Advances in telerobotics are making it possible to conduct remote explorations of distant worlds. Human operators can now control their mechanical surrogates from Earth, and will soon be able to do so from space outposts as well. But with the desire for exploration seemingly built into human DNA, will the 'telepresence' provided by robotic systems be a satisfactory substitute for truly being there?

Remote telepresence

A new tool for space exploration?

by Leonard David
Contributing writer

Significant strides are being made in telerobotics, the ability to place human cognition and dexterity in places too perilous for flesh and bone, whether to probe the deepest oceans, dig out resources from mines, or maintain undersea oil pipelines and telecommunications cables. In addition, above our heads, passenger aircraft increasingly share the skies with all manner of unpiloted airborne vehicles, controlled from a distant command center.

Space exploration planners are now contemplating how they can adapt telerobotics to achieve tasks on other worlds. Extending human cognition to the Moon, Mars, near-Earth objects, and other bodies could reduce the challenges, expense, and danger of hurling humans to such hazardous surfaces and deep gravity wells.

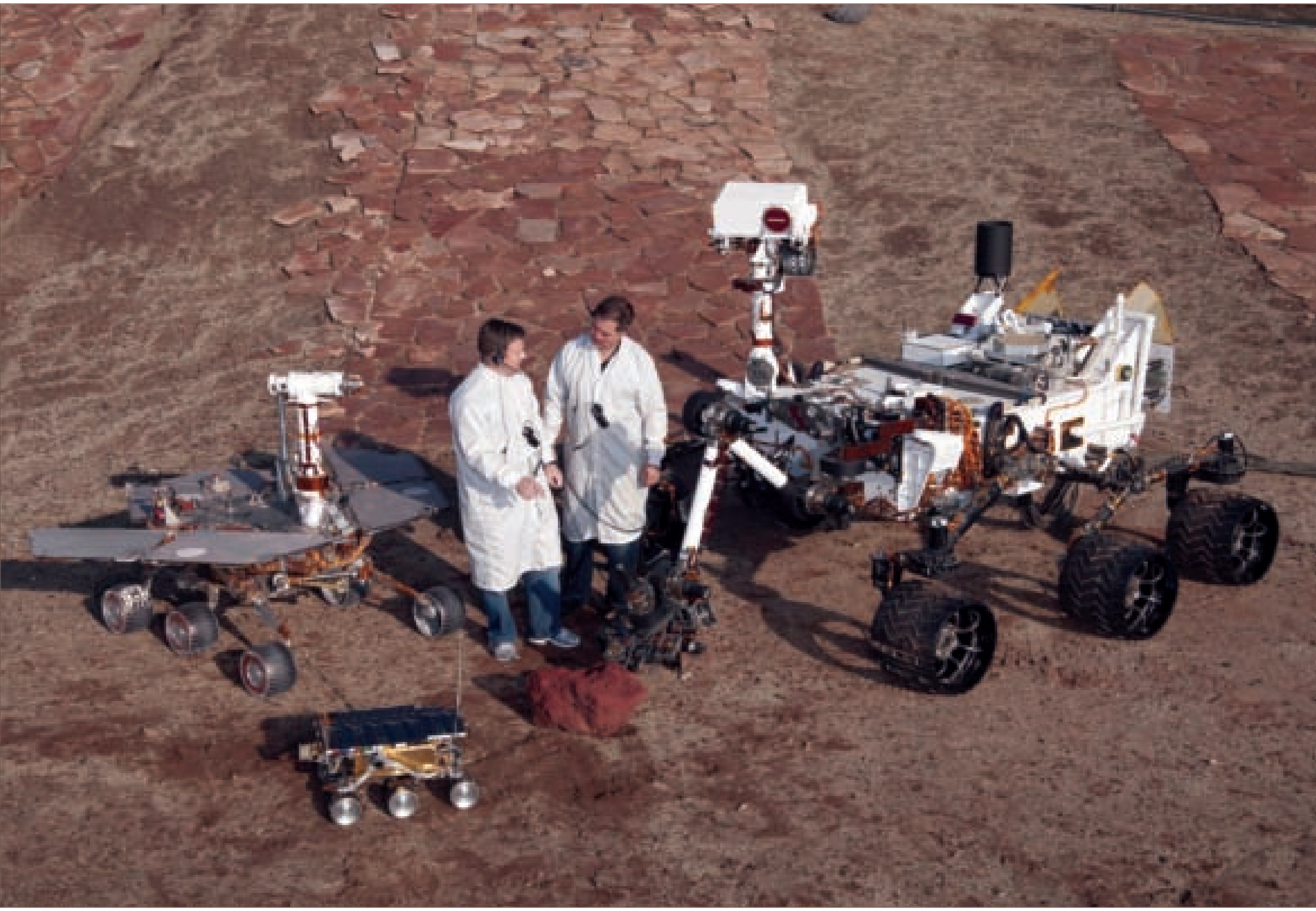
Conversely, some believe that sending mechanical surrogates to do an astronaut's work runs counter to the core value of human space exploration—that crewed space exploration is built into our DNA and answers the call of destiny.

But pitting astronauts against machines is not just contentious; it also overlooks the advantages of combining their attributes to create a true human-robot partnership.

Early pathfinders

Momentum appears to be building for future space expeditionary crews who remotely operate systems that are deployed on planetary bodies, doing so from, say, in-space locales. From a habitat circling a planet or in a module situated at a Lagrange point, astronauts could use high-quality telepresence to conduct surface science, piece together infrastructure, or scout out and unearth resources on other worlds.

In some cases, while landing crews on



Three generations of Mars rovers include tiny Sojourner, a Spirit/Opportunity-class rover, and the larger, Curiosity-class robot now on Mars. Developed at JPL, these NASA robots are seen as steps toward more advanced human-machine interaction to investigate a variety of worlds. Credit: NASA/JPL-Caltech.

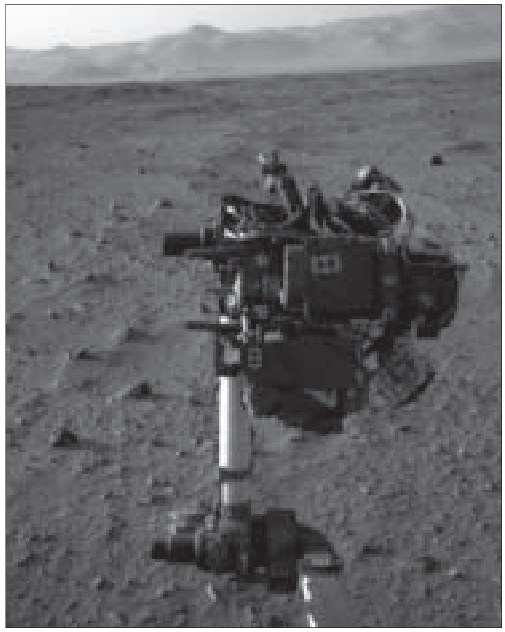
celestial surfaces may be the ultimate ambition, planting human cognition at these locations via telepresence could be achieved far more quickly and at lower cost. In addition, if remote telerobotic control can be established on the Moon, for example, could this capability help hone future activities at other planetary bodies, particularly at Mars?

"Telepresence has the potential to vastly increase the capabilities for human exploration of the most challenging and revealing locations in the solar system," says Harley Thronson, senior scientist for advanced concepts in the Astrophysics Science Division, Science and Exploration Directorate, at NASA Goddard.

"Landing humans or robots on the surfaces of other worlds and within deep gravity wells, with a subsequent ascent, is a very expensive undertaking. In advance of landing humans on another world, astronauts from orbit operating sophisticated robotic surface explorers may be the far less expensive pathfinders, surveying, testing, and sampling for the humans that would follow," Thronson tells *Aerospace America*.

This major enhancement of human exploration potential, says Thronson, is enabled by three parallel technological advances: high-bandwidth communication, advanced robotics, and low latency—that is, placing human operators outside the deep gravity wells of other worlds, yet 'close enough' so that the round-trip light-travel time is comparable to time scales associated with the human hand-eye-brain system. "The key technologies to enable effective telepresence are nearly at hand, first to the vicinity of the Moon, then one day beyond the Earth-Moon system," he says.

"Effective telepresence offers the opportunity for humans to explore worlds



NASA's Curiosity rover now on Mars is well armed...but are human arms better? The increasing role of telepresence is yielding new insight into the value of robots and human explorers—and perhaps the melding of both to increase the productivity of space exploration in the future. Credit: NASA/JPL-Caltech.

safely from orbit that they will never visit directly—like the surface of Venus, or beneath the clouds of Titan," Thronson says. "Sophisticated telepresence on Earth gives us great confidence that this new capability for human spaceflight can be achieved, such as we now see in telesurgery, robotic mining, and robotic undersea exploration."

Cognitive compromises

Holding a similar view is Dan Lester of the Dept. of Astronomy at the University of Texas in Austin. Lester, who is working with NASA on cislunar operations involving science and exploration, notes that there are countless lessons to be learned from the terrestrial telerobotics community. "That's all happening right now, in a big way, and space exploration has a lot to learn from those endeavors. They don't use space-qualified hardware. But their operations management and protocols have important lessons for us."

The Justin mobile robotic system was developed at the German Aerospace Center, DLR. With compliant controlled lightweight arms and two four-fingered hands, Justin is an ideal experimental platform. Credit: DLR.

It is precisely this explosion of technological capability that prompts talk about extending telepresence into space, Lester explains. "Decades ago, when we wanted to put human cognition on the Moon, there was exactly one way to do it…and that was putting people there—boots on the ground. But this is no longer the only option."

Fast forward to today

Lester underscores what he believes is an important and perhaps overriding question: To what extent do the public and the U.S. Congress buy into an exploration strategy that does not involve humans going all the way to an exploration site? "In many respects," he suggests, "what telepresence is making us do is redefine what we mean by the word 'exploration.' To what extent do we have to 'be there' to be explorers? What does 'being there' mean? It doesn't mean what it used to mean," he contends.

Still, the distances over which robots are exercised impose a time delay on their control. For the Moon, that two-way delay is at least 2.6 seconds; for Mars it is far longer, in the 8-40-minute range.

These delays are, at minimum, what is routinely endured in 'experiencing' Mars through rover automatons. What kind of personal experience has you turning your head, then waiting 40 minutes to see the view? Lester asks: Is experiencing distant space destinations through electromechanical surrogates really possible?

Minimizing communication delay time, or latency, says Lester, is a key to achieving telepresence, and that translates into putting human cognition at distant sites. "In order to achieve it, humans need only be close, so the travel problem becomes sending astronauts to the *vicinity* of exploration sites, and not necessarily landing on them. Landing humans can be almost half the cost of putting human cognition at these sites."

Thronson and Lester were key organizers of an Exploration Telerobotics Symposium held last May at Goddard that brought together astronauts, scientists, engineers, and robotic specialists from a mix of Earth and space applications fields.

In many respects, Lester says, telepresence is a strategy that challenges traditional definitions of exploration. Can we be explorers without actually setting foot at an exploration site? The space science community is comfortable with that premise, though control of robotic assets from Earth involves serious cognitive compromises. "It was clear to the symposium participants that exploration by telepresence established clear synergy between robotics and human spaceflight, and had a strong generational grounding. The 'wired' generation may be far more accepting of such a strategy than an older generation," he surmises.

Robotic right stuff

The Mars Science Laboratory's Curiosity rover provides a good opportunity to contrast the exploration effectiveness of space robots with that of on-the-spot humans.

First, it depends on what you run into on Mars, explains John Grotzinger, MSL project scientist from the California Institute of Technology. Curiosity, the size of a small car, is essentially an automated geologist operated by a large team of handlers on Earth. The team is also using orbital imagery of the site the rover is exploring.

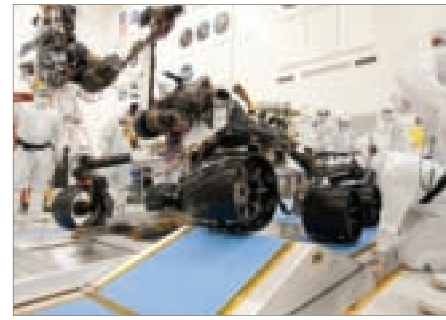
Already, Curiosity has shown its robotic right stuff in surveying its surroundings. "With a robot we can actually test the hypotheses, including the alternatives, pretty quickly and efficiently and arrive at a consensus opinion," Grotzinger says. "I would say it's simply an issue of signal to noise. If the geological signal of the process is large enough, it's very easy to build consensus."

On the other hand, what if Curiosity rolls up to the unexpected, something that has no earthly analogs or is hard to analyze? "I think if you're working with a robot—and a very large team—it becomes very difficult to reach consensus. Therefore, there's really no substitute for a human when it comes to exploring very complex situations. The triage that you can do mentally as you pass your judgment over the options and command yourself to walk to different places and make different measurements is really the compelling reason for wanting to do human exploration. It's just so much more efficient, and you probably will arrive at conclusions that are more likely to be correct than if you had just a robot," Grotzinger responds.

"But it's the same problem you'd go through as an individual saying, 'Do I have enough water, or do I need to go back to the car and refill my water bottle before I go up there?' So we're always doing the optimization…there's always a compromise in terms of how far you go versus the geology you achieve," he adds.

According to Paul Spudis, senior staff scientist at the Lunar and Planetary Institute (LPI) in Houston, Texas, the extent to which true telepresence is needed for effective geological exploration is unclear. "This is a result of both the lag in telepresence technology—for example, very high bandwidth visual and tactile sensory systems—and our poor understanding of what the field experience entails from a human cognitive viewpoint."

Spudis says his experience with using remote systems to conduct geology has been less than edifying. "I note both poor situational awareness and a significant diversion of concentration on technical means of the human-robot interface versus conducting surface exploration. In other words, as a replacement for human field exploration, it leaves a lot to be desired."



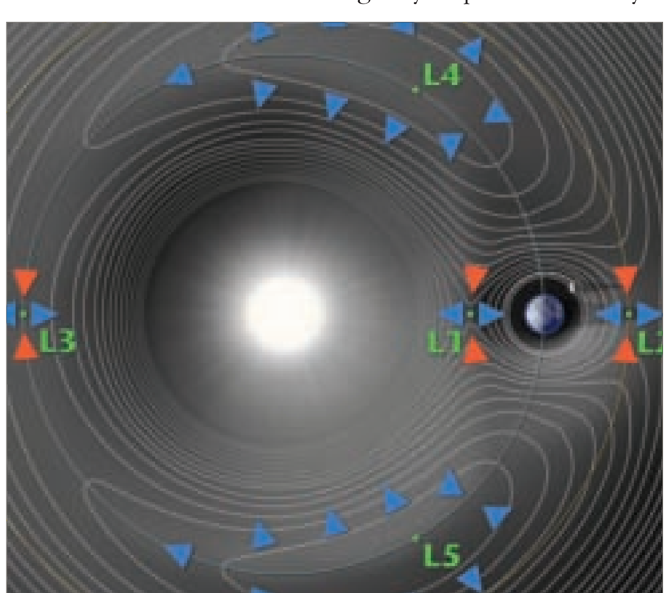
NASA's Curiosity drives up a ramp during a test at JPL on September 10, 2010. The rover uses a rocker bogie suspension system to drive over uneven ground. Image Credit: NASA/JPL-Caltech.

Libration point practice

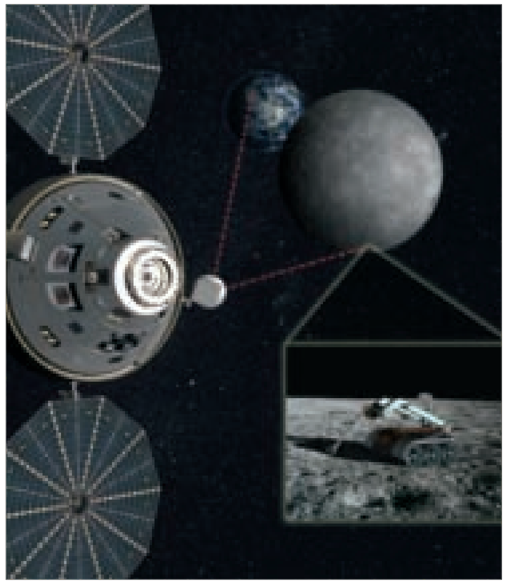
There are new studies under way to use an Earth-Moon Lagrange point (E-M L2) to conduct human-controlled telepresence exploration on the lunar landscape.

Last February, NASA's William Gerstenmaier, associate administrator for human exploration and operations, requested that a team be formed to develop a 'cohesive' exploration concept aimed at the E-M L2 spot in space. Libration or Lagrange points are places in space where the combined gravitational pull of two large masses roughly balance each other out, allowing spacecraft to essentially 'park' using minimal amounts of propellant.

An earlier appraisal of E-M L2, which is near the lunar far side, labeled this destination the 'leading option' for a near-term exploration capability. E-M L2 could serve as a gateway for capability-driven exploration of destinations such as near-lunar space, the Moon, asteroids, the moons of Mars and, ultimately, Mars itself. This capabilities-driven NASA architecture is one that should use the agency's Space Launch Sys-



Studies are under way to use an Earth-Moon Lagrange point to conduct human-controlled telepresence exploration on the Moon.

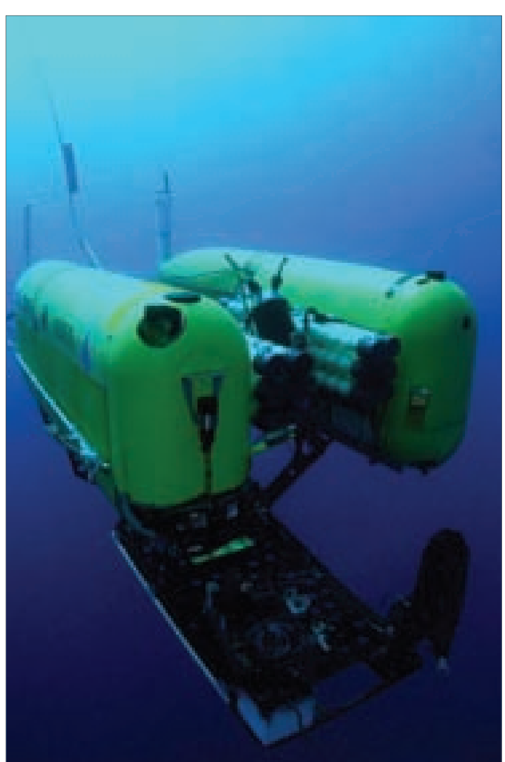


An artist's depiction shows the Earth and Moon as they would appear from an L2 halo orbit reached by an Orion spacecraft. From that site, astronauts would control robotic hardware on the surface. Now under way are discussions on building up a human-tended habitat at the Earth-Moon L2 location to enable telerobotic activities on the lunar surface. Credit: Lockheed Martin.

tem and the Lockheed Martin-built Orion multipurpose crew vehicle "as the foundational elements."

Planners at Lockheed Martin Space Systems in Denver have blueprinted a plan using Orion to support an E-M L2 far-side Moon mission that would permit an astronaut crew to have continuous line-of-sight visibility to the entire far side of the Moon and to Earth.

Josh Hopkins, a Lockheed Martin space exploration architect, says that, from a halo orbit around that L2 point, a crew could control robots on the lunar surface. Teleoperated science tasks include snagging rock specimens for return to Earth from the Moon's South Pole-Aitken basin and robotically unfurling a low-frequency array of radio antennas to observe the first stars in the early universe. The E-M L2 outing would be a stepping stone toward treks to asteroids, and toward human missions to the moons of Mars in later years, he advises.



The Nereus underwater robot investigates hydrothermal vents along Earth's deepest mid-ocean ridge in the Cayman Trough. This unique vehicle can operate either as an autonomous, free-swimming robot for wide-area surveys, or as a tethered vehicle for close-up investigation and sampling of seafloor rocks and organisms. Credit: Advanced Imaging and Visualization Laboratory, Woods Hole Oceanographic Institution.

A Lockheed Martin white paper provided to *Aerospace America* on the E-M L2 proposal cites a number of benefits that would evolve from such an effort:

- Astronauts on an L2/far-side mission would travel 15% farther from Earth than did the Apollo astronauts—and spend almost three times longer in deep space.
- Each flight would prove out Orion's life support systems for one-month missions before attempting a six-month-long asteroid mission.
- It would demonstrate the high-speed reentry capability needed for return from the Moon or deep space—40-50% faster than reentry from LEO.
- The mission would measure astronauts' radiation dose from cosmic rays and solar flares to verify that Orion provides sufficient protection. Currently the medical effects of deep space radiation are not well understood, so a one-month mission would improve our understanding without exposing astronauts to excessive risk.

Meanwhile, NASA strategic space planners also foresee that an E-M L2 waypoint would facilitate assembly and servicing of satellites and large telescopes, among a host of other benefits. As Lockheed Martin notes, if an astronaut-tended E-M L2 waypoint were established, it would also represent the farthest distance travelled by humans since the Apollo 17 Moon landing in 1972. Extended stays at E-M L2 require advances in life sciences and radiation shielding for crews that sojourn outside the protection of Earth's Van Allen radiation belts.

In a memo written last year, Gerstenmaier added that E-M L2 "is a complex region of cislunar space that has certain advantages as an initial staging point for exploration, but may also have some disadvantages that must be well understood."

Testing from ISS

Jack Burns, director of the LUNAR (Lunar University Network for Astrophysics Research) Center at the University of Colorado, Boulder, has been spearheading an

E-M L2 exploration and science mission concept using Orion and a teleoperated lander/rover.

Burns is working with NASA Ames to use its K10 rover to simulate deployment of polyimide film antennas as they would be unfurled on the Moon's far side. That activity, scheduled for later this year, would be linked to astronauts onboard the ISS who would teleoperate the Ames-situated K10 to stretch out antennas via control from space. At the Moon, using astronauts positioned at the E-M L2 site, the polyimide film would be unrolled to form the array. The far-side-deployed antennas would then be electronically phased to produce a sensitive radio interferometer that would conduct cosmological investigations in silent solitude, free of the buzz and static emitted on Earth.

The use of astronauts at L-2 to teleoperate surface robots on the far side of the Moon is possible, but offers no real advantage over controlling them from Earth, says LPI's Spudis. Much is made of the latency factor or time delay, but the specific tasks envisioned for this mission—retrieval of a kilogram of lunar rock and soil, and the surface layout of the radio dipole antenna for astronomy—can be easily accomplished by time-delayed teleoperation, he argues.

Spudis says he has no problem with using the L-points, "but they are means to an end, not an end unto themselves." Unless you are on the Moon cranking out propellant for export, you are not creating new spaceflight capability. Rather, you are just checking a box in an attempt to make people think you are accomplishing something, he asserts.

"I actually think these telerobotic initiatives are very exciting, and can increase exploration efficiency considerably. I do not want to appear to be opposed to them," notes Ian Crawford of the Department of Earth and Planetary Sciences at Birkbeck College, University of London. However, he adds, they will not be as good as having people on planetary surfaces, where this is possible, for several reasons. First, teleoperated vehicles are unlikely to be as versatile or nimble as human explorers. Second, the various life sciences investigations that have been proposed for the lunar surface cannot be done telerobotically, because humans are the test subjects!

ESA astronaut Christer Fuglesang works with an exoskeleton in the robotics lab at ESTEC. This wearable robot—a combination of arm and glove with electronic aids to reproduce the sensations a human hand would feel—enables a remote operator to work as though he were at a distant site. With haptic telepresence, which adds the sense of touch, anyone purportedly can operate a robot without training. Credit: ESA, J. v. Haarlem.

Most important, Crawford says, is that "to make them cheap, telerobots are likely to be left on the planetary surface when their mission ends. But this means that geological samples are less likely to be returned, which was a major benefit of the manned Apollo missions. Since the astronauts had to come back, they could bring soil and rock samples back with them."

Low latency telepresence

James Garvin, chief scientist at NASA Goddard, helped chair last May's Exploration Telerobotics Symposium. The lessons he took away were many. They include some specific examples where a low latency telepresence on a planetary or asteroidal surface could permit the level of situational awareness and in-situ cognition needed for

Why explore via telepresence?

•EDL (entry, descent, and landing) and subsequent ascent are risky and expensive. The last 100 km can be the hardest part of a trip to a planetary surface, the return takeoff equally difficult.

•Low latency, advanced robotics, and high communication bandwidth are independently enabling and important to apply. Together, they provide a powerful new capability in human exploration.

•Key technologies for low latency telerobotics are at hand, or will be in the near future.

•Human surface exploration requires environmental control and life support systems that are different from in-space systems proven on ISS—and entails greater expense if humans operate within gravity wells.

•Surfaces of other worlds present contamination issues such as dust and toxicity. These complicate human operations involving items such as pressure seals for EVA suits and habitats.

•Human explorers can be in only one place at a time at an exploration site.

•Radiation issues make planetary surfaces potentially harmful to humans and may also be very expensive to ameliorate.

•Remote telepresence opens up possible destinations (Venus, Mercury, Io, and Titan, for example) that humans may never directly visit because of surface conditions such as heat and pressure.

•Space-based telepresence can build on terrestrial experience and capabilities, extending field science to new places 'as if we were there,' beyond the scope of high latency robots such as Spirit, Opportunity, and Curiosity.

Adapted from findings of the Exploration Telerobotics Symposium held May 2-3 at NASA Goddard. Courtesy of Azita Valinia , Harley Thronson, Jim Garvin, and George Schmidt (NASA/Goddard); and Dan Lester (University of Texas).

Telerobotic control from ISS

A test slated for later this year is designed to develop an ISS-to-ground interface for telerobotic control, to be staged by ESA's Multi-Purpose End-To-End Robotic Operation Network (METERON). This experiment and architecture are keyed to validating future human-robotic mission operations concepts from space, using the ISS. André Schiele, founder in 2011 of ESA's Telerobotics and Haptics Laboratory, is leading the effort.

In the first METERON tests, station astronauts will operate ESA's Eurobot prototype from a computer equipped with special screens and a joystick. In the next phase, the engineers will allow astronauts to control a robot that has the sense of force and of 'touch.' It can be connected to robots like Justin, developed by the German Aerospace Center, DLR.

These senses will give astronauts "a real feeling of the forces that the arms of the robots are experiencing in their environment," says Schiele.

"The space station is the perfect orbital platform to simulate very realistic scenarios for human exploration," says Kim Nergaard, ESA's METERON ground segment and operations manager. "First we have to set up a robust communication architecture, establish an operations system, and define a protocol to allow astronauts, robots, and our ESA control center to work efficiently together. This is not as easy a task as it seems," he reports.

What these efforts will accomplish is to prove out at least the basic operational and communication concepts and protocols for on-orbit telerobotics, which may be used for work on the lunar or Martian surface, with control from human operators in orbit above, observes Dan Lester of the University of Texas in Austin. "It is an important first step for this kind of work, and makes excellent use of the ISS."

That strategy, however, does have some disadvantages, Lester adds.

"In order to achieve very low latency, you can't go through the Tracking and Data Relay Satellite System, which is what ISS uses for most of its data communications. You need a direct-to-ground link. But the problem with that is that such linkages are only possible when you're flying overhead. So for a given single ground receiving antenna, you'll only get 5-10 minutes of connect-time…maybe once a day. So while you can prove the operational concepts and protocols, you sure won't be able to exercise them very much," Lester notes. "That's why telerobotic control from ISS won't really completely prove out strategies for on-orbit telerobotics at Mars. Doing work from Earth-Moon L1 or L2 on the lunar surface will be far more instructive in this regard."

One could ask why one even needs to practice telerobotic control from ISS and not just do it from the next room?

*There are several reasons, says Lester. First, the communication strategy is an important one. Orbit-to-ground communication is challenging, in an error-and-delay-tolerant mode. Second, it turns out that carrying out telerobotic control in 0-*g *is not quite like operating it in 1-*g*. That is, operating a joystick properly is really helped by having your arm gravitationally 'grounded.' Furthermore, it is not completely clear how good a sense of telerobotic control one has for a vehicle in a gravity well, done from a control station in 0-*g*. "Your brain isn't quite 'thinking' gravity anymore," he says.*

advanced scientific investigations involving the highest priorities in planetary science. "But more work is needed to develop specific scenarios by which they could be implemented," he suggests.

For the near term, Garvin proposes, a continued dialogue among scientists, technologists, engineers, and experienced terrestrial telerobotics/telepresence experts is needed. More workshops, perhaps virtual ones, could help develop specific activities, experiments, studies, and investments to refine the key questions and capability gaps associated with space-based low latency telepresence in specific locations and for particular purposes.

The K10 planetary rover has four-wheel drive and all-wheel steering on a passive rocker suspension, a design that allows operation on moderately rough terrain.

On the science side, Garvin stresses, "There is a profound lack of real experience with low latency telepresence here on Earth, in geological field situations, with which to understand how to utilize the obvious benefits of this approach on the Moon, Mars, asteroids, or beyond." This experience gap limits our understanding of how to develop the engineering and technology capabilities required for using low latency telepresence in deep space field science.

Garvin senses that there is "bona fide enthusiasm" for low latency telepresence as part of a "flexible path" approach for deep space human exploration. Indeed, human spaceflight can provide significant field science and other activities at new destinations without having to initially place human boots on the ground.

Clearly there are settings and environments where human field explorers on other worlds *should never go*, Garvin emphasizes. In such places, even very local low latency telepresence operations, with robots there and people in nearby safe havens, could be essential.

"My general feeling is that low latency telerobotics is a critical capability that must be investigated so that future human-robotic scientific activities can open up new frontiers in our scientific understanding of Mars, the Moon, asteroids, Venus, and other targets of exploration opportunity," Garvin concludes. ▲