Summary

INTRODUCTION

On July 20, 1989, two decades after the first Apollo landing on the Moon, President George Bush proposed "a long-range, continuing commitment"[1] that would take the United States "back to the Moon...back to stay,"[2] and then on to Mars. The President elaborated further on his vision in May 1990, when he stated, "I am pleased to... announce anew Age of Exploration, with not only a goal but also a timetable: I believe that before Apollo celebrates the 50th anniversary of its landing on the Moon [2019]—the American flag should be planted on Mars."[3]

In response to the President's proposals, the National Aeronautics and Space Administration (NASA), the Department of Defense (DoD), and the Department of Energy (DOE) have begun work on the Space Exploration Initiative (SEI),[4] an endeavor to plan and implement the human exploration of the Moon and Mars. NASA is the principal implementing agency. The National Science Foundation will participate in a limited way through a joint Antarctic Program, testing technologies and methods for Mars exploration.[5]

Although the SEI is devoted principally to developing and analyzing the steps required for human exploration of the Moon and Mars, NASA's plans for SEI also include robotic science missions: first to gather scientific data[6] prior to a landing by humans, and later as adjuncts to human exploration on the surface.[7] Data from the first set of robotic spacecraft would further scientific studies and assist planners to select the best sites for landing and erecting base camps. The appropriate mix of human and robotic exploration is currently under study by NASA, and by several internal and external advisory groups.[8]

As a result of their concern over the extent and scope of science objectives that can be accomplished within potential NASA appropriations over the next three decades, the Subcommittees on Veterans Administration, Housing and Urban Development, and Independent Agencies of the House and Senate Appropriations Committees asked OTA to examine 'Whether an unmanned, robotic mission or missions might not be a viable option for us to consider" for scientific study of the Moon and Mars, and in the utilization of physical resources on the two celestial bodies.[9]

This report focuses primarily on the possible roles of automation and robotics (A&R) technologies in the exploration and utilization of the Moon and Mars. More generally, it examines issues related to the decisions Congress faces in

[1]George Bush, "Remarks by the President at 20th Anniversary of Apollo Moon Landing, ''The white House Office of Press Secretary, July 20, 1989, p. 3.

[2]Ibid.

[3]George Bush, "Text of Remarks by the president in Texas A&I University Commencement Address," The White House Office of 'he Press Secretary, May 11, 1990, p. 5.

[4]Specific policy guidance is cited i. Memorandum t. National Space Council from Mark Albrecht, "Presidential Decision on the Space Exploration Initiative," Feb. 21, 1990.

[5]Arnold D. Aldrich, NASA Office of Aeronautic, Exploration, and Technology, "The Space Exploration Initiative," presented to the American Association for the Advancement of Science Symposium on the Human Exploration of Space, Feb. 17, 1990, p. 4.

[6]These efforts would extend NASA's planetary exploration program, which hasa history of more than 30 years of scientific missions to the solar system.

[7]Aldrich, op. cit., footnote 5, p" 4.

[8]For example, the Space Studies Board of the National Academy of Science and the Synthesis Group, a committee chartered by the White House and NASA to examine alternative ways to establish a lunar base and reach Mars. See *America at the Threshold* (Washington, DC: The White House, June 1991).

[9]Letter to John H. Gibbons from Senator Barbara Mikulski, congressman Bob Traxler, and Congressman Bill Green, July 24, 1990.

acting on administration funding requests for the SEI. This report derives in part from a workshop on the robotic exploration of the Moon and Mars held at OTA on February 20,1991. The workshop dealt with issues in robotic and human exploration, the state of A&R research and development (R&D), and the potential for international cooperation. In preparing the report, OTA gathered information from numerous articles and reports. It also conducted personal interviews with a wide variety of individuals familiar with the assessment's issues.

WHAT IS ROBOTICS?

The term "robotics," which generally comprises a significant proportion of automation technologies as well, has within the space program and elsewhere come to connote a wide variety of activities involving humans and machines in partnership. In today's parlance (box l-A) robotics may be applied to machines entirely under direct human control at short or long distance, but with no automated capability; 2) or it may refer to completely automated devices that carry out preprogrammed tasks on command, but with essentially no capacity to make decisions. Alternatively, 3) the term may apply to machines with a relatively high decisionmaking capacity, capable of operating for extended periods between commands. Finally, 4) robots may continually interact with humans, sometimes acting at a high or low level of autonomy; the human maybe nearby or at some distance, even very far away. It is in this last context that future human/robot teams hold particular promise for space activities.

Most applications within NASA have involved robotic devices in category 4, in which the device has always had at least a low capacity for autonomous decisionmaking. Thus, what have previously been termed "unmanned missions" or "planetary spacecraft" are now often called robotic missions. The robotic devices on these missions can be considered ***telerobots*** because they receive commands over telecommunication links. In addition, NASA has provided their planetary exploration spacecraft a small but growing capacity for ***autonomous*** action. For example, they are capable of going to a fail-safe mode by automatically recognizing, for example, a loss of navigation lock on guide stars and instituting procedures for recovering to a 3-axis inertially stabilized mode and automatically pointing the communications antenna toward Earth.[10]

Box l-A–Automation and Robotics for Applications in Space

A central mission of automation and robotics (A&R) technology is to provide a high level of autonomy, or decisionmaking capability, to robotic devices that will enable more effective management of spacecraft, landers, rovers, and other instruments of discovery. Human team members can then guide at any level, and from both small and large distances, because the robot members will have increased capacity for making decisions, as well as increased mobility and manipulative skill. More effective robotics would leave humans free to reason and to control at the most effective level for discovery.

Such ***autonomous*** robots will largely replace purely "automated" ones that carry out a specified set of preprogrammed functions. Robots with a high degree of autonomy would be capable of responding to new situations with little or no additional guidance from mission control.

From time to time these robots maybe ***teleoperated*** – guided by a human on a continuing basis — at low or high level, and from some distance with possible time lag.

Thus, two of the most important areas of robotics research are to provide humans with greater capability by giving robots: 1) more autonomy, and 2) greater mobility and capacity for manipulation.

SOURCE: Robert Cannon, Stanford University and the Office of Technology Assessment, 1991.

[10] Because of this capability, in Iwo the *Magellan* spacecraft, which is providing U.S. scientists with a detailed radar map of Venus, was able with the help of mission controllers to recover from a loss of navigation lock. It was the lack of just such an autonomous capability that doomed the 1990 Soviet spacecraft while on its way to Phobos, one of the moons of Mars.

Thus, future efforts in robotics are expected to use advanced techniques, including artificial intelligence,[11] to impart greater capability to humans by giving machines greater autonomy. Robotics research will also involve imparting mobility and a higher capacity for manipulation to robotic devices. In this report, OTA generally uses the term automation and robotics (A&R) to indicate these two major thrusts.

THE HUMAN-ROBOTICS PARTNERSHIP

Both humans and machines can contribute as partners in a Mission from Planet Earth. This partnership raises the following question: what is the appropriate mix of humans and robotic machines on the surface of the Moon and Mars? The answer to this question will shape the program and necessary funding over decades.

Atone extreme, the United States could mount Apollo-like expeditions to the Moon and Mars, in which the United States would place maximum emphasis on science and technology to support humans in transit and on the surface, but put relatively little emphasis on A&R. In the Apollo era, because the available A&R technologies were quite primitive, the United States sent men to the Moon with very little robotic support. Most of the control remained on Earth where thousands of support personnel followed every detail of the crew's progress and controlled most of their actions.

At the other extreme, the United States could focus on the development of advanced A&R technologies for exploration and indefinitely defer sending humans to the Moon and Mars.

In the most effective exploration program, people and machines would function as interactive partners, with people on Earth or perhaps on the surface of the Moon or Mars, as need and funding allow. A&R experts believe that it will soon be possible to develop machines, guided by controllers on Earth where appropriate, but acting autonomously most of the time, to carry out many exploration duties. On the Moon, robots controlled from Earth could be used to explore for lunar resources, to conduct scientific observations, and to carry out a variety of simple construction tasks. On Mars, robots could be employed to survey the planet's composition and structure, monitor its weather, and return samples for analysis on Earth.

However, experts infield research methods believe that, even with advances in A&R, human explorers would be needed to carry out geological field studies on the Moon or Mars, or search for signs of indigenous life on Mars — tasks that require a broad experiential database and the ability to link disparate, unexpected observations in the field. Nevertheless, robotic devices would be needed to assist human explorers in a wide variety of tasks as they work on either planetary body.

In the past, A&R technologies have received relatively little emphasis, in part because they have lacked capability. **In the future, giving A&R technologies a more central role in exploration activities could greatly enhance scientific understanding and contribute to increased human productivity in other parts of the economy. Congress can play an important part in assuring that the partnership between humans and machines evolves as productively as possible.** It could, e.g., encourage NASA to:

- devote greater and more consistent effort to A&R research and development; and
- include far more A&R technologies in future projects involving space exploration and humans in space than is the practice today.

EXPLORATION TIMETABLE

Congress also faces a decision regarding the timetable of a Mission from Planet Earth. **Given the existing Federal budget crisis and chronic shortages of public capital, acceptance of the**

[11]Machine techniques that mimic human intelligence, e.g., perception, cognition, and reasoning.

President% timetable (2019) for landing humans on Mars might require a major emphasis on the development of technologies to support human crews and thus greatly constrain the options for developing A&R technologies.

Some argue that the United States should demonstrate its leadership in advanced technology to the rest of the world by embarking on the human exploration of Mars as soon as possible. However, it is far from clear what the United States would gain from demonstrating leadership in human exploration. For the next decade or even two, the United States has no effective competitors in sending human missions to the Moon or Mars. **If the United States emphasized human exploration and failed to fund the development of A&R technologies directly related to the U.S. economy, it might slip in economic competition with other nations.** A U.S.-led Mission from Planet Earth could assist in boosting international leadership in space activities, but only if it were part of a balanced space program that rested on a solid foundation of space science and technology development.

In the near term, Congress could:

1. ***defer decisions on a Mission from Planet Earth indefinitely and fired the scientific exploration of the Moon and Mars within the existing planetary exploration program;*** or

2. ***agree in principle with the goals of a Mission from Planet Earth, but emphasize the development and use of A&R technologies to accomplish them;*** or

3. ***agree in principle with the long-term goals of a Missionfiom Planet Earth, but wish to focus on measured efforts to develop technologies supporting human exploration;*** or

4, ***accept the President's timetable of people reaching Mars by 2019.***

Options 1 through 3 would tend to extend the timetable for humans to reach Mars beyond 2019.

MANAGEMENT OF A MISSION FROM PLANET EARTH

U.S. experience with large science and technology projects having long-range goals suggest that **program planners need to maintain considerable planning flexibility and a broad set of intermediate objectives within the general program plan. Operational success in each successive phase should be favored over forcing a fit to a detailed long-term plan.**

The scientific success of missions to the Moon and Mars will depend directly on the quality of the scientific advice NASA receives and the relative influence of engineers and designing robotic missions to the Moon and Mars. **If the Nation wishes to maximize the quality of its scientific returns, planetary scientists should have a major role in the decision process about the exploration program.**

EXPLORING AND EXPLOITING THE MOON

Despite U.S. and Soviet successes during the 1960s and early 1970s in studying the Moon, scientists still have a relatively rudimentary understanding of its structure and evolution. A detailed scientific study of the Moon would assist in understanding the geological and climatological history of the Earth. Most of this work could be carried out robotically with a variety of instruments.

The United States may in time wish to establish a permanent lunar base in order to study the Moon more intensively and to exploit its unique properties for scientific observations and experiments. For example, the Moon would provide an excellent site for astronomical observatories operating at all wavelengths. However, the costs of lunar observatories would have to be balanced against the costs of placing observatories in competing locations, e.g., geostationary orbit, or on the Earth.

Exploitation of the Moon's material resources might eventually prove cost-effective, for example, in constructing surface or orbital infrastructure, or in providing additional sources of energy.

Robotic devices would provide human explorers with support for field studies, emergencies, surveys, and construction.

EXPLORING MARS

It is too early to plan a detailed, integrated program of robotics and human exploration of Mars. However, it is not too early to begin a series of projects to continue the scientific investigation of Mars, and to study human physiology in space in order to reduce the uncertainties facing human exploration of the planet.

Robotic exploratory missions will first be needed to explore Mars, whether or not the United States decides to land humans on Mars by 2019. These missions could provide important geological and atmospheric data about Mars, help refine planning for human missions, and assist in choosing potential landing sites.

If the United States ultimately decides that it is important to send human crews to Mars, A&R technologies could provide crucial assistance to these crews while on the Martian surface. A&R could provide support for field studies; assistance in surveying prior to human exploration, especially over dangerous terrain; and emergency support.

A trip to and from Mars would experience much higher risk than a return to the Moon, but would also provide greater challenge and adventure. If the United States decides to send human crews to Mars, it must accept the potential for loss of life, either from human error or mechanical failure.

A&R RESEARCH AND DEVELOPMENT

Robotics exploration will be needed as a prerequisite to human exploration. The United States has many promising A&R technologies, but to date it has not spent sufficient time or funds to incorporate them into devices for exploring the Moon and Mars. **Yet, aggressive pursuit of robotic devices would assist exploration efforts and make humans much more capable on the Moon and Mars than they could otherwise be. However, at present NASA lacks the A&R capability to carry out a vigorous exploration program using advanced robotics. Since the development of robotic technologies does not receive high priority within NASA, there is little evidence to suggest this will change.**

A number of reports, including the recent report of the Advisory Committee on the Future of the U.S. Space Program, have urged increased attention to, and funding for, developing the requisite U.S. technology base. Congress could assist the development of A&R technologies by funding a set of A&R projects that culminated in a variety of scientific capabilities for missions to the Moon and Mars.

The potential applications for A&R technologies extend far beyond the space program and include manufacturing and service industries, as well as the defense community. Yet because the A&R discipline derives from a widely splintered set of subfields, only in weak contact with one another, NASA has a relatively thin technology base upon which to draw for its own needs. An **integrated A&R program to serve government needs and assist industry will require the collaborative efforts of the universities, government laboratories, and industry.**

COSTS

Sending humans back to the Moon and/or on to Mars would be extremely expensive. According to experts OTA consulted, because of the need to support human life in extremely harsh environments, exploration by human crews could cost more than ten times the costs of robotics exploration (see ch. 7). Yet, because cost estimates depend critically on the range of planned activities, schedule, and new information developed in the course of the program, it is too early to judge the total costs of a Mission from Planet Earth. As more information is gained from robotic missions e.g., Mars Observer, and from technology research and development, it will eventually be possible to develop more credible cost estimates.

A comprehensive search for cost-reducing methods and techniques and for alternative approaches will be of high priority. Congress should ask NASA how it plans to control costs. NASA's plans should also include plans for controlling operational costs. As experience with the Space Shuttle has demonstrated, operational costs for crew-carrying systems can constitute an extremely high percentage of total system costs.

A return to the Moon and the exploration of Mars would have a major impact on NASA's yearly budget, and, in times of constrained budgets, pursuit of these goals would almost certainly adversely affect the funding of NASA's other activities, e.g., space science, and the Mission to Planet Earth (NASA'S program to address environmental and other Earth-bound problems). Hence, it will be important for Congress and the administration to test continually whether the President's aspirations for human activity in space can be accommodated within NASA's likely budget, and adjust its projects accordingly.

INTERNATIONAL COOPERATION AND COMPETITION

Issues of international competition and cooperation will continue to play important roles in the development of U.S. space policy. The United States is part of a rapidly changing world in which the political and military challenge from the Soviet Union has substantially decreased but the technological and marketing capabilities of Europe and Japan have markedly increased. How the United States invests in its space program could deeply affect other segments of the economy. The **experience gained in applying A&R technologies to tasks in space could assist their development in other parts of U.S. industry and help the United States to compete in this important arena of the world economy.** It is less clear how investments to support human exploration of space would benefit U.S. industry.

Politically and technologically, the United States could gain from leading an international cooperative program to advance in space exploration. But for such a space program we will have to learn how to pursue *shared* goals, which would give the United States less latitude in setting the program objectives. Cooperative activities with other countries also could reduce U.S. costs and increase the return on investment for exploration by bringing foreign expertise and capital to bear on the challenge. The Soviet Union has far more experience with supporting humans in space than any other country. More extensive cooperation with the Soviet Union could markedly reduce U.S. expenditures for life sciences research, and lead to much better understanding of the risks of extended spaceflight and how to reduce them.

Japan, Europe, and the Soviet Union have made significant progress in applying A&R to space activities. Cooperative scientific programs that would incorporate robotic devices contributed by several countries might significantly advance U.S. experience in this important area. For example, nations might cooperate in sending small rovers to the Moon or to Mars to do reconnaissance and simple chemical analysis, and to return samples to Earth.