ROBOTS v

Who Should

Unmanned spacecraft are exploring the solar system more cheaply and effectively than astronauts are

by Francis Slakey

The National Aeronautics and Space Administration has a difficult task. It must convince U.S. taxpayers that space science is worth $13.6 billion a year. To achieve this goal, the agency conducts an extensive public-relations effort that is similar to the marketing campaigns of America's biggest corporations. NASA has learned a valuable lesson about marketing in the 1990s: to promote its programs, it must provide entertaining visuals and stories with compelling human characters. For this reason, NASA issues a steady stream of press releases and images from its human spaceflight program.

Every launch of the space shuttle is a media event. NASA presents its astronauts as ready-made heroes, even when their accomplishments in space are no longer groundbreaking. Perhaps the best example of NASA's public-relations prowess was the participation of John Glenn, the first American to orbit Earth, in shuttle mission STS-95 last year. Glenn's return to space at the age of 77 made STS-95 the most avidly followed mission since the Apollo moon landings. NASA claimed that Glenn went up for science—he served as a guinea pig in various medical experiments—but it was clear that the main benefit of Glenn's space shuttle ride was publicity, not scientific discovery.

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NASA AND CARNEGIE MELLON UNIVERSITY

NOMAD ROVER developed by the Robotics Institute at Carnegie Mellon University is shown traversing the icy terrain of Antarctica late last year. Scientists are testing the prototype in inhospitable environments on Earth to develop an advanced rover for future unmanned space missions.

s. HUMANS

Explore Space?

Astronaut explorers can perform science in space that robots cannot

by Paul D. Spudis

NASA

APOLLO 17 **ASTRONAUT Harrison Schmitt investigates a huge boulder at the Taurus-Littrow landing site on the moon in 1972. Schmitt, a geologist, made important discoveries about the moon's composition and history, thus demonstrating the value of astronauts as space explorers.**

Criticism of human spaceflight comes from many quarters. Some critics point to the high cost of manned missions. They contend that the National Aeronautics and Space Administration has a full slate of tasks to accomplish and that human spaceflight is draining funds from more important missions. Other critics question the scientific value of sending people into space. Their argument is that human spaceflight is an expensive "stunt" and that scientific goals can be more easily and satisfactorily accomplished by robotic spacecraft.

But the actual experience of astronauts and cosmonauts over the past 38 years has decisively shown the merits of people as explorers of space. Human capability is required in space to install and maintain complex scientific instruments and to conduct field exploration. These tasks take advantage of human flexibility, experience and judgment. They demand skills that are unlikely to be automated within the foreseeable future. A program of purely robotic exploration is inadequate in addressing the important scientific issues that make the planets worthy of detailed study.

Many of the scientific instruments sent into space require careful emplacement and alignment to work properly. Astronauts have successfully deployed instruments in Earth orbit—for example, the Hubble Space Telescope—and on the sur-

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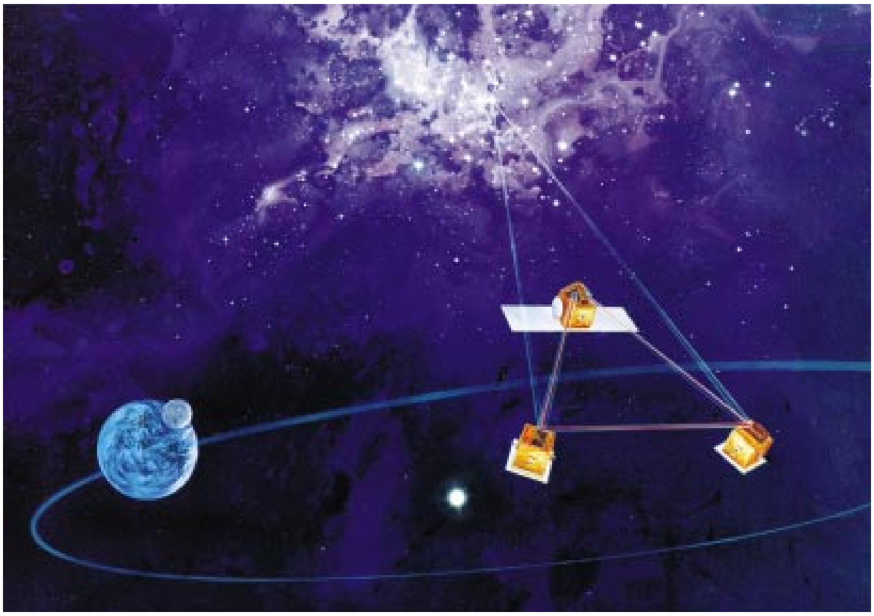
NASA is still conducting grade-A science in space, but it is being done by unmanned probes rather than astronauts. In recent years the Pathfinder rover has scoured the surface of Mars, and the Galileo spacecraft has surveyed Jupiter and its moons. The Hubble Space Telescope and other orbital observatories are bringing back pictures of the early moments of creation. But robots aren't heroes. No one throws a ticker-tape parade for a telescope. Human spaceflight provides the stories that NASA uses to sell its programs to the public. And that's the main reason NASA spends nearly a quarter of its budget to launch the space shuttle about half a dozen times each year.

The space agency has now started building the International Space Station, the long-planned orbiting laboratory. NASA says the station will provide a platform for space research and help determine how people can live and work safely in space. This knowledge could then be used to plan a manned mission to Mars or the construction of a base on the moon. But these justifications for the station are largely myths. Here are the facts, plain as potatoes: The International Space Station is not a platform for cutting-edge science. Unmanned probes can explore Mars and other planets more cheaply and effectively than manned missions can. And a moon colony is not in our destiny.

The Myth of Science

In 1990 the American Physical Society, an organization of 41,000 physicists, reviewed the experiments then planned for the International Space Station. Many of the studies involved examining materials and fluid mechanics in the station's microgravity environment. Other proposed experiments focused on growing protein crystals and cell cultures on the station. The physical society concluded, however, that these experiments would not provide enough useful scientific knowledge to justify building the station. Thirteen other scientific organizations, including the American Chemical Society and the American Crystallographic Association, drew the same conclusion.

Since then, the station has been redesigned and the list of planned experiments has changed, but the research community remains overwhelmingly opposed. To date, at least 20 scientific organizations from around the world have determined that the experiments in their respective fields are a waste of time and money. All



NASA/JET PROPULSION LABORATORY

UNMANNED SPACECRAFT are becoming more versatile. In the Deep Space 3 mission, scheduled for launch in 2002, three vessels will fly in formation to create an optical interferometer, which will observe distant stars at high resolution. The spacecraft will fly between 100 meters and one kilometer apart.

these groups have recommended that space science should instead be done through robotic and telescopic missions.

These scientists have various reasons for their disapproval. For researchers in materials science, the station would simply be too unstable a platform. Vibrations caused by the movements of astronauts and machinery would jar sensitive experiments. The same vibrations would make it difficult for astronomers to observe the heavens and for geologists and climatologists to study Earth's surface as well as they could with unmanned satellites. The cloud of gases vented from the station would interfere with any experiments in space nearby that require near-vacuum conditions. And last, the station would orbit only 400 kilometers (250 miles) overhead, traveling through a region of space that has already been studied extensively.

Despite the scientific community's disapproval, NASA plans to go ahead with the proposed experiments on the space station. The agency has been particularly enthusiastic about studying the growth of protein crystals in microgravity; NASA claims the studies may spur the development of better medicines. But in July 1998 the American Society for Cell Biology bluntly called for the cancellation of the crystallography program. The society's review panel concluded that the proposed experiments were not likely to make any serious contributions to the knowledge of protein structure.

The Myth of Economic Benefit

Human spaceflight is extremely expensive. A single flight of the space shuttle costs about $420 million. The shuttle's cargo bay can carry up to 23,000 kilograms (51,000 pounds) of payload into orbit and can return 14,500 kilograms back to Earth. Suppose that NASA loaded up the shuttle's cargo bay with confetti before launching it into space. Even if every kilogram of confetti miraculously turned into a kilogram of gold during the trip, the mission would still lose $270 million.

The same miserable economics hold for the International Space Station. Over the past 15 years the station has undergone five major redesigns and has fallen 11 years behind schedule. NASA has already spent nearly twice the $8 billion that the original project was supposed to cost in its entirety. The construction budget is now expected to climb above $40 billion, and the U.S. General Accounting Office estimates that the total outlay over the station's expected 10-year lifetime will exceed $100 billion.

NASA had hoped that space-based manufacturing on the station would offset some of this expense. In theory, the microgravity environment could allow the production of certain pharmaceuticals and semiconductors that would have advantages over similar products made on Earth. But the high price of sending anything to the station has dissuaded most companies from even exploring the idea.

NASA/JET PROPULSION LABORATORY

DEEP SPACE 4 mission will test the technologies for landing an unmanned probe on a comet. Slated for launch in 2003, the spacecraft will rendezvous with Comet Tempel 1, land a probe on the comet's nucleus and return drilling samples to Earth.

So far the station's only economic beneficiary has been Russia, one of America's partners in the project. Last year NASA announced plans to pay $660 million over four years to the Russian Space Agency so it can finish construction of key modules of the station. The money was needed to make up for funds the Russians could not provide because of their country's economic collapse. U.S. Congressman James Sensenbrenner of Wisconsin, who chairs the House Science Committee, bitterly referred to the cash infusion as "bailout money" for Russia.

But what about long-term economic benefits? NASA has maintained that the ultimate goal of the space station is to serve as a springboard for a manned mission to Mars. Such a mission would probably cost at least as much as the station; even the most optimistic experts estimate that sending astronauts to the Red Planet would cost tens of billions of dollars. Other estimates run as high as $1 trillion. The only plausible economic benefits of a Mars mission would be in the form of technology spin-offs, and history has shown that such spin-offs are a poor justification for big-money space projects.

In January 1993 NASA released an internal study that examined technology spin-offs from previous missions. According to the study, "NASA's technology-transfer reputation is based on some famous examples, including Velcro, Tang and Teflon. Contrary to popular opinion, NASA created none of these." The report concluded that there have been very few technology-transfer successes at NASA over the past three decades.

The Myth of Destiny

Now it's time to get personal. When I was seven years old, I had a poster of the Apollo astronauts on my bedroom wall. My heroes had fearlessly walked on the moon and returned home in winged glory. They made the universe seem a bit smaller; they made my eyes open a bit wider. I was convinced that one day I would follow in their footsteps and travel to Mars.

So, what happened? I went to Mars three times—twice with the Viking landers in the late 1970s and the last time with the Mars Pathfinder mission in July 1997. I wasn't alone: millions of people joined me in front-row seats to watch Pathfinder's rugged Sojourner rover scramble over the Martian landscape. I've also traveled to Jupiter's moons with the Galileo spacecraft and seen hints of a liquid ocean on Europa. In 2004 I'll go to Saturn with the Cassini probe and get a close-up view of the planet's rings.

In recent years there have been tremendous strides in the capabilities of unmanned spacecraft. NASA's Discovery program has encouraged the design of compact, cost-effective probes that can make precise measurements and transmit high-quality images. Mars Pathfinder, for example, returned a treasure trove of data and pictures for only $265 million. And NASA's New Millennium program is testing advanced technologies with spacecraft such as the Deep Space 2 microprobes. These two-kilogram instruments, now riding piggyback on the Mars Polar Lander spacecraft launched earlier this year, will plunge to the surface of Mars and penetrate up to two meters underground, where they will analyze soil samples and search for subsurface ice.

These spacecraft will still need human direction, of course, from scientists and engineers in control rooms on Earth. Unlike astronauts, mission controllers are usually not celebrated in the press. But if explorers Lewis and Clark were alive today, that's where they would be sitting. They would not be interested in spending their days tightening bolts on a space station.

Building a manned base on the moon makes even less sense. Unmanned spacecraft can study the moon quite efficiently, as the Lunar Prospector probe has recently shown. It is not our destiny to build a moon colony any more than it is to walk on our hands.

What's Next?

For the present, NASA appears committed to maintaining its human spaceflight program, whatever the cost. But in the next decade the space agency may discover that it does not need human characters to tell compelling stories. Mars Pathfinder proved that an unmanned mission can thrill the public just as much as a shuttle flight. The Pathfinder World Wide Web site had 720 million hits in one year. Maybe robots can be heroes after all.

Instead of gazing at posters of astronauts, children are now playing with toy models of the Sojourner rover. The next generation of space adventurers is growing up with the knowledge that one can visit another planet without boarding a spacecraft. Decades from now, when those children are grown, some of them will lead the next great explorations of the solar system. Sitting in hushed control rooms, they will send instructions to far-flung probes and make the final adjustments that point us toward the stars. SA

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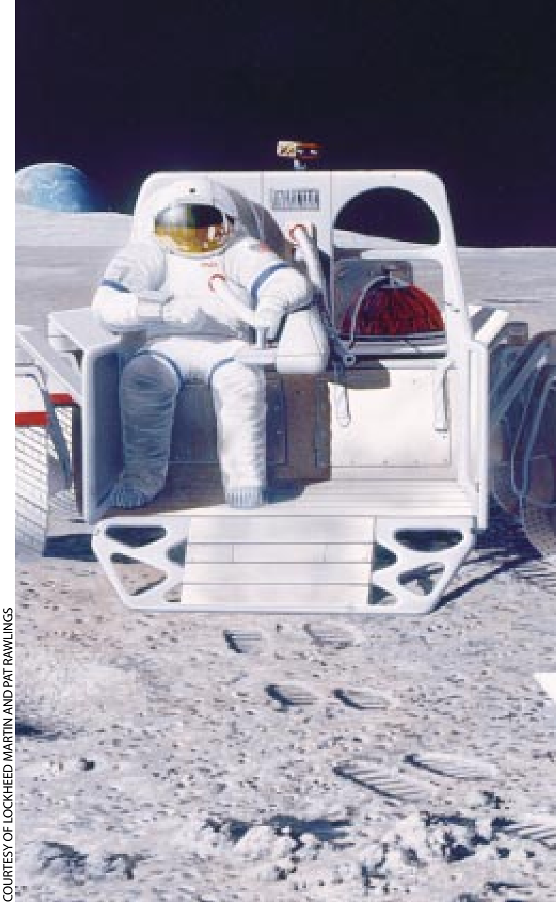

FUTURE ASTRONAUTS perform maintenance on a telescope on the moon's surface in this artist's conception. Humans are far more capable than robots in deploying scientific instruments and repairing complex equipment in space.

COURTESY OF LOCKHEED MARTIN AND PAT RAWLINGS

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face of Earth's moon. In the case of the space telescope, the repair of the originally flawed instrument and its continued maintenance have been ably accomplished by space shuttle crews on servicing missions. From 1969 to 1972 the Apollo astronauts carefully set up and aligned a variety of experiments on the lunar surface, which provided scientists with a detailed picture of the moon's interior by measuring seismic activity and heat flow. These experiments operated flawlessly for eight years until shut down in 1977 for fiscal rather than technical reasons.

Elaborate robotic techniques have been envisioned to allow the remote emplacement of instruments on planets or moons. For example, surface rovers could conceivably install a network of seismic monitors. But these techniques have yet to be demonstrated in actual space operations. Very sensitive instruments cannot tolerate the rough handling of robotic deployment. Thus, the auto-deployed versions of such networks would very likely have lower sensitivity and capability than their human-deployed counterparts do.

The value of humans in space becomes even more apparent when complex equipment breaks down. On several occasions astronauts have been able to repair hardware in space, saving missions and the precious scientific data that they produce. When Skylab was launched in 1973, the lab's thermal heat shield was torn off and one of its solar panels was lost. The other solar panel, bound to the lab by restraining ties, would not release. But the first Skylab crew—astronauts Pete Conrad, Joe Kerwin and Paul Weitz—installed a new thermal shield and deployed the pinned solar panel. Their heroic efforts saved not only their mission but also the entire Skylab program.

Of course, some failures are too severe to be repaired in space, such as the damage caused by the explosion of an oxygen tank on the *Apollo 13* spacecraft in 1970. But in most cases when spacecraft equipment malfunctions, astronauts are able to analyze the problem, make on-the-spot judgments and come up with innovative solutions. Machines are capable of limited self-repair, usually by switching to redundant systems that can perform the same tasks as the damaged equipment, but they do not possess as much flexibility as people. Machines can be designed to fix expected problems, but so far only people have shown the ability to handle unforeseen difficulties.

Astronauts as Field Scientists

Exploration has two stages: reconnaissance and field study. The goal of reconnaissance is to acquire a broad overview of the compositions, processes and history of a given region or planet. Questions asked during the reconnaissance phase tend to be general—for instance, What's there? Examples of geologic reconnaissance are an orbiting spacecraft mapping the surface of a planet, and an automated lander measuring the chemical composition of the planet's soil.

The goals of field study are more ambitious. The object is to understand planetary processes and histories in detail. This requires observation in the field, the creation of a conceptual model, and the formulation and testing of hypotheses. Repeated visits must be made to the same geographic location. Field study is an open-ended, ongoing activity; some field sites on Earth have been studied continuously for more than 100 years and still provide scientists with important new insights. Field study is not a simple matter of collecting data: it requires the guiding presence of human intelligence. People are needed in the field to analyze the overabundant data and determine what should be collected and what should be ignored.

The transition from reconnaissance to field study is fuzzy. In any exploration, reconnaissance dominates the earliest phases. Because it is based on broad questions and simple, focused tasks, reconnaissance is the type of exploration best suited to robots. Unmanned orbiters can provide general information about the atmosphere, surface features and magnetic fields of a planet. Rovers can traverse the planet's surface, testing the physical and chemical properties of the soil and collecting samples for return to Earth.

But field study is complicated, interpretive and protracted. The method of solving the scientific puzzle is often not apparent immediately but must be formulated, applied and modified during the course of the study. Most important, fieldwork nearly always involves uncovering the unexpected. A surprising discovery may lead scientists to adopt new exploration methods or to make different observations. But an unmanned probe on a distant planet cannot be redesigned to observe unexpected phenomena. Although robots can gather significant amounts of data, conducting science in space requires *scientists*.

It is true that robotic missions are much less costly than human missions; I contend that they are also much less capable. The unmanned Luna 16, 20 and 24 spacecraft launched by the Soviet Union in the 1970s are often praised for returning soil samples from the moon at little cost. But the results from those missions are virtually incomprehensible without the paradigm provided by the results from the manned Apollo program. During the Apollo missions, the geologically trained astronauts were able to select the most representative samples of a given locality and recognize interesting or exotic rocks and act on such discoveries. In contrast, the Luna samples were scooped up indiscriminately by the robotic probes. We understand the geologic makeup and structure of each Apollo site in much greater detail than those of the Luna sites.

For a more recent example, consider the Mars Pathfinder mission, which was widely touted as a major success. Although Pathfinder discovered an unusual, silica-rich type of rock, because of the probe's limitations we do not know whether this composition represents an

igneous rock, an impact breccia or a sedimentary rock. Each mode of origin would have a widely different implication about the history of Mars. Because the geologic context of the sample is unknown, the discovery has negligible scientific value. A trained geologist could have made a field identification of the rock in a few minutes, giving context to the subsequent chemical analyses and making the scientific return substantially greater.

The Melding of Mind and Machine

Human dexterity and intelligence are the prime requirements of field study. But is the physical presence of people really required? Telepresence—the remote projection of human abilities into a machine—may permit field study on other planets without the danger and logistical problems associated with human spaceflight. In telepresence the movements of a human operator on Earth are electronically transmitted to a robot that can reproduce the movements on another planet's surface. Visual and tactile information from the robot's sensors give the human operator the sensation of being present on the planet's surface, "inside" the robot. As a bonus, the robot surrogate can be given enhanced strength, endurance and sensory capabilities.

If telepresence is such a great idea, why do we need humans in space? For one, the technology is not yet available. Vision is the most important sense used in field study, and no real-time imaging system developed to date can match human vision, which provides 20 times more resolution than a video screen. But the most serious obstacle for telepresent systems is not technological but psychological. The process that scientists use to conduct exploration in the field is poorly understood, and one cannot simulate what is not understood.

Finally, there is the critical problem of time delay. Ideally, telepresence requires minimal delays between the operator's command to the robot, the execution of the command and the observation of the effect. The distances in space are so vast that instantaneous response is impossible. A signal would take 2.6 seconds to make a round-trip between Earth and its moon. The round-trip delay between Earth and Mars can be as long as 40 minutes, making true telepresence impossible. Robotic Mars probes must rely on a cumbersome interface, which forces the operator to be more preoccupied with physical manipulation than with exploration.

Robots and Humans as Partners

Currently NASA is focusing on the construction of the International Space Station. The station is not a destination, however; it is a place to learn how to roam farther afield. Although some scientific research will be done there, the station's real value will be to teach astronauts how to live and work in space. Astronauts must master the process of in-orbit assembly so they can build the complex vehicles needed for interplanetary missions. In the coming decades, the moon will also prove useful as a laboratory and test bed. Astronauts at a lunar base could operate observatories and study the local geology for clues to the history of the solar system. They could also use telepresence to explore the moon's inhospitable environment and learn how to mix human and robotic activities to meet their scientific goals.

The motives for exploration are both emotional and logical. The desire to probe new territory, to see what's over the hill, is a natural human impulse. This impulse also has a rational basis: by broadening the imagination and skills of the human species, exploration improves the chances of our long-term survival. Judicious use of robots and unmanned spacecraft can reduce the risk and increase the effectiveness of planetary exploration. But robots will never be replacements for people. Some scientists believe that artificial-intelligence software may enhance the capabilities of unmanned probes, but so far those capabilities fall far short of what is required for even the most rudimentary forms of field study.

To answer the question "Humans or robots?" one must first define the task. If space exploration is about going to new worlds and understanding the universe in ever increasing detail, then both robots and humans will be needed. The strengths of each partner make up for the other's weaknesses. To use only one technique is to deprive ourselves of the best of both worlds: the intelligence and flexibility of human participation and the beneficial use of robotic assistance. SA

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