitive extreme exploration robotics challenge.

NeBula-SPOT resembles the artificially intelligent, four-legged robots you've probably seen getting rudely kicked around by their designers at Boston Dynamics, the ones that always bounce back to continue on their merry way. This attribute is important given the nature of its mission over uneven, rocky, and sometimes unstable terrain. For this rover, agility is vital as its main habitat will be the rocky terrain of a planet or the Moon, and as one scientist noted during a December 14, 2020 meeting of the American Geophysical Union, "Toppling does not mean mission failure."

"Caves are pretty important for NASA, because they are one of the most likely places to find signs of life," said Ali Agha, a lead roboticist and task manager for the project. "They also can provide a natural shelter for astronauts, when it's a human exploration mission, so caves are really very important."

These cave explorers will incorporate artificial intelligence. Unlike every other rover people have put on our celestial neighbors, these are not likely to have recent satellite imagery available to pinpoint the best routes to the destination, so exploration will be up to the robot itself. Everything from finding the most efficient way through the cave, to knowing when its battery is running low and it needs to return to its home base to recharge, will be controlled by AI.

Nebula-SPOT's agility and resilience are paired with sensors that allow it to avoid obstacles and choose between multiple paths while also building virtual maps of buried tunnels and caverns. The 70-pound (31.8-kilogram) rover can also walk up to three times the pace of current rovers at a speedy three miles per hour (about 5 kilometers per hour) and is approximately 12 times lighter than its traditional rover cousins.

"One of the things that's really important for caves is that all we know about them is what we see from orbit," said Benjamin Morrell, Deputy Task Manager for the project. "So, you see an entry to a cave, you might see that there's some type of lava tube formation. We don't know what's in the cave, we don't have any orbital imagery to suggest where there's hazards. We can't have very strong communications when in the cave, and so, there's a really strong requirement for the [exploration systems] to be autonomous. With a battery, you have limited life and can't sit and wait for communications back to Earth to make decisions—that's where autonomy is super important for cave exploration." So far, 1,029 possible cave openings have been discovered on Mars, promising a potentially bright future for machines like NeBula-SPOT.

BRUIE

When visualizing BRUIE, or the Buoyant Rover for Under-Ice Exploration, imagine something that resembles a lawn mower—one that floats under ice. Here on Earth, marine life in icy waters is often found at the boundary between the ice and water, so JPL scientists have devised a buoyant rover that uses wheels to creep along the ice's underbelly upside-down, looking for life or a biosignature. Future iterations of BRUIE may see service at places such as Europa and Enceladus, but for now, researchers are content to use it to make new aquatic discoveries on Earth.

The first BRUIE prototype began testing in 2012 in an arctic lake in Alaska, with further tests occurring in Antarctica's icy oceans in 2019.

"When we were working with scientists to explore where life might form in these analog environments here on Earth, we traveled to Alaska and these thermokarst lakes [lakes caused by thawing tundra] where methane was bubbling up," said lead engineer Andy Klesh. "We noticed that life often forms on interfaces; it forms at the bottom of water, such as ocean bottoms and hydrothermal vents. It tends to form on the ice layer as well, where we see many critters living in the ice in those first couple of centimeters, just between the ice and the water."

The three-foot (0.9-meter) buoyant rover uses its two wheels to roll along beneath the ice, snapping images and collecting data on the important region where water and ice meet, what scientists call the "ice-water interface." Most submersibles have a challenging time investigating this area, as ocean currents can cause them to drift or crash, and they tend to waste power maintaining position. BRUIE's buoyancy and its firm grip on the ice from the traction on its wheels, however, keeps it anchored to the icy underside, resistant to most ocean currents which would sweep other rovers away.

"We often use what we call a lawnmower pattern in order to fully cover an area when we're looking around," said Klesh. "Because it is constantly in contact with the ice, we can stop driving and keep it anchored in place. This means that we can sit and stare for very long periods of time at areas of interest where we think life might be and better understand the chemistry and characteristics of that space without having to recharge the rover."

Artist's concept of LEMUR (Limbed Excursion Mechanical Utility Robots) hard at work far from Earth
Credit: NASA/JPL-Caltech

Eventually, the BRUIE team is hoping to develop the robot into a version that can spend months at a time exploring below ice sheets that are from six to 12 miles (10 to 19 kilometers) thick. Says Klesh about the future of the rover, "We hope that BRUIE and BRUIE's technology will be advantageous to help explore the many ocean worlds out there."

LEMUR

Think of LEMUR (Limbed Excursion Mechanical Utility Robots) as the ultimate canyon-climbing data-taking robot. The spider-like rover sports legs bearing hundreds of tiny fishhooks in each of its 16 fingers that can attach themselves to vertical walls, allowing the rover to take data from the most hard-to-reach spaces, which other robots and people could have a hard time investigating. Though not a future explorer itself, the systems that allow LEMUR to climb up vertical cliff faces may be incorporated in future generations of space-exploring robots.

"LEMUR is a highly articulated legged system," said Nesnas. "The latest iteration of LEMUR was given micro spines to grab onto walls and be able to climb. One of the things that LEMUR is very good at is the ability to climb up slopes if the wall is made out of rocky solid material."

In a 2019 field test in Death Valley, California, the small robot chose a route up a cliff using onboard artificial intelligence while scanning the rock for ancient fossils from the sea that once filled the area. The test was successful and allowed scientists to find evidence of previous life in the area in the form of fossilized remains. They are hoping that similar successes will be repeated on distant planets and moons.

Previous generations of the rover were originally conceived as repair robots for the International Space Station. While that project never got off the ground and has since concluded, it helped lead to this new generation of walking, climbing, and crawling robots. In future missions to Mars and the Moon, newer generations of robots using LEMUR technology will be capable of operating in extreme terrains such as cliffsides and former lakebeds.

With onboard AI giving LEMUR an awareness in three dimensions, and its inherent climbing technology, future iterations could aid in the search for signs of life on foreign worlds.

FOR ALL HUMANKIND

The robotic rovers, crawlers, and divers of the future, descended from these prototypes, will go where no one has gone before. Robots have always gone first into the forbidding landscapes of the solar system, and this will remain the case in the future. While there are some locations robots explore that people may never tread, these clever machines will be the first to explore places we will go. They are truly exploration's best friends. ■