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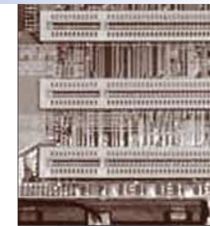

NASA's navigators: Outdoing themselves

As impressive as the Curiosity landing was, NASA's navigation technologists think they can do even better next time.

The Curiosity descent vehicle was equipped with a sophisticated inertial measurement unit, but mission planners still could only promise to deliver the rover somewhere within a 20 X 7-km ellipse. Once the vehicle deployed its parachute and released its heat shield, its exact landing spot was determined by the Martian winds. A camera called the Mars Descent Imager snapped photos to tell scientists where within the ellipse the spacecraft was coming down. A radar bounced signals from the surface to measure speed and altitude, and eight rockets automatically kicked on at precisely the right moment. Their job was not to steer around obstacles. It was to slow the vehicle so Curiosity could dangle blindly down to the surface on tethers. If there had been dangerous rocks or slopes below, there would have been no way to detect or steer around them.

Scientists had to see where Curiosity came down before they could decide where to drive to test out the rover's rock drill. Using orbital images, they picked a place about 400 m away and named it Glenelg (after a northern Canadian location where Precambrian rocks are exposed). The journey there was expected to take weeks, followed by many months of driving through a gap in some dark dunes to reach the main science objective of the two-year mission: the base of the 5-km-tall Mount Sharp. The mountain's rocky layers might tell scientists whether the area could have harbored life of any kind.

While Curiosity is busy leaving tracks on Mars, teams of navigation engineers led by NASA Johnson and JPL are working on technologies that might someday deliver spacecraft right to the heart of the dangerous places that tend to be the most scientifically interesting. Those teams want to leap from unpowered descents like Curiosity's to landings in which a spacecraft sees the terrain all the way down and steers around obstacles. The new sensors and algorithms could be applied not just to Mars, but also to asteroids and new destinations such as Jupiter's moon Europa. Most of those missions would be robotic, but Johnson has not given up on human missions, even as it seeks to contribute to the robotic ones as well.

Go 'smartly'

The two teams have a largely common goal: They want to use rockets to steer to a preprogrammed landing zone that would be 100 m wide instead of kilometers across. Precise navigation algorithms would be needed to avoid running out of fuel as the trajectory is corrected. At an altitude of perhaps 1,000 m, light detection and ranging instruments called lidars would snap on to scan the landing zones for hazards too small to be seen from orbit or by the craft's camera. An onboard computer would autonomously choose a safe landing spot from amid the boulders, slopes, or craters. The Johnson team, for example, thinks it can spot all hazards greater than 30 cm and stick the landing to within 3 m.

This image was taken during a flight test of JPL's Autonomous Descent and Ascent Powered-flight Testbed (ADAPT). The testbed was flown aboard a Masten Space Systems Xombie rocket. The test took place at the Mojave Air and Space Port, California, on July 9, 2012. Image credit: NASA/JPL-Caltech.

For NASA's technologists, the objective of more precise landings is not meant as a slight on the Curiosity mission. One engineer calls it an inevitable progression: "Human beings, I think, want the power over time—to say, 'Go there, exactly where we told you, and do it smartly, by yourself, spacecraft,'" says electrical engineer MiMi Aung, manager of NASA JPL's Guidance and Control Section, which helped plan the Curiosity landing.

Both teams are entering the low-altitude flight test phase of their projects, and if they succeed, they could change NASA's mission planning forever. Curiosity's science team had to pick a smooth-looking ellipse that would minimize the odds of landing on large rocks. The tradeoff for the safe arrival was the time it will take to reach the base of Mount Sharp.

California dreaming

To test a better method, JPL has begun low-altitude flights at the Mojave Air and Space Port, using a rocket it calls ADAPT, for Autonomous Descent and Ascent Powered-Flight Testbed.

At the moment, ADAPT consists of a Masten Space Systems Xombie terrestrial test rocket programmed with 'canned' Mars descent scenarios, just to see if Xombie could fly them. Engineers from Masten and JPL flew ADAPT three times, once in July and twice in August. The craft took off straight up on each flight, and at about

500 m was allowed to fall straight down 50 m to gain speed before swooping downrange as though it were descending to Mars.

"We are very relieved and happy that Xombie can fly such an aggressive trajectory, because we just didn't know walking in," Aung says. "These are three possible trajectories you might see on Mars." In the last test, on August 14, ADAPT was diverted 750 m downrange.

Ultimately, JPL wants to move away from the canned trajectories and shift control entirely to an 8-kg sensor now in development. Called the Lander Vision System, it would provide the necessary entry, descent, and landing functions all rolled into one sensor, says Aung.

Its imaging camera would photograph the terrain on the way down. Algorithms would use those images to determine the real-time position of the spacecraft relative to the desired landing site in a process called terrain relative navigation. A separate algorithm, called G-FOLD for guidance-fuel optimal large divert, would snap into action to calculate the best path toward the target. To avoid running out of propellant, a "fuel optimal solution" would be critical, Aung cautions.

Closer to the surface, the vision system's flash lidar would bounce lasers off the terrain to produce 3D maps. Hazard detection and avoidance software would use these to pick a spot for touchdown.

At each critical point, the calculations would have to be made autonomously in seconds.

G-FOLD was the key innovation, because it allows the course corrections to be calculated on a computer small enough to fit in the descent vehicle. "If you have supercomputers on the ground, you can still crank out—after an hour or two—the optimal solution, but we don't have those hours and we don't have a supercomputer," Aung says.

Next, the JPL team wants to load the G-FOLD algorithm onto a computer and install it on Xombie this year. During the flight, G-FOLD will calculate the optimal path and send it

Xombie had several successful test flights.

to Xombie's computer, which will steer the rocket on that route.

Without the Lander Vision System installed, engineers would need to give the G-FOLD starting and ending points. Even with the preprogrammed points, "that's going to be pretty gutsy," Aung says. G-FOLD will need to work fast. In 2014, Aung's team plans to install the Lander Vision System on the Xombie for end-to-end tests.

When that happens, "It'll be a truly autonomous system where we don't need GPS, we don't need any information from the vehicle," Aung says.

Bad break

At NASA Johnson, engineers have been working for six years on their own precision landing system under a project called ALHAT, for autonomous landing and hazard avoidance technologies. JSC has overall management responsibility for ALHAT. Integrating the technologies, though, is a joint effort by engineers from JSC, JPL, and NASA Langley, with contributions from contractors including Draper Lab of Cambridge.

Earlier this year, the timing for the start of ALHAT flights looked as though it would coincide nicely with the attention the Curiosity mission was expected to draw to planetary landings. When Curiosity touched down on August 5, ALHAT engineers expected that by October they would be landing their low-altitude test craft

Morpheus rises just after ignition.

The Morpheus lander was built to carry the ALHAT equipment. On August 9 it rose a short distance, veered off course, and crashed.

amid a field of rocks and craters set up at NASA Kennedy to look like the Moon. It would be a key test of the low-altitude Flash Lidar built by Advanced Scientific Concepts of Santa Barbara. The lidar rapidly bounces light off the surface and measures the time of return to map features in 3D. It was adapted for real-time hazard detection with help from Langley, and it will map terrain to an 8-cm resolution, says ALHAT manager Chirold Epp.

The October tests were not to be, however.

Morpheus, the lander built by Johnson to carry the 150-kg ALHAT equipment, rose a short distance from the Kennedy launch pad on August 9, veered out of control, and crashed. It was the second attempt at a free flight after numerous flights on a tether slung from a crane. Flames flickered for a while and then Morpheus exploded. Moments earlier, in the mobile mission control shelter, controllers had noticed that the vehicle's computer stopped receiving inertial measurement unit data. The IMU had worked fine two days earlier during a soft abort caused by false indication of an engine burn-through. Without the IMU feed, the rocket could not tell up from down.

Luckily, NASA had not yet installed the ALHAT equipment. The team must decide what to do while Morpheus manager Jon Olansen investigates the mishap and tries to avoid repeating the problem, whatever it was, on the new version that will be assembled.

The ALHAT team does not want to give up on Olansen's project. "We're still planning to fly on Morpheus when they get their vehicle rebuilt and prove that they can fly at the kind of trajectory that we need to demonstrate ALHAT," says Epp. "Hopefully, that will be sometime next spring."

Epp is looking for ways to continue making progress in the meantime. "We would like to take advantage of the hazard field at KSC and fly a helicopter and collect some flash lidar data," he says. "We cannot reproduce the trajectory that Morpheus will give us, but we can collect some information and use that as test data for our systems."

He also has not ruled out trying another terrestrial rocket. "If we can find a different vehicle that can fly something similar to Morpheus, we may try to fly at least some components of it," he says.

One thing is certain: Both Olansen and Epp are anxious to try out the hazard field. The field was patterned after the Moon, right down to the size of its craters and rock piles. Epp cautions observers not to conclude that the ALHAT technology applies only to landing on the Moon. Success in the lunar hazard field would show potential for landing virtually anywhere, he says, including Mars.

"Curiosity program people eventually would like to have some kind of an ALHAT system on board so that they can go to certain regions that they're kind of afraid to go to right now. It would give them more capability, with higher probably of success in more hazardous areas," Epp says.

He also knows that at 150 kg, critics say ALHAT is much too heavy for robotic missions. "We already know how to reduce that to about 100 kg, and we believe there are ways to reduce it a whole lot more," he adds.

Once Morpheus starts flying with ALHAT, the profile will be similar to that of JPL's Xombie-based ADAPT. It will fly up about 500 m and then follow a slanting trajectory about 800 m to the ground. The big difference is this: JPL does not plan to land in a hazard field any time soon, but for JSC, that is the main purpose.

The idea is to verify that ALHAT is smart enough to decode the field. "We actually know that we put two safe areas in there, but anyplace else is not necessarily safe for that lander," Epp says. "We will turn on the Flash Lidar, and we will image the hazard field in 4 seconds, and 6 seconds later, we hope to tell Morpheus, 'You were going to the center of that field. That's not safe. Divert and go here to this safe site," he explains. "And then we will track a feature down to the ground to make sure that we stay locked onto that safe site as we're coming down."

Working at NASA Johnson, Epp is steeped in the history of the Apollo lunar missions, and he thinks they hold important lessons on how to apply the new technologies.

"If you step back to Apollo for a minute, they landed pretty much by eyeballs, as human beings, to avoid hazards. Of course Neil Armstrong didn't like where he was going down, so he actually flew the vehicle a little bit farther downrange and almost ran out of fuel," he says.

What if so much dust had been kicked up in the final 30 or so meters that it had prevented Armstrong from seeing? Therein lies a big lesson when it comes to relying on the Flash Lidar. "We don't believe you want to try to sense through that dust. Several people have talked to us about that," Epp says.

So, in addition to the Flash Lidar, Morpheus will test a Doppler lidar. It will not generate images, but it will pierce the dust well enough to measure closing velocities in three axes to an accuracy of 1 cm/sec. "That gives you such a good navigation state relative to the surface that the last 30-50 m, you can dead reckon down to the surface," Epp says.

Now all he needs is a rocket to prove it.

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