

An Argument for Human Exploration of the Moon and Mars

Robots can be trained to do straightforward tasks only with difficulty. Is it realistic to expect them to do field science on a distant planet?

Paul D. Spudis

Many scientists view the manned space program as a colossal waste of resources. The usual argument is that Neil Armstrong did nothing on the moon that a clever robot could not have done easier and cheaper (Van Allen 1986). At the same time, other scientists are unimpressed by the accomplishments of robotics and artificial intelligence. They tend to be rather amused by the general public's fascination with the notion that computers or robots might soon rival human abilities. Since these views are usually discussed in different contexts, it rarely occurs to anyone that they might be inconsistent.

The long-standing debate over the merits of human space missions was revived three years ago by the announcement of the Space Exploration Initiative. On July 21, 1989 (the 20th anniversary of the first landing on the moon), President Bush proposed that the United States commit itself to establishing a permanent base on the moon and to an expedition to the planet Mars. Bush's speech emphasized the presence of people in space, but the initiative is taking shape as a program that integrates human and robotic missions.

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Since the president's speech, the Space Exploration Initiative has been criticized on a variety of grounds. Should we put more money into space when we allegedly don't have the resources to address pressing problems here on earth? Should we start another space program when NASA already has a full slate of missions and is having trouble carrying them out? These are important questions, but in this article I wish to limit discussion to another issue. Do people have a role in the scientific exploration of space? Within the research community, it is almost an article of faith that robotic missions are always the best way of doing science in space. Is this view really the only tenable one?

The skepticism about human missions has some historical justification. I believe it arose in part because past missions did not always make the best use of human abilities. During the Apollo landings, for example, detailed mission plans inhibited the astronauts from engaging in the kind of free-style exploration at which people excel.

On the other hand, the past two decades of work in robotics and artificial intelligence have taught us that some human skills are difficult or impossible to automate. Furthermore, the skills we take most for granted are often the ones that present the greatest challenge to a machine. It is harder for a computer to recognize a familiar face than to prove a mathematical theorem. And it is harder for a robot to pick a spark plug out of a bin than to probe and test a microcircuit for electrical faults. The Space Exploration Initiative provides an opportunity to reassess the division of labor in space and to arrive at one that better reflects our new understanding of the strengths of both people and machines.

Although the goals of the initiative have not yet been determined, it seems likely that one goal will be conducting

planetary science on the moon and Mars. Exploring a planet is the sort of endeavor that brings out the best in people and the worst in machines. This can be seen by considering specific tasks, such as installing complex instruments, repairing equipment and doing field work. Each such task requires a combination of manipulative and cognitive skills and their interplay. In short, they are the kinds of tasks that have consistently frustrated attempts at automation.

The response might be that human skills, however superior, come at too high a price. Automated landers and orbiters may not be able to do as much, but 10 or 20 of them cost the same as a single human mission. I would argue, however, that it makes no sense to talk about cost without also talking about return. And any calculation of the return from a space mission must tally not just rocks retrieved or instruments delivered but also knowledge gained. If success is measured in terms of knowledge, a human exploratory program is likely to prove much more cost-effective than a robotic one.

Custom Installation

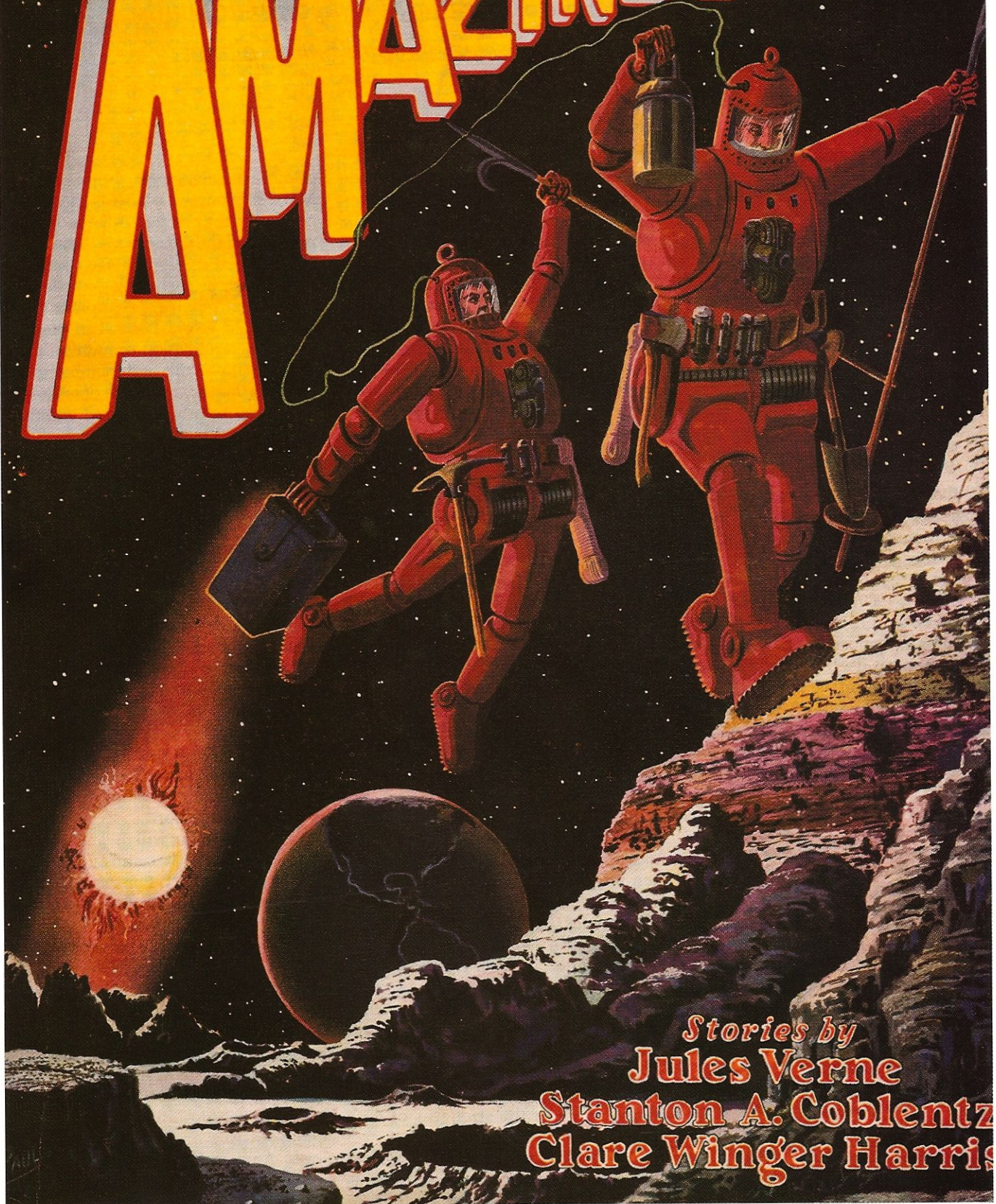
Exploring a planet will mean installing a variety of complex and delicate scientific instruments. For example, networks of geophysical instruments might be deployed on the surface of the moon and Mars as part of an effort to determine the composition of their interiors. Or the moon might be employed as an observatory from which to view the rest of the universe. The geophysical stations would probably include seismometers, magnetometers and heat-flow probes. The astronomical observatories might consist of single telescopes or of interferometer arrays. Any exploratory mission would undoubtedly install many other scientific instruments as well.

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Elaborate means for the automatic installation of instruments have been envisioned (for a summary, see Spudis and Taylor 1990). One possibility is a penetrator—essentially an arrow, carrying selected instruments, that is shot into the ground. Another is a “soft-hard” lander—a vehicle whose impact would be cushioned by a device similar to an automobile airbag. A third possibility is a surface rover, which would carry an instrument to the desired location and then deploy it in a more controlled way. Although these techniques may sound feasible, none has been fully demonstrated in space.

Moreover, installing complex equipment requires more than putting it down gently and in a designated spot. A seismometer, for example, must be leveled and thermally insulated from the environment. The best signal quality is obtained if the instrument is coupled directly to bedrock. A magnetometer must be leveled, and its orientation with respect to the planet’s coordinates must be precisely determined. A heat-flow probe must be lowered to a prescribed depth within a hole drilled in the planet’s surface. Moreover, all of this equipment is likely to need minor adjustment or maintenance after it is installed.

Whether robots could install complex equipment on the surface of a planet is uncertain. Those familiar with recent robotics programs may be forgiven a certain skepticism. For example, it recently took six years of concerted effort to teach a robot to assemble an electromechanical switch.

Although no one really knows whether robots could install instruments without assistance, we do have

Figure 1. Space exploration has long entailed much more than scientific information-gathering; in the public mind it also includes an important component of adventure, which implies human presence. This emphasis on people in space is clearly apparent in science fiction, where the point of space technology is almost invariably to enable people to travel to other planets and to meet other beings. *Amazing Stories* was one of several science-fiction magazines founded in the 1920s and 1930s by Hugo Gernsback. The caption for the cover of the May 1929 issue reads: “This month’s [cover] depicts a scene from ‘The Moon Strollers’ by J. Rogers Ullrich, in which two of the scientists who had gone to the Moon, while on an exploration expedition became aware of the very low gravitational attraction, because they experienced such complete ease in climbing to the top of the beacon, despite their heavy strollers, which on Earth would have made even ordinary walking extremely difficult.” (Photograph courtesy Special Collections, Syracuse University Library.)

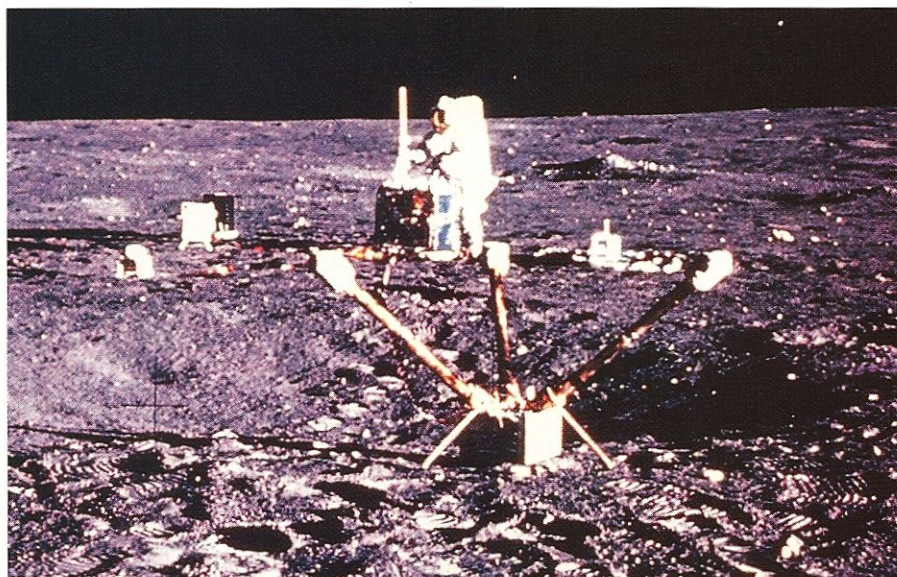


Figure 2. Deploying scientific instruments on a planet’s surface is one of several tasks that could benefit from human intervention. Setting up instruments may seem a simple chore, but it requires skills that are difficult to automate. Here a member of the Apollo 12 crew erects an ALSEP (Apollo Lunar Surface Experiment Package) station on the moon. Each station consisted of several types of geophysical instruments. The astronaut stands beside the central station, which houses data processing and transmission facilities. A passive seismic station is to his left. The three-pronged device in the foreground is a magnetometer.

some practical experience with astronauts. In the late 1960s and early 1970s the Apollo Lunar Surface Experiment Packages, called ALSEPs, were placed at five sites on the moon (Bates et al. 1979). They operated as a surface network for more than eight years. The Apollo astronauts were called upon to select sites for the packages, to align the instruments (most of which had complicated isolation or orientation requirements) and to verify that they were operating properly.

Reviewing the ALSEP experience with robotics in mind is not encouraging. The process of installing the heat-flow probes may suggest why. The probes were inserted into holes that had been drilled to depths of a few meters in the lunar surface. The holes were drilled manually and in stages. When the limit of travel of one bit was reached, the drill was removed, and a new stem was added to the bit. If the bit ran into buried rock, the astronauts decided whether to continue drilling or to try a different site. Once a hole was complete, the probe was lowered to the bottom of the drill tube, and its lead wires were connected to an electronics box on the surface, tasks that required some dexterity. In short, installing the probes required a uniquely human coupling of manipulative skills and cognitive abilities.

I don’t mean to suggest that robotic installation has no role to play, but rather that reliance on robots would lim-

it the science that could be done. The use of the moon as an astronomical observatory serves as an example. The moon could be a superb observatory because its nights are two weeks long and the skies are dark, cold and crystal clear (Smith 1990). An initial lunar observatory might consist of small, automated “suitcase” instruments. Significant science could be done with such equipment. An occupied base on the moon, however, would allow the construction of much more sophisticated instruments, including large interferometer arrays (Burns et al. 1990). Because the moon is not subject to seismic disturbances and there is no atmosphere to limit resolution, an interferometer array could operate at optical wavelengths as well as the radio wavelengths employed by terrestrial interferometers. Such a lunar array might provide an angular resolution approaching a microarcsecond, almost a million times better than the resolution of the best earth-based telescopes. One can only guess what it would enable us to see. Even on the earth, however, installing and aligning an interferometer array is difficult. Erecting one on the moon by robotic means alone would be impossible.

Bubble Gum and Baling Wire

In addition to scientific instruments, any exploratory mission will include many other types of equipment, all of them inevitably subject to breakdowns.

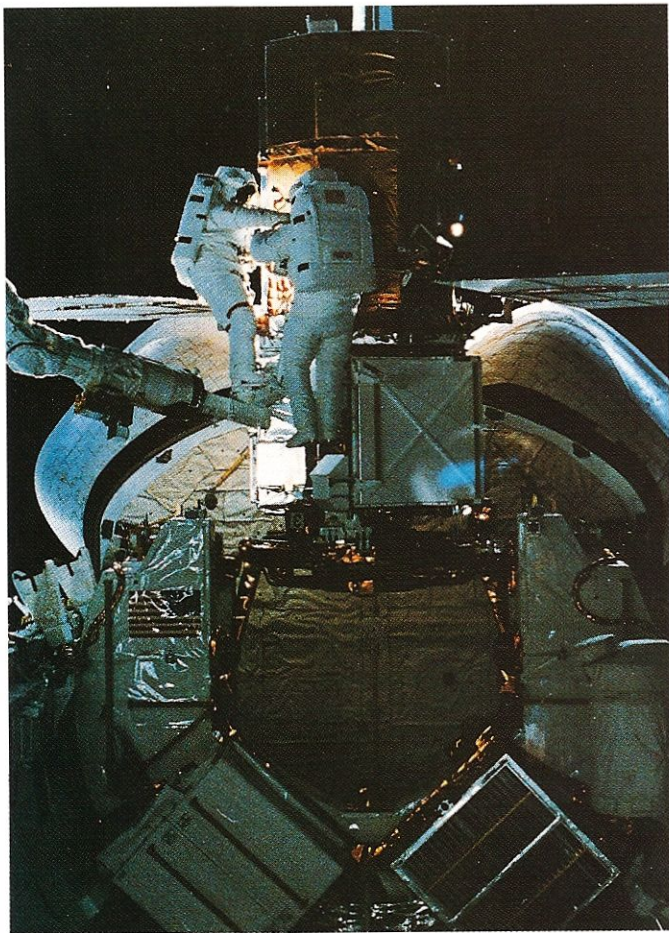


Figure 3. Equipment repair is another task at which people have a seemingly insuperable advantage over machines. Here two astronauts repair the Solar Maximum Mission satellite, whose attitude-control system had failed in 1981, after eight months in earth orbit. In April of 1984 the shuttle Challenger was launched with the primary aim of repairing the satellite. Capturing the 5,000-pound satellite, which had begun to tumble, was more difficult than expected, but the actual repairs were completed in a few hours. The failure was caused by three blown fuses.

The repair and maintenance of this equipment will require the same elusive combination of skills as installing and adjusting scientific instruments. How do people determine whether to replace a fuse, to stick in a shim or to administer a swift kick? Again the answer seems to be through the poorly understood fusion of manipulative and cognitive skills.

Robotic craft can undertake some limited repairs under human guidance, but the process is notoriously ponderous. The Viking 1 lander provides a representative instance. Its surface sampler jammed the first time it was operated on Mars. Determining why the sampler was jammed was difficult because the lander was returning only modest amounts of engineering data, such as motor currents and the last successfully executed command. The problem was finally diagnosed by recreating it with a

full-scale lander mock-up in a simulated Martian setting. It turned out that a latch pin had failed to fall clear of the surface-sampler mechanism when the sampler's boom was first extended. The solution was to extend the boom farther. The pin fell free, and the problem was solved, but it had taken three days of effort to solve it.

One of the less-recognized benefits of manned missions is much more flexible and capable response to contingencies. During the Apollo 17 mission, for example, one of the lunar rover's fenders broke off, and fine dust began to spray up over the rover and crew. The dust covered the lens of the television camera and the astronauts' helmets, blinding them. And when electronic equipment became coated with dust, it began to overheat. The astronauts solved the problem by making a replacement fender out of extra maps of the area

they were to traverse (Lewis 1974). Without this clever repair, they might have had to cut short exploratory trips.

In the case of Skylab, human ingenuity can be credited with saving the spacecraft, the mission and the entire program. When the orbital workshop was launched atop a Saturn 5, a protective shroud pulled off. The shroud took with it a solar panel and most of the workshop's thermal insulation, making the lab uninhabitable. The first crew to be sent up had to spend several days repairing the structure, installing improvised fixes and adjusting them until they worked properly (Cooper 1976). Of course there are equipment failures that cannot be solved in space, no matter what techniques are employed. But astronauts can repair or work around failures that would require the curtailment or abandonment of a robotic mission.

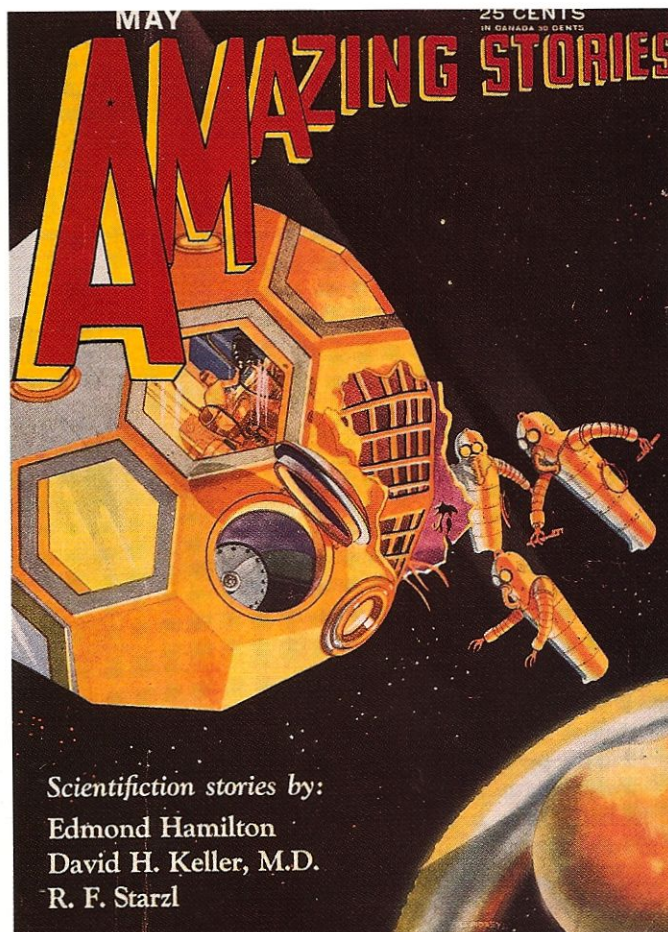


Figure 4. Repair of spacecraft was also a frequent theme of the early science-fiction writers. The cover of the May 1930 issue of *Amazing Stories* is explained as follows: "This month's [cover] illustrates a scene from part I of the story entitled, 'The Universe Wreckers' by Edmond Hamilton, in which the four travelers, fitted out in their space-walker suits, are making the necessary repairs to their space-flier, which sustained some damages while going through the asteroid zone on their way to Neptune." (Photograph courtesy Special Collections, Syracuse University Library.)

Swinging a Rock Pick

Most of what we know about the earth we have learned from 200 years of field work by hundreds of scientists. If we are to obtain a comparably detailed understanding of other planets, we must provide scientists with similar opportunities to explore them. Field work is *not* synonymous with sample collection, although the intelligent retrieval of samples is one of the activities field work includes.

The natural sciences follow similar strategies for field study; here I use my own discipline of geology as an example. Geological exploration has two phases, reconnaissance and field study, which place different requirements on the scientist (Spudis and Taylor 1988, 1991; Ryder, Spudis and Taylor 1989). The goal of reconnaissance is to acquire a broad overview of the composition of a given area, region or planet and of the geological processes at work there both now and in the past. The goal of field study is more ambitious. It is to construct a conceptual model of ongoing and historical geological processes that is consistent with field observations and to conduct further field work with the goal of confirming, refining or refuting that model.

Reconnaissance is the type of geological exploration most suited to robots. The broad questions it poses can be answered by collecting data according to some prearranged scheme. Tasks can accordingly be simple and well-focused. Several types of robotic missions could provide general information about planetary bodies. Orbiters could map the surface features of planets at a variety of resolutions, and landers could determine the characteristics and composition of surface materials. Rovers could test for small-scale spatial variations in physical and chemical properties and collect representative samples of large geological units for return to the earth. Robots might also be able to deploy networks of simple instruments or take shallow subsurface samples.

Field study, however, requires a guiding human presence. The reason is that its basic aim is understanding, and understanding demands some of the more elusive human skills. What a geologist mostly does in the field is think. His or her thoughts guide and are guided by observations, in ways that cannot be anticipated. Moreover, the geologist must be able to observe both the minute and the panoramic, both the individual instance and the overall

pattern. Finally, field study requires the ability to recognize the interesting, which is almost always the unexpected, and to modify the plan of study on the fly. Robots are good at none of these things. Although robots could play a significant role in gathering data, conducting science in space will require scientists.

Telepresence

Given that field study requires a human presence, does this mean people have to be present in body? What about telepresence, or the operation of a robot as an extension of a person (Wilson and MacDonald 1986; Sheridan 1989)? Wouldn't this allow true field study without posing the logistical problems of human missions (Spudis and Taylor 1988; Taylor and Spudis 1990)?

Telepresence is the most sophisticated form of teleoperation. The operator wears an exoskeleton of motion sensors and views stereo-converged images projected by a helmet-mounted display. As the operator moves, commands are

telemetered to the robot that cause it to duplicate his or her motions. Simultaneously, high-fidelity feedback signals give the operator the sensation of being inside the robot and physically present at the remote location. One advantage of telepresence is that the robot can be endowed with superhuman abilities. The robot might, for example, be equipped with infrared cameras or provided with great strength.

If telepresence is such a great idea, why do we need people in space? There are several answers to this question. For one thing, the technology for telepresence is not yet available, although it is within reach. A geologist relies on his or her vision more than on any other sense. To be a useful surrogate, a robot would have to be equipped with very-high-definition television cameras. A person with 20/20 vision is able to resolve details that extend through about 30 seconds of arc. This resolution is roughly equivalent to that of 10,000-line television. (Broadcast television images in the U.S. have 525 lines.) Such imaging systems, and the data subsystems needed to support



Figure 5. Fragile fender of the Apollo Lunar Rover provides an example of the ingenuity people bring to repair work. The commanders of the last three Apollo missions each broke a fender on the Rover. With the fender missing, the wheel sprayed lunar dust over the vehicle, which was more than a nuisance: By coating optical and electronic equipment, it could have curtailed exploration. A replacement fender was fashioned out of spare maps held by clamps.

them, have not yet been developed. Moreover, the schemes currently used for controlling robot manipulation and locomotion do not lend themselves to teleoperation. The kinesthetic feedback is likely to be confusing enough that the operator will feel even more clumsy than an astronaut in a pressure suit.

An experiment conducted at Oak Ridge National Laboratory in 1985 suggests the current limitations of teleoperation. Earlier that year two astronauts, working outside the shuttle in earth orbit, had assembled a metal frame of the kind that might be used in a space station. At Oak Ridge, a man and a teleoperated robot were set the same task. They successfully assembled the frame, but it took them three times as long as the astronauts. Although this might be acceptable for certain construction tasks, it is not acceptable for field work, which requires intimate involvement with the environment under study.

A second problem arises when telepresence is attempted over long distances. An operator has the sensation of being present at the remote location only if the delay between a command and feedback on the execution of that command is very brief (Wilson and MacDonald 1986). It takes 2.6 sec-

onds for a signal to travel from the earth to the moon and back. This might seem like a small time lag, but in fact it can be quite cumbersome, as the videotapes from the Apollo lunar-surface missions amply demonstrate. In the case of Mars, it can take up to 40 minutes for signals to make the round trip from the earth, and this delay renders true telepresence impossible. When the delays are so long, telepresence degenerates into remote operation. The operator inevitably becomes preoccupied with negotiating space and manipulating objects and can no longer be considered to be freely exploring the environment.

There are two ways around this problem. One approach is a technique called supervised telerobotics. Tasks requiring "higher intellectual functions," such as deciding which outcrop to examine or where to position an instrument, are accomplished by remote control. Simpler, allegedly more mechanical tasks, such as collecting a scoop of soil and placing it in a container, are accomplished without human direction. If the people operating the robots were field scientists, supervised telerobotics could be an effective reconnaissance technique.

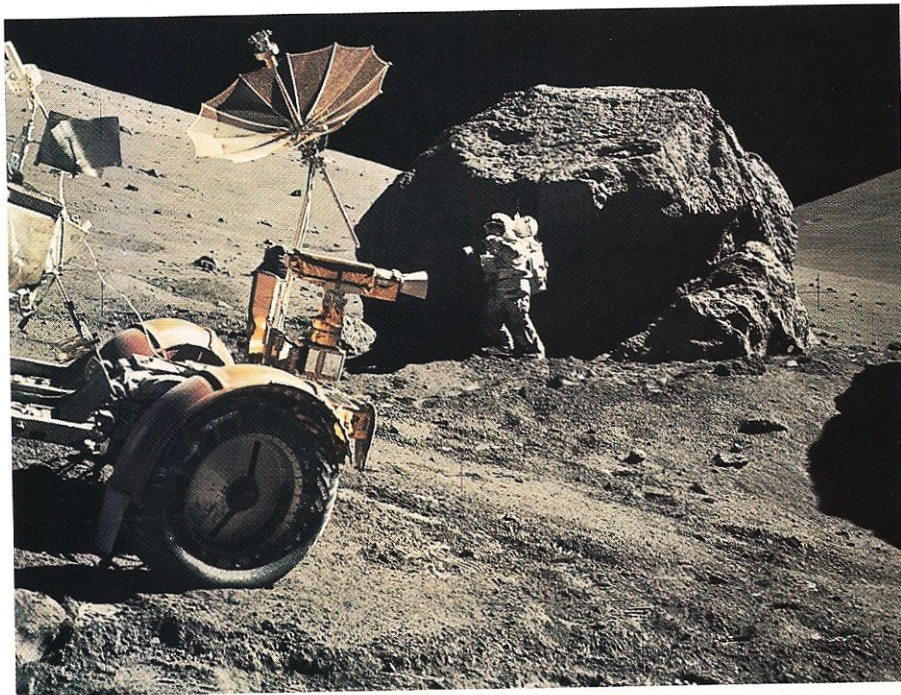


Figure 6. Field work is the most intellectually demanding part of an astronaut's work and the least likely to be successfully automated. Here Harrison H. Schmitt, the only geologist ever to fly to the moon, collects and documents samples from a boulder at the mountainous Taurus-Littrow site during the Apollo 17 mission in 1972. The boulder, a fragment of a melt sheet formed during a meteoritic impact, has rolled to its present position from the top of the massif that slopes upward to the left in this image. Schmitt recognized it as a breccia with multiple subunits and was able to photograph and collect specimens of each subunit. His on-site observations and later analysis of the specimens led to a reconstruction of the boulder's history, showing that it is a stratigraphic section through the melt sheet of the multi-ring Serenitatis basin.

The other possibility is to construct a simulacrum, or "virtual reality," of the planet here on earth, based on data collected by robot missions. Again sophisticated interface devices would assist the user in achieving the illusion of being in the simulated world. The user would be able to select an object at will, retrieving progressively more detailed images of it. The images might include ones made at nonvisible wavelengths that would provide information about mineral composition. The great attraction of such a simulacrum is that it could be studied by people with diverse interests and experiences. Ideally their insights would be used to guide later telerobotic or human field work on the planet itself.

The technologies needed for teleoperation and the construction of virtual realities are worthy of further development, but whether either technique will ever be an adequate substitute for people is another question. Can either achieve human presence? What does human presence mean anyway? I contend that for scientific work, human presence means it is possible to interact in real time with the environment in such a way that all of the human sensory and cognitive abilities can be brought to bear on the problem being studied.

I submit that we do not yet know whether teleoperation and virtual realities could achieve human presence. Ultimately, both technologies are hampered not by any failure of technological ingenuity but by our lack of psychological insight (McGreevy and Stoker 1990). In field work, the way that tactile and visual feedback combine with cognition to result in recognition and understanding is poorly understood. So is the means by which people extract a few significant observations from a flood of sensory data. I do not mean to suggest that the experience of field work is mystical. It is merely poorly understood and therefore very difficult or perhaps impossible to reproduce. Although we may not fully understand how people do field work, we know they can do it; the capabilities of potential robotic surrogates are uncertain.

Teaming Up

In past space efforts, the robotic and human phases of exploration were conducted separately. Indeed the assumption seems to have been that there is a natural sequence to space exploration, in which robotic precursors pave the way for later human missions (see, for

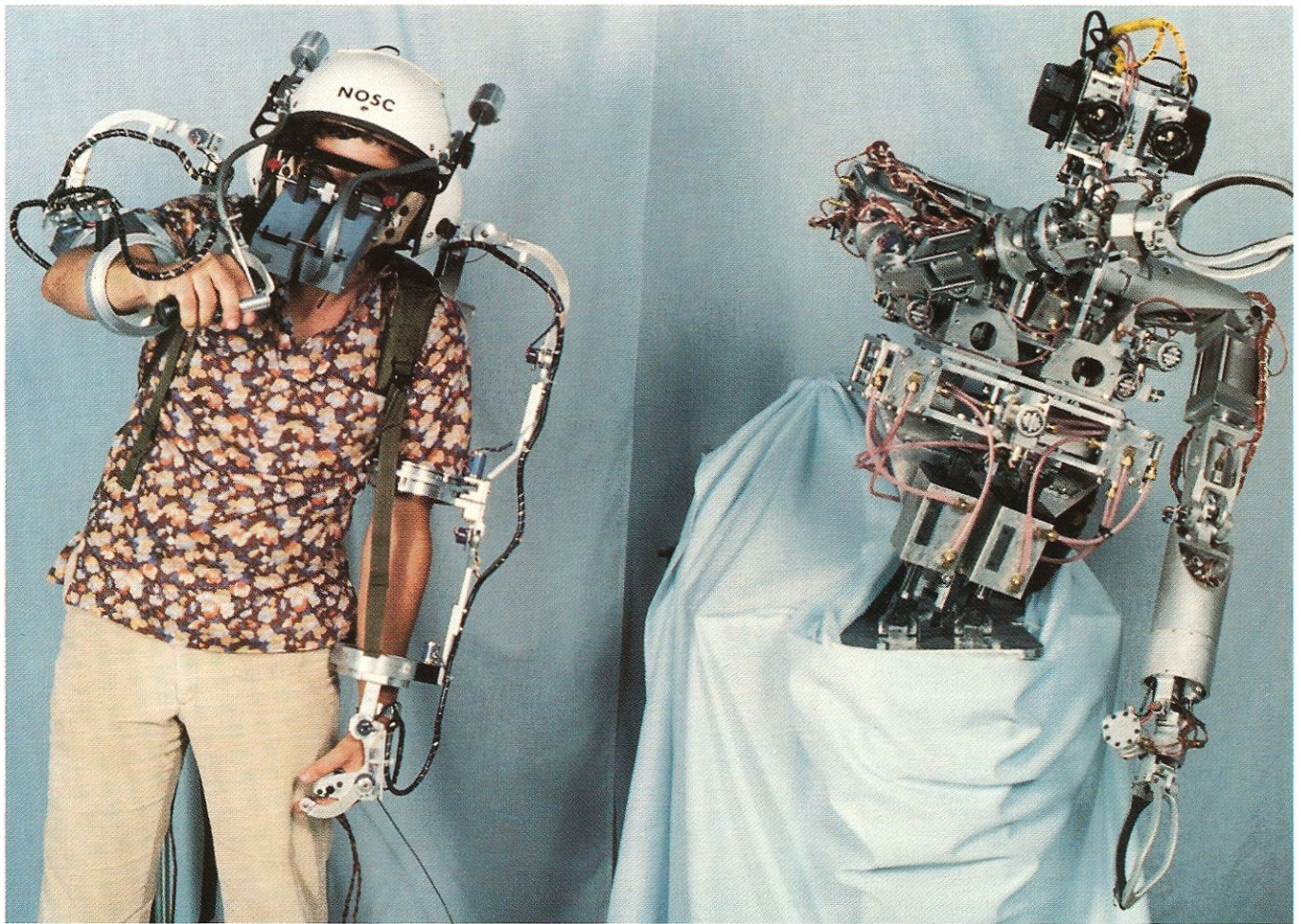


Figure 7. Telepresence, or the sensation of being present at a remote location, has been suggested as an alternative to direct human exploration of the extraterrestrial environment. Telepresence requires a sophisticated interface between a robot and its operator. Shown here is a telepresence test-bed system being developed for the U.S. Marine Corps at the Naval Command, Control and Ocean Surveillance Center in San Diego. The Marines are interested in robots for undersea work. The operator wears an exoskeleton of position sensors, whose outputs are transmitted to the robot, which mimics the operator's motions. The robot is equipped with a pair of cameras and a pair of microphones that communicate with the operator's helmet-mounted stereo display and binaural audio system. Robots designed for telepresence are of necessity more anthropomorphic than the ordinary industrial robot. A serious drawback to the use of such systems in space exploration is the long communications delay for interplanetary signals, which disrupts the operator's illusion of being present in the remote environment.

example, NASA 1989). This separation of roles accounts in part for the rise of two distinct spaceflight subcultures, one advocating the near-exclusive use of robotic spacecraft for exploration and the other preoccupied with the operational problems of human missions but largely oblivious to the contributions people could make to exploration.

I would argue that the combined and coordinated use of robots and people would produce a far greater scientific return than robotic or human missions alone or both separately. If people and machines act as partners, each can be assigned appropriate tasks. The robots can conduct simple reconnaissance operations under human control, whereas the people can perform detailed field study, with appropriate robotic assistance.

There are many opportunities for collaboration, but the richest will arise dur-

ing the course of detailed field studies. Scientists could study the area near a base first-hand and could survey outlying areas with the assistance of teleoperated robots. Autonomous and teleoperated rovers and landers could conduct long traverses of the planet, locating promising sites for visits by people. Robots could also be sent out repeatedly to collect samples as new information directed attention to new sites. With automated assistance, the scientists would be able to explore the planet in a fraction of the time it has taken to explore the earth.

But wouldn't it be much more expensive to establish a colony of scientists and robot assistants on a distant planet than to send up a volley of robotic craft? It has become an article of faith that robotic missions are much less costly than manned missions (Office of Technology Assessment 1991). I would con-

tend that they are also much less capable and therefore less cost-effective.

The truth is robotic craft have trouble with even the rudiments of field work. The Soviet Luna 15, 16, 20 and 24 sample-return spaceflights are frequently cited as examples of cost-effective space exploration. The automated techniques these spacecraft used to sample the moon's surface were only partly effective, however. One of the spacecraft failed to return, and the other Luna missions encountered various difficulties during core drilling and extraction that resulted in the loss of much of the core. Only one of the craft returned a complete core.

The Apollo missions were much more successful even though they also encountered difficulties. The Apollo 15 mission was the first to attempt to return a deep drill core. No one had anticipated



Figure 8. Creation of a virtual environment offers another alternative to personal presence in space. With digital imagery and other data gathered by robotic missions, it might be possible to construct a virtual planetary surface—one that exists only as a computer model—that an earthbound astronaut could wander over at will. The user typically wears a head-mounted stereoscopic display, which the computer operates in such a way that the scene changes appropriately as the user moves his or her head. The device shown here is the Virtual Planetary Exploration system developed at the NASA Ames Research Center by Michael W. McGreevy (*standing*) and his colleagues, one of whom is wearing a head-mounted display. The two monitors show the two slightly different images of the Martian landscape that are being projected within the goggles. The imagery comes from the Viking 2 lander. McGreevy and his colleagues have observed and interviewed planetary geologists to determine how they do field work and are currently attempting to design interface modes that will accommodate the geologists' needs.

how difficult it would be to extract an eight-foot core. In the end the astronauts wrestled it out bodily. The next two missions were equipped with a jack for core extraction, and all three returned a complete regolith drill core (Lewis 1974). Hauling a drill core out of the ground may not seem like the kind of high-level cognitive function for which a human presence is most indispensable, but that is part of the point. Not every problem can be solved by computation alone.

Conclusion

If one of the goals of the space program is to study the universe and to understand the solar system, human exploration must be a part of it. Robots and machines are tools. Used judiciously they can reduce risk and increase effectiveness, but they are not yet adequate substitutes for people. Despite the initial

enthusiasm, the accomplishments of artificial intelligence have been unimpressive so far. Telepresence and related technologies promise to extend human reach, but there is good reason to doubt a teleoperated robot will ever be an acceptable substitute for a human explorer.

Finally, I would like to glance briefly at the larger context of the debate over human missions. Many scientists assume that large, human spaceflight projects consume the bulk of NASA's budget, leaving little for the conduct of purely scientific missions. But space science is not now and never has been the primary purpose of the space program. Roughly 20 percent of NASA's budget is devoted to space science, and the fraction has remained the same throughout the history of the space program—even during the Apollo missions.

Moreover, some scientists suppose

that if the human space program were scaled back, more money would be available for space science. This seems to me highly unlikely. We should remember that support for the space program comes not from public enthusiasm for science but rather out of a long-standing romance with the notion of space travel. The reality is the nation is not going to spend billions of dollars a year just to look at solar heliopauses and to rendezvous with comets. Anyone who doubts this or questions whether human spaceflights are crucial to political support would be well-advised to read the record of last summer's congressional debate over the space station.

Nor do I think we should be impatient with the public's insistence that we explore space in person. The impulse to explore has stood us in good stead over the two million years of hu-

man evolution. It is this impulse that motivates many of our earth-bound scientific endeavors, after all. And it is this impulse that would give a human scientist an insuperable advantage over a robotic one on a distant planet.

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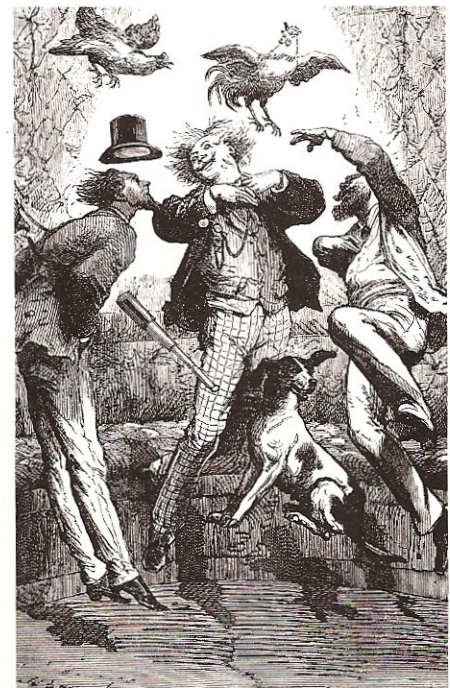
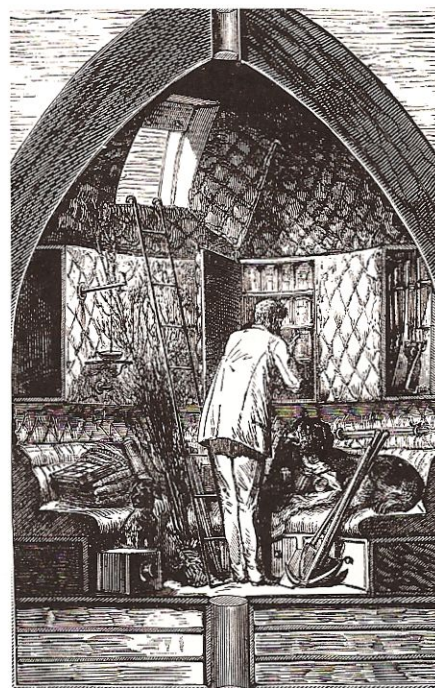
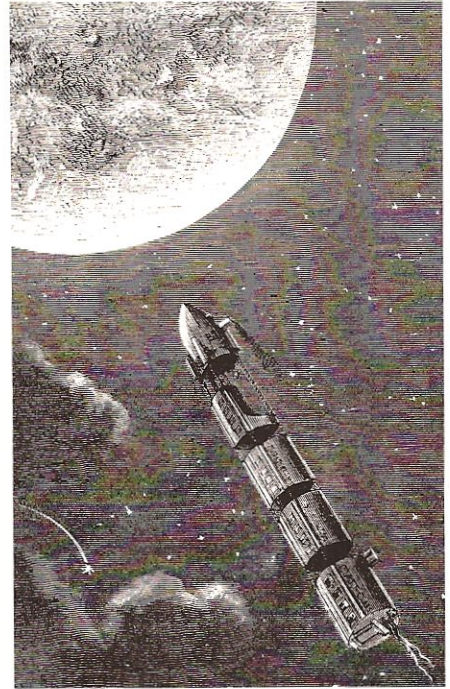


Figure 9. Romance of space travel, which accounts for a large measure of public interest in the space program, was already apparent in Jules Verne's *From the Earth to the Moon*, published in 1865 (a little more than a century before the first Apollo landing on the moon). In this novel and its sequel three men and two dogs make a trip around the moon, splashing down in the Pacific 12 days after their departure. The space capsule is actually a bullet fired from a gun (upper left), although it is not too different in form from the Apollo command capsules. One of the explorers envisions "trains of projectiles" in which people will be able to travel comfortably from the earth to the moon (upper right). The interior of the capsule may look at first glance like a Victorian gentleman's library, but it has many practical features at well (lower left). For example, the floor is a sliding wooden disk. Below it are horizontal compartments holding water, which can be driven upward through pipes toward the top of the projectile; this contraption is meant to act as a strong spring and absorb the shock of the violent launch. During their flight, the explorers become weightless, although they mysteriously retain their vertical orientation in this condition (lower right). Verne thought weightlessness would occur only at the "neutral point" where the earth's gravity is perfectly balanced by the moon's. Wernher von Braun wrote, "The science in *From the Earth to the Moon* is nearly as accurate as the knowledge of the time permitted."