Chapter 6

Automation and Robotics Research and Development

Except for the six Apollo excursions on the Moon, all planetary exploration by the United States and the Soviet Union has been carried out with automated or partially automated systems. However, these spacecraft had only limited capacity to act autonomously,[1] in other words, to evaluate conditions and make decisions on their own; they also had limited capability for teleoperation. Mission controllers programmed them to carry out a specific set of tasks in a specific sequence. As computers have grown smaller and more powerful, automation and robotics (A&R) engineers have increased their capability to design and build semiautonomous mechanical systems capable of performing a wide variety of tasks with minimal direction from mission controllers. A&R experts can now envision, within the next decade or two, the development of both large and small robotics systems capable of traversing a planetary surface, observing the terrain, manipulating and analyzing rock samples, and selecting from the many available samples particular ones to return to Earth for detailed analysis. Such systems would be able to perform a variety of tasks, e.g., construction, equipment installation, and maintenance, telerobotically.

The many engineering disciplines that contribute to A&R are undergoing rapid evolution. If properly managed, they could provide major advances in A&R over the next 30 years, leading to machines capable of assuming a substantially greater share of the human-machine partnership. In the near term, A&R could provide gains in productivity and potential fiscal savings in servicing and maintaining space station ***Freedom.***[2] As noted by the Advisory Committee on the Future of the U.S. Space Program, advanced A&R could contribute to the U.S. space program in many areas.[3]

AUTOMATION AND ROBOTICS APPLICATIONS

The basic capabilities involved in space A&R are shared with many other existing or potential A&R applications. For the Moon and Mars, today's A&R research efforts are focused on remotely controlled (teleoperated), and semiautonomous manipulation and mobility. If aggressively pursued, these developments can be expected to provide robots with greater strength, dexterity, and range of motion than humans possess. Improvements in teleoperation, in particular, would extend and enhance human presence in hostile environments.[4] A&R systems of various kinds are most commonly used in manufacturing and in areas hostile to humans e.g., toxic or radioactive cleanup.

The nuclear power industry has made significant use of mobile robots for working in high-radiation environments.[5] The Electric Power Research Institute and the Department of Energy are funding the development of robots for maintenance of nuclear reactors and cleanup of nuclear wastes. Using advanced robot technology in

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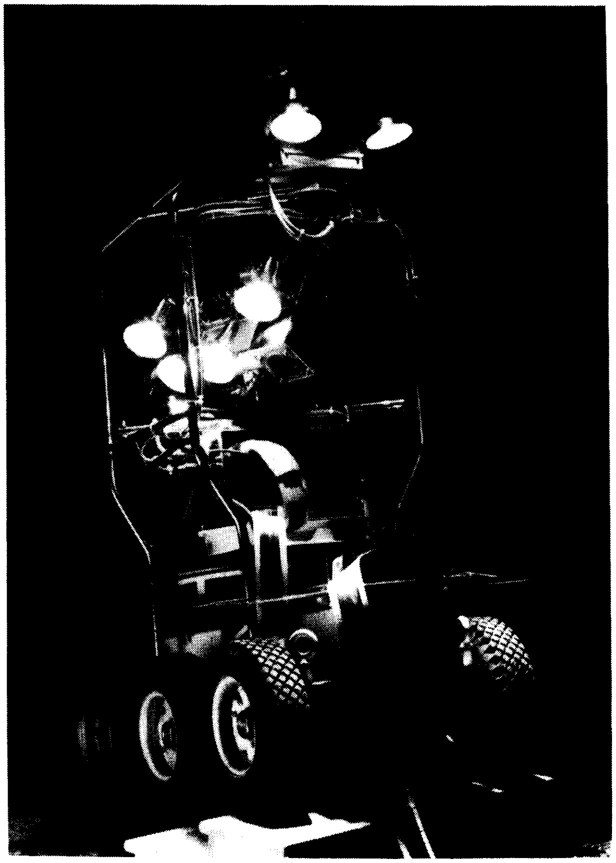
[1] U.S. planetary exploration spacecraft have had a small degree of autonomous capability, for example, in the automatic recognition of loss of star lock and procedures for recovering to a 3-axis intertidally stabilized mode and pointing the communications antenna toward Earth. The lack of this capability in the Soviet Phobos spacecraft contributed to their failures: Ben Clark, Martin Marietta Corp., personal communication, 1991.

[2] William F. Fisher and Charles R. Price, *Space Station Freedom External Maintenance Task Team, Final Report* (Houston, TX: Lyndon B. Johnson Space Center, July 1990); Mitre Corp., *The Assessment of the Potential for Increased Productivity,"* March 1990.

[3] Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* (Washington, DC: U.S. Government Printing Office, December 1990), pp. 6 and 31.

[4] Thomas B. Sheridan, "Merging Mind and Machine," *Technology Review,* October 1989, pp. 33-40.

[5] J.T. Lovett and D. Tesar, "Task Requirements for Robotic Maintenance Systems for Nuclear Power plants," Report to the Department of Energy, University of 'I&mat Austin, August 1989.



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In the future, the heavy equipment and service industries can be expected to rely on A&R technologies to carry out dangerous and/or highly repetitive tasks where a high degree of autonomy is required.[8] For example, the mining industry could make use of autonomous vehicles to haul Earth for short distances in open-pit mines, or teleoperated mobile devices to extract minerals in deep shafts. Teleoperated robots are now used for toxic waste cleanup.[9]

The Air Force, Navy, and Army are all investigating the use of A&R technologies for a variety of tasks in hazardous environments, and for repetitive tasks requiring skills in sorting, manipulating, etc. The Defense Advanced Research Projects Agency (DARPA) is supporting basic A&R research for a wide variety of defense applications.[10] A&R technologies can serve important functions for support and for combat.

A recent report by the Air Force Studies Board of the National Research Council examined A&R systems for Air Force primary and support operations. It noted such applications as aircraft servicing, refueling, and assembly; handling munitions; aircraft systems diagnostics; and inspection. It also noted the potential use of A&R systems for a variety of space-related tasks, including spacecraft repair and servicing, and refueling.[11] Figures 6-1 and 6-2 list these technologies and estimate their state of readiness for applications.

The applications of A&R to underwater tasks have many similarities to space applications, especially in the areas of robotic manipulation.[12] In

[6] Delbert Tesar, College of Engineering, The University of Texas at Austin, personal Communication, 1991.

[7] M.D. Pavelek, B.W. McMullen, and K.A. Kreider, "Operational Experiences With Remotely Controlled and Robotic Devices at TMI-2," *Proceedings of the American Nuclear Society Topical Meeting on the TMI-2 Accident: Materials Behavior and Plant Recovery Technology,* Washington, DC, November 1988.

[8] William Whittaker, Robotics Institute, Carnegie Mellon University, personal communication, 1991.

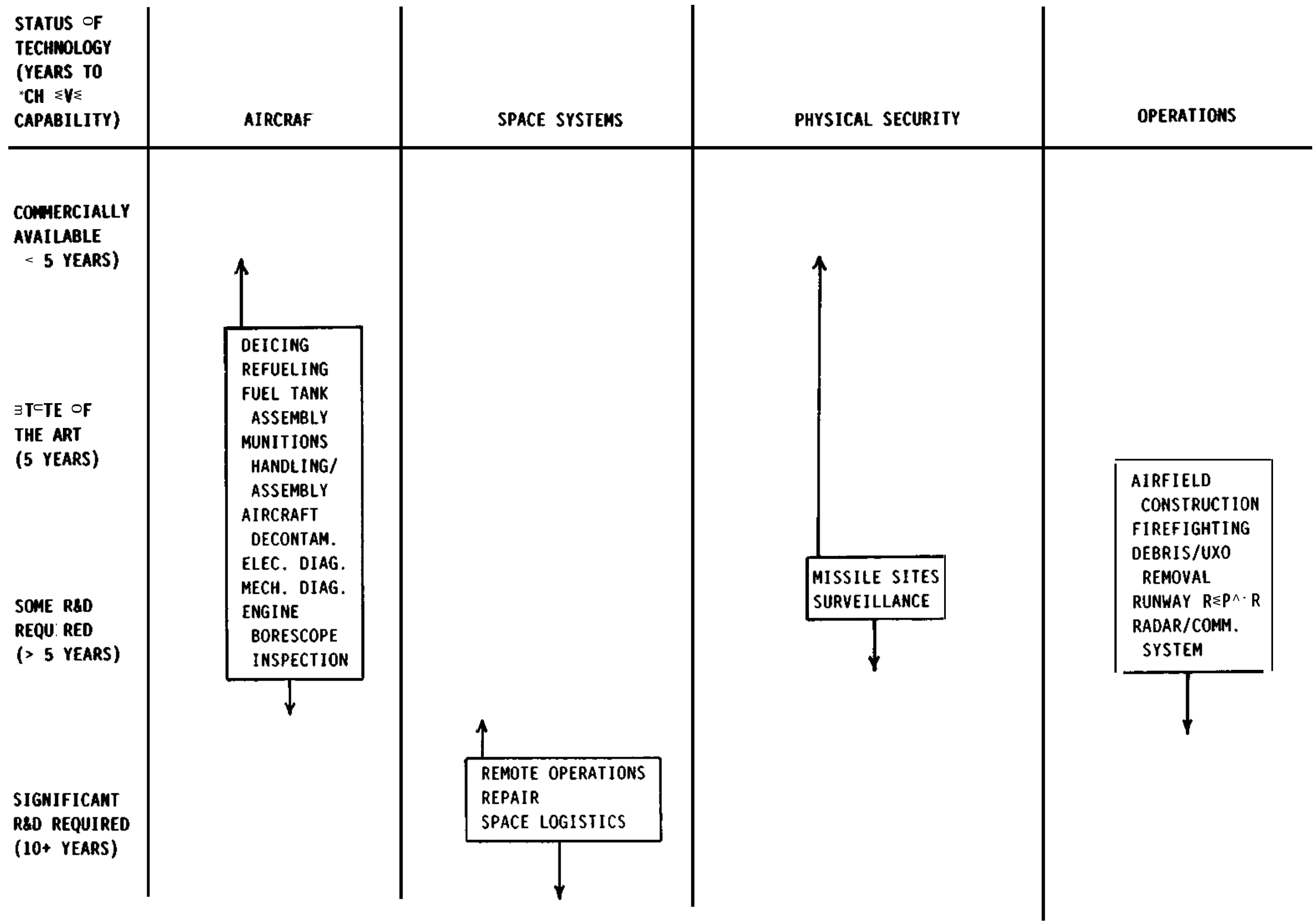
‘Ibid.

[10] Eric Mettala, The Defense Advanced Research Projects Agency, personal communication, 1991.

[11] National Research Council, Air Force Studies Board, *Advanced Robotics for Air Force Operations* (Washington, DC: National Academy of Sciences, 1989).

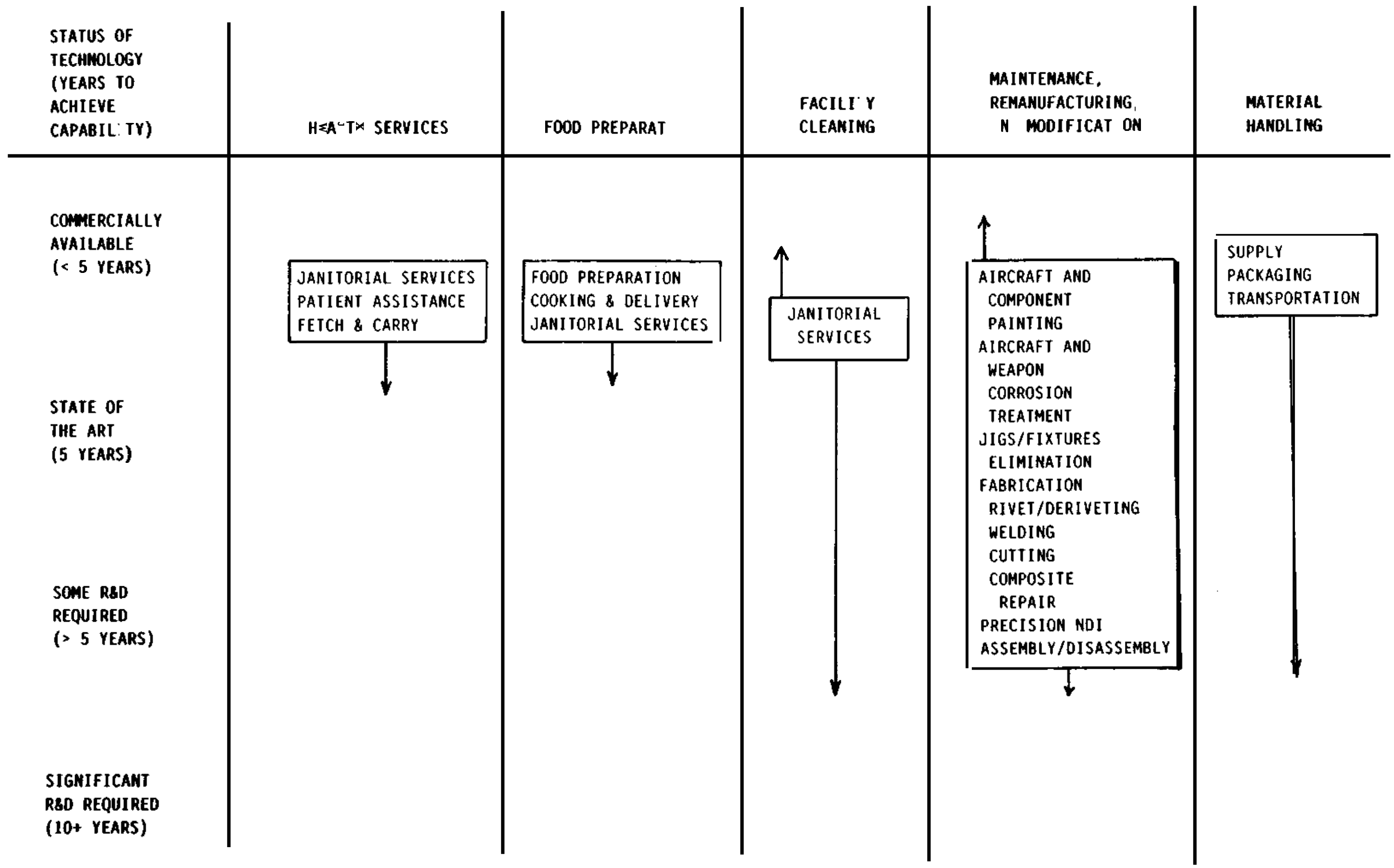
[12] Philip J. Ballou, Graham S. Hawkes, and David Jeffrey, "Tactile, Force and Motion Mechanisms for Manipulator Systems," *Proceedings, ROV'85,* Marine Technology Society, San Diego, CA, 1985, pp. 92-95; Graham S. Hawkes, "Advanced Manipulator Concepts and Applications," *Proceeding, ROV'83,* Marine Technology Society, San Diego, CA, 1983, pp. 72-81.

Figure 6-1—Potential Areas for the Application of Advanced Robotics Primary Operations



SOURCE: National Research Council, Air Force Studies Board, *Advanced Robotics for Air Force Operations* (Washington, DC: National Academy of Sciences, 1989).

Figure 6-2—Potential Areas for the Application of Advanced Robotics Support Operations



SOURCE: National Research Council, Air Force Studies Board, *Advanced Robotics for Air Force Operations* (Washington, DC: National Academy of Sciences, 1989).

conjunction with Deep Ocean Engineering, the National Aeronautics and Space Administration (NASA) Ames Research Center is developing a telepresent underwater system[13] for use in Antarctic research.[14] Earlier use of a remotely operated, underwater vehicle to support research in Lake Hoare, Antarctica was highly effective.[15] Because of these crosscutting applications of A&R technology for underwater, defense, and industrial applications, it will be important to foster supportive relationships in developing technologies for the specific applications.

A&R applications for manufacturing, while important commercially, now only provide a tiny, constrained niche for the development of robotic technologies. The fried-based manipulators generally used in manufacturing applications can be used in only a narrow range of highly structured tasks. A&R experts face several unsolved problems in extending this technology to unstructured applications. For example, there is no general method for controlling a robot's motions when its hand or tool encounters strong, unpredicted forces or torques in the environment. Today, robot manipulators are still extremely limited when compared to the human hand.

SPACE AUTOMATION AND ROBOTICS TECHNOLOGIES

Robotics in space can assist in a variety of tasks including: exchange of orbital replaceable units; handling of scientific experiments and manufacturing processes; assistance in rendezvous and docking; repair; supply and maintenance of platforms; refueling; and assembly of structures. Until recently, NASA's Flight Telerobotic Servicer (FTS) was being developed for servicing space station *Freedom.*[16] *The FTS* program provides a testbed for the development and testing of various teleoperated technologies that would extend human capabilities in space. The space shuttle carries the Canadian Remote Manipulator Arm, which astronauts use to perform such manipulative tasks as retrieving and deploying satellites, while they remain inside the shuttle.

The following list of technology elements pertains primarily to space A&R. Each of them have been developed and tested at various levels of readiness for spaceflight. Continued progress in these areas is critical for the development of autonomous spacecraft, planetary rovers, and analytical devices capable of supporting scientific exploration of the Moon and Mars. The robotic exploration of the Moon and Mars will require improvements in technologies that extend perception, cognition, and manipulation in an autonomous mode. Such improvements should materially chance the human-machine partnership for exploration.

- ***Mobility*** — Laboratories in NASA and several universities are pursuing both wheeled and legged robotic locomotion. For example, the Jet Propulsion Laboratory (JPL) has constructed a six-wheeled roving vehicle ("Robby") capable of autonomously navigating a path around obstacles from point A on a rugged terrain to a predetermined point B.[17] Under contract to NASA, the Robotics Institute of Carnegie Mellon University (CMU) has designed and built a six-legged, 15-foot-high walking robot called

[13] Philip J. Ballou, "Report: A Telepresent Underwater Remotely Operated Vehicle System," report to the NASA Ames Research Center (San Leandro, CA: Deep Ocean Engineering, Jan. 22, 1991).

[14] D.T. Andersen, C.P. McKay, R.A. Wharton, and J.D. Rummel, "Testing a Mars Science Outpost in the Antarctic Dry Valleys," *Advances in Space Research, 1991,* in press.

[15] The remotely operated vehicle allowed experimenters to conduct reconnaissance on the bottom of the lake and to plan their research, thus freeing them to concentrate on the most important tasks in the limited amount of time they had underwater (about one-half hour per dive); Steven W. Squyres, David W. Andersen, Susan S. Nedell, and Robert A. Wharton, Jr., "Lake Hoare, Antarctica: Sedimentation Through a Thick Perennial Ice Cover," *Sedimentology*, in press.

[16] In early 1991, the FTS was downgraded to a technology demonstration project within the Office of Aeronautics, Exploration and Technology. Its future is uncertain, but FTS will no longer support space station operations and maintenance.

[17] Jet Propulsion Laboratory, *NASA Planetary Rover Program*, JPL 1990 Annual Technical Report, Jan. 15, 1991.

Photo credit: Carnegie Mellon University, Robotics Institute

Six-legged *Ambler* developed by the Robotics Institute at Carnegie Mellon University, under contract to NASA. *Ambler* varies between 4 and 6 meters high and can accommodate a variety of scientific and sampling tools and equipment. *Ambler* can navigate across rugged terrain and climb 30 degree slopes.

the Ambler. The Ambler combines perception, planning, and real-time motion control, and is capable of navigating boulder-strewn terrain.[18]

Researchers at the Massachusetts Institute of Technology (MIT) have concentrated on developing microrovers that employ six legs to "crawl" across the landscape like insects.[19] They represent a radical departure from the larger rovers, both in their size and their modes of navigation (see ***Technology Issues,*** below).

Researchers have demonstrated all three types of mobile robots in the laboratory and under field conditions. However, they need considerably more experimentation and testing before mission designers can determine which avenue would be most fruitful for planetary exploration. Other approaches to mobility on Mars have been considered as well, including airplanes, balloons,[20] and small, suborbital rockets.

Mobility in space will be equally important in many missions. Staging and executing a mission to Mars, for example, would require assembling independently launched subsystems on orbit. Researchers at Stanford University have concentrated on experimental development of new concepts for freeflying robots in a weightless environment, having fully cooperating arms capable of deft manipulation, either gas-jet or push-off body motion control, and the capability to respond to commands to "fetch, carry and attach."[21]

- ***Manipulative dexterity and tactile sensors*** — Robotic manipulation systems will eventually be capable of dextrous manipulation far beyond human capability: very long arms could have a pair of short arms at their ends, which in turn may have still smaller arms, agile wrists, and finally, hands with fingers. Such a system is essential in space. Stanford researchers have pioneered the experimental development of well-controlled, long, very flexible arms that carry very quick mini-manipulators at their end capable of per-

[18] Eric Krotkov, John Bares, Martial Hebert, Takeo Kanade, Tom Mitchell, Reid Simmons, and Red Whittaker, "Ambler: A l-egged Planetary Rover," *1990 Annual Research Review,* Robotics Insitute, Carnegie Mellon University, 1991, pp. 11-23.

[19] David H. Freedman, "Invasion of the Insect Robots," *Discover,* March 1991, pp. 42-50.

[20] The Soviet Union and France hope to deploy a balloon on Mars later this decade to provide mobility for a package of sensors.

[21] Marc Unman and Robert H. Cannon, Jr., "Experiments in Global Navigation and Control of a Free-Flying Space Robot." In *The Proceedings of the Winter ASME Meeting,* San Francisco, CA, December 1989.

forming delicate force-controlled tasks with high precision and agility.[22] Robotics engineers in several laboratories have built various kinds of tactile sensors and manipulators of three and four fingers. JPL and CMU engineers have coupled them with automated vision systems capable of recognizing and selecting among pebbles in a heap. They have also begun to develop specialized automated tools for handling and examining geological specimens.[23]

- ***Navigation and path planning — The*** development of autonomous navigation and path planning has proved much more difficult than investigators had first expected two decades ago. The decisions humans take for granted when driving a vehicle along a highway or on a rough dirt road involve sophisticated perceptive and cognitive processes that take years to develop. Vehicles that navigate autonomously must be able to recognize a path, guide the vehicle, avoid stationary and moving obstacles, maintain a safe speed, and respond to emergencies.

  In 1990, at JPL, the six-wheeled experimental vehicle Robby has demonstrated, using onboard power and machine vision and computation,[24] its capability to traverse rugged natural terrain at very low speeds. In 1991, Robby demonstrated semi-autonomous speeds of 80 meters per hour. Future development will focus on increasing Robby's speed to 2 to 3 kilometers per day.

  Using a neural network controller, researchers at the Robotics Institute at CMU have achieved the ability to "teach" a vehicle to drive autonomously along a highway, gravel, and dirt roads, and even paths at speeds of 20 to 40 miles per hour.[25] Vehicle speeds are currently limited by computing speed and available computing algorithms. Much faster speeds can be expected in the future as computers increase in capability and researchers develop new methods of navigating obstacles. Although automated vehicles, using artificial intelligence methods for cognition, now provide some capability for exploration, goal seeking, and obstacle avoidance, they are still in the research stage, and have relatively limited capabilities. In particular, they have difficulty responding appropriately to situations unforeseen by their designers.

  JPL has shown that it is now possible in the laboratory to plan a path of activity by decomposing it into its component tasks and to predetermine the path of a robot arm to avoid obstacles and reach a preassigned goal or object.

- ***Internal representation —*** When communications delays become longer than a few minutes, mission controllers experience severe limitations in their ability to control an instrument on a distant body, particularly if the instrument is roving the surface. Hence, if the robot has the capability to form an internal representation of its own location and status, and of updating the representation with sensory inputs, it can operate on its own for a significant portion of the time. Additional commands can then be sent to the robot several times a day, if necessary. Such supervised autonomy may be the only

[22] E. Schmitz and R.H. Cannon, "Initial Experiments on the End-Point Control of a Flexible One Link Robot," *International Journal of Robotics Research,* vol. 3, No. 3, Fall 1984; Wen-Wei Chiang, Raymond Kraft, and Robert H. Cannon, Jr., "Design and Experimental Demonstration of Rapid, Precise End-Point Control of a Wrist Carned by a Very Flexible Manipulator," *The International Journal of Robotics Research,* vol. 10, No. 1, February 1991, pp. 30-40.

[23] Jet Propulsion Laboratory, *1990 Highlights JPL Automation and Robotics*, January 1991; T. Choi, H. Delingette, M. DeLouis, Y. Hsin, M. Hebert, and K Ikeuchi, "A Perception and Manipulation System for Collecting Rock Samples," *Proc. of the NASA Symposium on Space Operations, Applications, and Research,* Albuquerque, NM, June 1990.

[24] Erann Gat, Marc G. Slack, David P. Miller, and R. James Firby, "Path Planning and Execution Monitoring for a planetary Rover," *Proceedings of the IEEE Robotics and Automation Conference,* Cincinnati, OH, May 1990, pp. 20-25.

[25] Dean A. Pomerleau, "Efficient Training of Artificial Neural Networks for Autonomous Navigation," *Neural Computation,* vol. 3, No. 1, Terrence Sejnowski (cd.), 1991.

way of controlling a robot on the surface of Mars from Earth.

- ***Vision and perception sensors*** — Passive stereo vision and active microwave, infrared, or laser rangefinders have both been tested in the laboratory. The rangefinders tend to have larger power requirements than passive stereo vision and need to be qualified for use on the Martian surface. However, they require less computing power and provide more reliable three-dimensional information. Other perception sensors, e.g., those that could test the load-bearing capability of the soil, are in the very early stages of development.

- ***Operator interface and mission operation*** — The successful completion of a robotic mission will depend in large part on the development of intelligent software and other systems to enable mission controllers to interact with distant robots, having increasing autonomous capability. Engineers at Stanford University have developed an intuitive graphical interface that allows the operator to indicate the desired robotic movement and connection of objects. The tasks are then executed autonomously by a pair of cooperating robot arms. The system at Stanford has been operated from Washington, DC.[26] Equally important areas of research include the development of techniques to provide the operator with a sense of "virtual reality," executive and system simulation software, and force and torque reflection.

- ***Automated noncontact instruments*** — Both human and robotic missions could make use of these technologies, which include spectrometers, imaging spectrometers, elementary particle detectors, radars, and microwave detectors. Although these are well developed for remote sensing from orbit, they should be adapted for use in close range. JPL has demonstrated software for efficiently processing data in real time. This software would permit the robot to execute conditional commands, e.g., search commands, that depend on ongoing exploration.

- ***Computers*** — Experiments at JPL and other laboratories indicate the need for onboard, space-qualified computers capable of executing tens of millions of instructions per second (MIPS) to operate large rovers that navigate autonomously. An additional 50 to 100 MIPS-equivalent would be needed for specialized vision processors. Robotics will benefit substantially from advances in computers developed for other uses.

TECHNOLOGY ISSUES

The application of A&R research to the exploration of the Moon and Mars, as well as to industrial, defense, and other applications will require legislative, oversight, and appropriations attention to several crucial technology issues:

- ***Interdisciplinary concerns*** — A&R draws on a large number of other, rapidly changing engineering disciplines. Robotics traditionally relies on knowledge in such disciplines as mathematics, materials science, dynamics, electromechanical energy conversion, control theory and control engineering, computer engineering, sensor technology, industrial and operations engineering. It draws increasingly on advances in artificial intelligence technology, real-time computing systems and programming methods, simulation technology, and computer networking methods and technology. Despite some significant improvements in A&R as a result of these interactions, artificial intelligence and robotics are generally treated as separate disciplines rather than as one overall discipline that focuses on the develop-

[26] Stanley A. Schneider and Robert H. Cannon, Jr., "Experimental Object-Level Strategic Control with Cooperating Manipulators." In *The Proceedings of the ASME Winter Annual Meeting,* San Francisco, CA, December 1989.

ment of intelligent systems to define and carry out a variety of well-defined tasks.

Robotics for exploring the Moon and Mars requires advances in the three broad areas of machine perception, cognition, and action, which in the past have developed in relative isolation. For example, machine perception, which requires a variety of sensors, has evolved from applications such as photo interpretation and manufacturing part recognition, which involve the sensing of still images. These applications, which involve only minimal time constraints, therefore require comparatively simple technology. Machine cognition has evolved as artificial intelligence technology, applied to purely cognitive tasks that are also not constrained by time. Machine action has evolved in robotics and control technologies, usually coupled with simple sensor technology (as opposed to complex perception, which would require sensing and cognition in real time).

The addition of a requirement that robotic devices operate in real time adds a significant constraint into the development of these technologies. Because these areas have evolved relatively independently, A&R experts have relatively little experience with integrating techniques, methods, and hardware developed in each area into an intelligent, functioning whole.[27]

Systems integration — Because robots are complex systems that integrate perception, cognition, manipulation, control, human interaction, and must accommodate system architecture, error detection and recovery mechanisms, and mission planning, systems integration techniques assume a crucial role in making them function effectively. At present, the absence of systematic techniques for creating complete robot archetypes in which the characteristics of interacting subsystems can be fully accommodated is a barrier to actualizing robots of the future. In addition, the design, manufacture, and operation of individual components has not reached a high level of maturity.

The scale of the problem faced by robotics engineers can be seen in an analogy to an automobile.[28] Automobile systems have matured over many years. The brakes, electrical systems, transmissions, and so forth are well understood. Furthermore, the transmission system interacts little or not at all with the brakes. Hence, improvements in the braking system can be pursued with little regard for its possible affects on the transmission system. In most robotic systems, however, even small changes in one subsystem, e.g., an acuator, may require changes in another subsystem.

Operation of the automobile provides another insight into the difficulty of crafting systems integration techniques. **A** human driver must constantly monitor the vehicle, sensing internal and external conditions, controlling the automobile in real time despite uncertainty concerning what lies around the next bend, and correcting control errors along the way. A robotic operator must do the same. The robotic system must cope with uncertainty in control (sensors never report exactly the state of nature) and with uncertainty in control (the robotic mechanism never performs exactly the issued command). Each of the subsystems must tolerate errors and mistakes committed by other subsystems. Furthermore, it must do so in real time, because the automobile is moving. Given the current state of robotics technology, all contingencies for robotics systems must be anticipated and accounted for by designer beforehand.

[27]Such integration is beginning, e.g., at Stanford University, where teams in aerospace robotic control and in artificial intelligence areworking closely together to solve problems of mutual interest.

[28]Eric Krotkov, Robotics Institute, Carnegie Mellon University, personal communication, May 1991.

Existing robots have little capability for responding to unforeseen circumstances and for learning from experience.

- The ***role of artificial intelligence –*** Intelligent systems (artificial, or machine intelligence) should play a major role in the development of robots. If properly implemented in a system architecture, intelligent systems provide the user with the capability to "use, modify, create, and exploit models" of which they are a part.[29] They provide the "brains" of a robotic device that ideally allows it to approach a problem with flexibility.

Areas of artificial intelligence and control engineering that can assist the development of effective A&R devices (table 6-1) include: human/machine interfaces; overall systems architecture, including the computational environment, languages, operating systems, and network interfaces; verification and validation of critical technology elements, e.g., software and processing elements; and the capability for evolutionary growth of the system architecture.

- ***Technology strategies – The*** current intellectual ferment in A&R technologies may offer opportunities for organizing missions in novel ways. For example, until recently, most scientists assumed that a Mars rover would be a relatively large vehicle (hundreds of kilograms) that would require a large amount of computing capacity to traverse the Martian surface. Although such a rover could carry a number of tools and use part of its computing power for scientific analysis, because it would be required to do so many tasks, NASA could probably provide funding for only one or two such rovers. Scientists would therefore suffer the risk that a failure in one or more major subsystems would destroy most or all of the mission. In addition, although a single rover might traverse many tens of kilometers, it would be unlikely to be able to explore a relatively small region of geographical interest.

In the last few years, A&R researchers have experimented with small rovers[30] and have suggested that sending many of these would increase the chances of acquiring significant scientific data. Several micro- or minirovers could be transported on existing launch vehicles to different locations, making possible broad coverage of the planet. Some researchers have expressed concern that small rovers would be unable to carry enough computing power to store or generate a map of their location in order to navigate safely among obstacles. However, if the small rover were given the capacity to move across the landscape without an internal map, the necessary computing capacity would decrease dramatically. Researchers at MIT have built legged small rovers based on so-called subsumption architecture, which requires no prior instructions about how to navigate.[31] These rovers are given only a set of rules about the order in which to move their "legs." Hence, they act more

Table 6-1 –Technological Challenges for Intelligent Systems

- **Improvements in multiple sensor integration, processing, and understanding.**
- **Development of distributed knowledge-based systems that can cooperate with each other in real-time distributed operational environment.**
- **Improvements in systems architecture and integration including the development of intelligent user interfaces, real-time fault management, and a high-performance, real-time computational environment.**
- **Improvements in systems verification and validation.**
- **Development of focused testbed and flight demonstrations.**

SOURCE: The National Aeronautics and Space Administration, Ames Research Center, 1991

[29] Eberhard Rechtin, *Systems Architecting: Creating and Building Complex Systems* (New York, NY: Prentice Hall, 1991), p. 100.

[30] David P. Miller, "Mini-Rovers for Mars Exploration," *Proceedings of the Vision-21 Symposium,* Cleveland, OH, April 1990.

[31] David H. Freedman, "Invasion of the Insect Robots," Discover, March 1991, pp. 42-50.

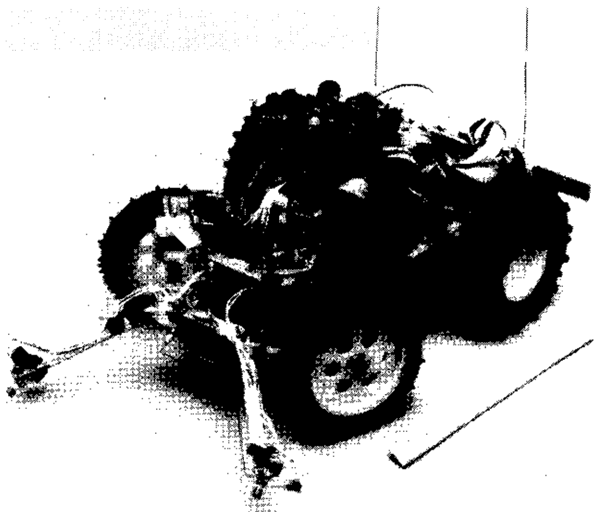


Photo credit: California Institute of Technology Jet Propulsion Laboratory

Experimental minirover, named *Tooth,* developed by the Jet Propulsion Laboratory. Tooth is capable of carrying out a limited number of tasks, operating either under command or autonomously.

like insects than higher level animals, making their way across the landscape by trial and error rather than by carrying an internal map and making decisions about which way to move. Provided with appropriate optics and sensors, they can nevertheless traverse the landscape.

Many A&R experts argue with this approach, pointing out that to do useful work on the planet, rovers would need internal guidance, which would require considerable computing capacity, unless they were operated from Earth remotely .32 They would also have to carry adequate electrical power and instrumentation (optics and electronics), which would be difficult or impossible in mini-or microrovers. Even carrying adequate vision and telemetry systems might severely strain the capacity of small rovers. As computers grow smaller and smaller and A&R engineers learn how to build smaller and lighter mechanical systems, they may be able to build rovers with sufficient computing capacity to do useful planetary reconnaissance and analysis in several regions.[33] Providing adequate electrical power to small rovers will prove a challenge, because existing batteries can carry only a limited amount of power compared to their weight and size, and solar power requires both storage batteries and a relatively large solar panel. A Radioisotopic Thermoelectric Generator (RTG), which could be used on a large rover, would be too heavy and bulky for a small one.

- ***Communications delays –*** Communications delays between the Earth and Moon (3 seconds) and between Earth and Mars (6 to 40 minutes) would introduce significant complications to the operation of robotic devices on the Moon or Mars directly from Earth. Research has shown that delays of the order of seconds can be accommodated by using a combination of machine vision and modeling of the environment in real time.[34] Hence, it appears likely that A&R engineers will learn how to overcome the time delays associated with the teleoperation of a rover on the Moon and having it carry out a complex set of tasks.[35]

The time delays inherent in communicating with Mars will require building much more autonomy into rovers or other robotic devices, or require considerably more patience and reduced scientific expectations. For example, after assessing the surround-

[32] Here again, the delay times could make such research agonizingly slow.

[33] As suggested in the last chapter, this may be an area for fruitful international collaboration, as the Soviet Union, the European Space Agency, and Japan are all considering employing rovers to explore the Moon and Mars.

[34] Lynn Conway, Richard A. Volz, and Michael W. Walker, "Teleautonomous Systems: Projecting and Coordinating Intelligent Action at a Distance," *IEEE Transactions on Robotics and Automation,* vol. 6, No. 2, April 1990, pp. 146-158.

[35] Soviet engineers demonstrated the possibility of accomplishing relatively simple teleoperation tasks in the mid-1970s when they drove the Lunakhod rover many kilometers across the lunar surface.

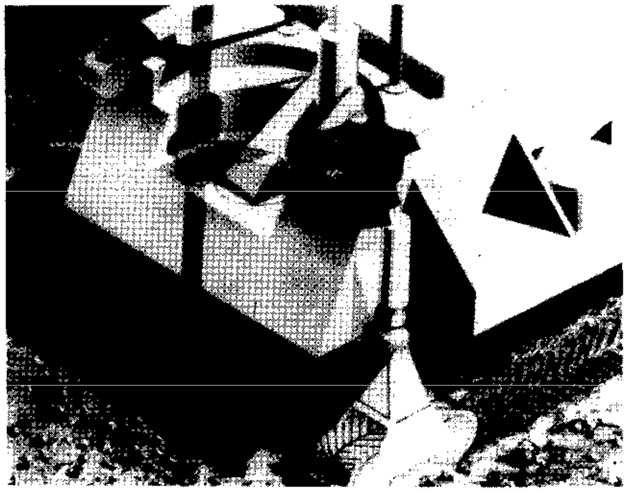


Photo credit: National Aeronautics and Space Administration

Artist's conception of a core sample (center) undergoing analysis after being obtained from the planetary surface by coring bit (shaded device left of center).

ings of a Mars rover, the human geologist on Earth could direct the rover to move around or over large and small obstacles to a specified location in the landscape, pick up a rock sample, examine it in several wavelengths, send the resulting data back to Earth, and wait for further instructions. These actions require the robot to be much more autonomous than existing ones. After the robot has accomplished that set of tasks, the geologist would be in a position to determine whether the sample should be retained for further examination or discarded. If the geologist decides to retain the sample, he or she might instruct the robot to analyze it further, or place the sample in a bin for eventual return to Earth. The scientist and the rover could then repeat their close collaboration in another promising geographical area. In this way, the distance between Earth and Mars would only slow up, not seriously impede, the robotic exploration of Mars.

- Flexibility ***and resilience* —** Flexibility and the ability to adapt to new situations are two qualities often cited as characteristic of human exploration. Robotic spacecraft also share these characteristics to some extent and have demonstrated the ability to tolerate some software and hardware deficiencies. For example, in the late 1970s, software engineers were able to work around a potentially crippling loss of one of the receivers and the failure of the frequency lock circuit on the other aboard the Voyager spacecraft. Because it was possible to reprogram the tiny memory (only 4 kilobytes) within Voyager, it went on to return startling images of the outer planets and their moons.[36] More recently, the Magellan spacecraft, which is generating a detailed radar map of the surface of Venus, began to spin slowly out of control.[37] With the help of ground controllers who developed means of working around the problems, the spacecraft was able to recover and continues to send crisp radar images to Earthbound scientists.[38]

The fact that ground controllers have been able to overcome such difficulties results in part from good spacecraft design, which incorporates redundancies and multiple paths for decisionmaking, but also from clever and insightful manipulation of the spacecraft's software. By building in more sophisticated fault-tolerant capability and self-healing processes, in both hardware and software, future spacecraft can be made even more flexible and may require less oversight from controllers on Earth.

[36] Giulio Varsi, "Advances in Space Robotics," IAF-89-032, Presented at the 40th Congress of the International Astronautical Federation, Malaga, Spain, Oct. 7-13,1989. Varsi also points out that, "Reprogrammability has made it possible to improve the precision of the spacecraft trajectory, as more information on the ephemeris of planets and satellites was acquired during the mission and to enhance the performance of the instruments by developing on the ground and then transmitting to the onboard computer better algorithms for image coding and for motion compensation of the scan platform. "

[37] Michael A. Dornheim, "Magellan Radar Produces Sharp Images, but Computer Problems Vex Controllers," *Aviation Week and Space Technology*, Aug. 27, 1990, p. 29.

[38] Richard A. Kerr, "Magellan paints a portrait Of Venus," Science, vol. 251, 1991, pp. 1026-1027.

Tomorrow's challenge is to design and build an equivalent level of flexibility, resilience, and fault tolerance[39] in machines that will experience direct mechanical contact with the environment. With few exceptions,[40] most spacecraft have had to deal only with celestial mechanics and long-range gravitational forces. The precise positioning and motion of the spacecraft platform has occurred in free space, with no mechanical contact with the surface.

FUTURE PROSPECTS FOR A&R RESEARCH AND DEVELOPMENT

Resolving these issues will require basic technology development and testing at both the subsystem and system level. It will also require consistent funding. One of the most important concerns expressed to OTA staff by project managers both within NASA and externally was the inconsistent pattern of funding for robotics programs.[41] programs would be started, begin to provide useful results, and then be canceled abruptly. Although technology research programs may commonly experience a certain lack of stability as research priorities change, sometimes abruptly, the United States is unlikely to see major progress in the development of A&R technologies until they are taken much more seriously.

The United States has the capability and the resources to implement a highly competitive A&R program. However, it presently lacks the structure to carry one out. An integrated A&R program to serve government needs could engage the capabilities of the universities, government laboratories, and industry. For example, universities could efficiently conduct basic research and then, in cooperation with the appropriate government laboratories, participate in further refinement and demonstration of technology feasibility and readiness. Promising technologies could then be handed over to development centers and aerospace industries for final development, validation, and implementation. If A&R programs in government laboratories and industry were more tightly coupled, A&R technologies would have a higher chance of finding their way into industrial applications and commercial ventures.[42]

In some respects, A&R technologies were oversold in the 1980s because the technology seemed more simple, tractable, and mature than it was. Continued technology development, and experience with successful systems, could raise public awareness of the utility of A&R systems and create a setting in which A&R engineers can be more innovative in applying them to space and Earthbound applications. There are many possible blendings of perception, cognition, and action at a distance. For example, we might employ teleautonomous systems that can operate autonomously most of the time, but easily be brought under teleoperated control when necessary. Greater understanding of both the promise and limits of A&R technologies would assist development of such systems. Tying the development of new robotic technologies to specific planetary projects, such as emplacing scientific instrument packages on the Moon, or exploring the surface of Mars, should help focus the development of new technologies.

39 Robotics engineers find continuing challenge in providing fault tolerance for mechanical structures that is equivalent to the fault tolerance now being incorporated in computer software.

40 For example, Viking spacecraft on Mars, and the Lunakhod rover on the Moon.

41 Although inconsistent funding may not be unique to NASA'S A&R program, it has hampered efforts within NASA to exploit the capabilities of A&R technologies.

42 At present, the aerospace industry is not closely coupled to other industries. Hence, effectiv technology transfer to the broader manufacturing and service industries will require sustained effort.