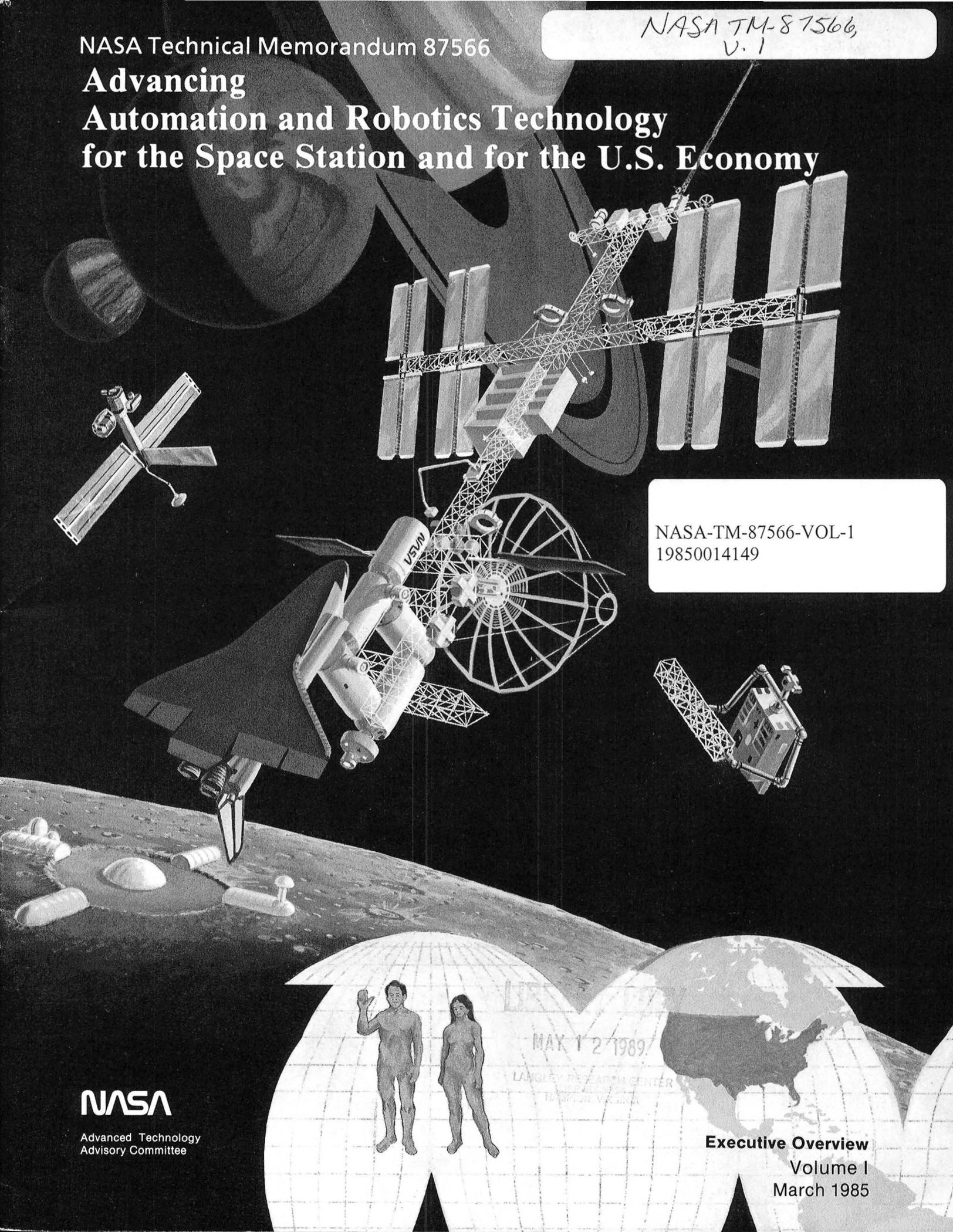


NASA Technical Memorandum 87566

NASA TM-87566,
V. 1

Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy



NASA-TM-87566-VOL-1
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Advanced Technology
Advisory Committee

Executive Overview
Volume I
March 1985

The cover painting captures the spirit of the machine intelligence and robotics policy described in this report. Prominently depicted are both the low Earth orbit Space Station complex of platform and core stations and the United States—the two recipients of productivity increases due to creating and using this technology. The man and woman represent each of us benefiting from an improved interaction with more capable machines—a few in space, the majority on Earth. The commercial use of space, made easier by the Space Station, is depicted by low cost, co-orbiting automated manufacturing facilities. The sweeping vision from a lunar manufacturing facility or base to Mars and Saturn and beyond to the deepest reaches of the cosmos pictures a continuing exploration of space.

The painting is an artistic rendition by Raymond J. Bruneau of an original design by Roy L. Magin, both of the Technical Information Branch at the Lyndon B. Johnson Space Center.

NASA Technical Memorandum 87566

Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy

Volume I — Executive Overview

Advanced Technology Advisory Committee
National Aeronautics and Space Administration

Submitted to the
United States Congress
April 1, 1985

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NASA



National Aeronautics and
Space Administration



ROBERT T. MCCALL ©1979

The space frontier.

Synopsis

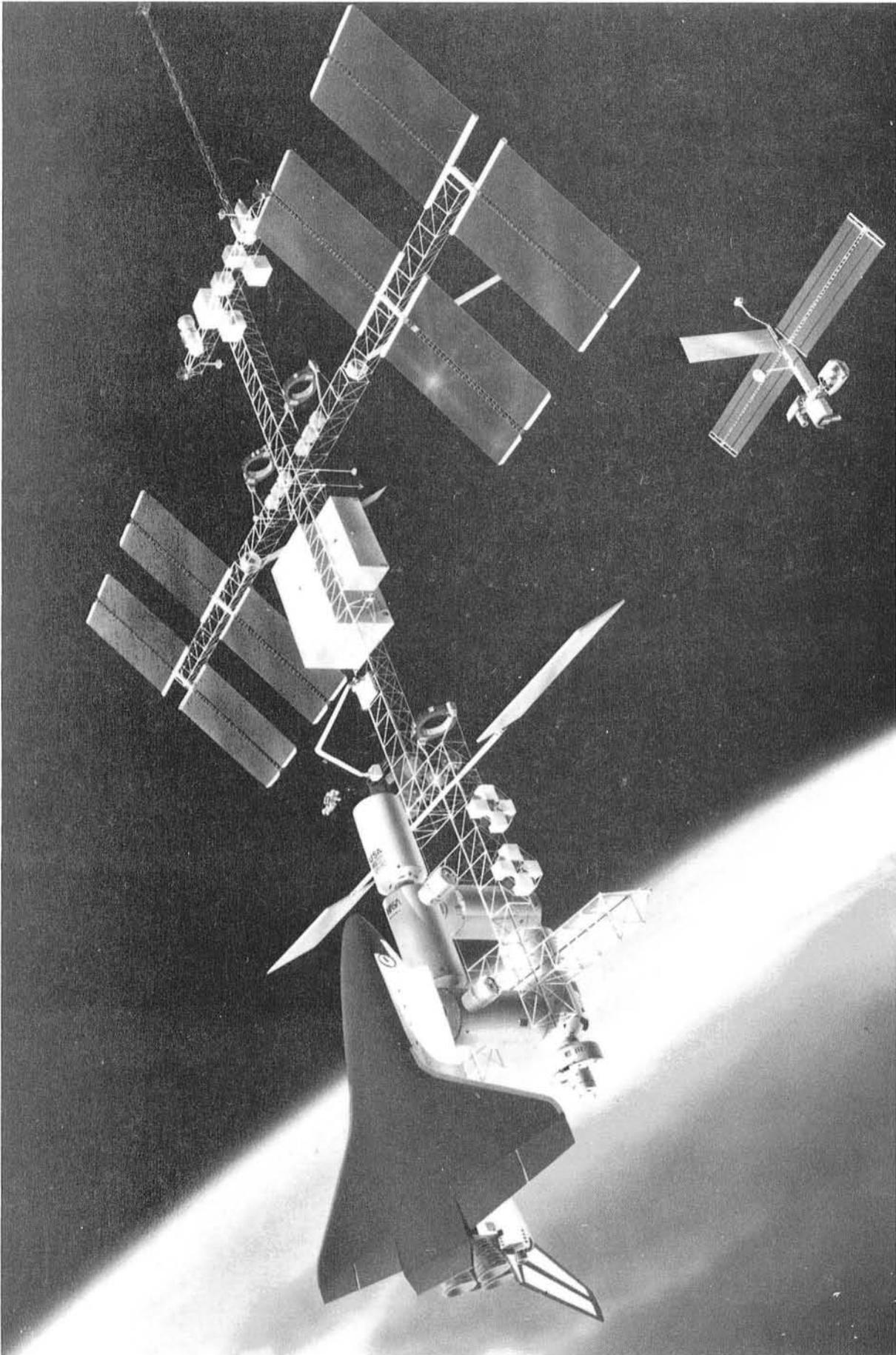
We are at the beginning of a new era in space. As we move into the second 25 years of the U.S. space program, we will meet significant challenges. This era will bring a major thrust in the commercial use of space. And, with the Space Station, it will bring the achievement of a permanent American presence.

The development of the Space Station offers us a chance both to advance the technology of automation and robotics, as proposed by Congress, and to put that technology to use. The use of advanced automation and robotics technology in the Space Station would greatly enhance its capabilities. And the Space Station would thereby provide a logical driving force for a new generation of machine intelligence and robotics technology, built on recent advances in artificial intelligence, robotics, computer science, and microelectronics.

The advances in automation and robotics stimulated by the Space Station Program could benefit the U.S. in many ways, notably,

- Increased productivity in space for commerce and science
- Increased productivity throughout the U.S. economy as the new technology is transferred back to Earth-based industries
- Preservation of U.S. leadership both in space and at the cutting edge of technology in general

To create a new generation of technology, NASA will have to overcome difficult obstacles. But the Advanced Technology Advisory Committee believes that NASA can achieve this goal.



Preface

In response to Public Law 98-371, dated July 18, 1984, the NASA Advanced Technology Advisory Committee has studied automation and robotics for use in the Space Station and prepared this report to the House and Senate Committees on Appropriations. The study has drawn on work by groups both within NASA and outside NASA, in the academic and industrial communities.

The report is divided into two volumes.

The Executive Overview, Volume I (this document), presents the major findings of the study and recommends to NASA principles for advancing automation and robotics technologies for the benefit of the Space Station and of the U.S. economy in general.

The Technical Report, Volume II, provides background information on automation and robotics technologies and their potential and documents the following:

- The relevant aspects of Space Station design
- Representative examples of automation and robotics applications
- The state of the technology and advances needed
- Considerations for technology transfer to U.S. industry and for space commercialization

This report is referenced in the request for proposals for definition and preliminary design of the Space Station. Volume II in particular provides guidance for prospective Space Station contractors to direct their efforts toward a planned advance in these technologies.

In response to an agreement with the Senate Appropriations Committee in April 1984, NASA funded and managed a number of studies in the general area of automation and robotics. These studies were done by academic and industrial specialists working in the field, and they provided important insight to the Advanced Technology Advisory Committee.

An Automation and Robotics Panel, led by the California Space Institute, prepared the report "Automation and Robotics for the National Space Program." Five aerospace firms conducted studies of critical issues (synopsized in this volume in the section on case studies). Further, SRI International studied the general state of the technology and areas in which research is needed. The documentation of all of these studies is referenced and should be read in conjunction with this report.



The blue planet.

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Introduction

The first 25 years of the U.S. space program have been exciting and successful and have advanced the **exploration** of space in countless ways. However, new times bring new challenges, and in coming years the U.S. space program must

- Expand its focus to include commerce as well as exploration
- Assure effective utilization of resources
- Meet international competition
- Establish a permanent manned presence in space

These challenges characterize a new era, one focused on meeting the needs of commercial customers, scientists, and other users of space.

There are two keys to success in meeting the challenges at hand. One is to develop and use the "right" technology; the other is to function as efficiently and effectively as possible, both within the Government and in dealings with the private sector.

Congress has seen the wisdom of developing a new generation of general-purpose automation and robotics technology. Such a general-purpose technology would be efficient and flexible enough to meet needs as yet unspecified. Therefore, Congress has given NASA a mandate to advance the state of the art in automation and robotics for the benefit not only of the Space Station but also of the U.S. economy as a whole.

The next 25 years of the U.S. space program promise to be more exciting and productive than the first 25, and the exploitation of advanced automation and robotics offers a means for the United States to meet the challenges of this era.

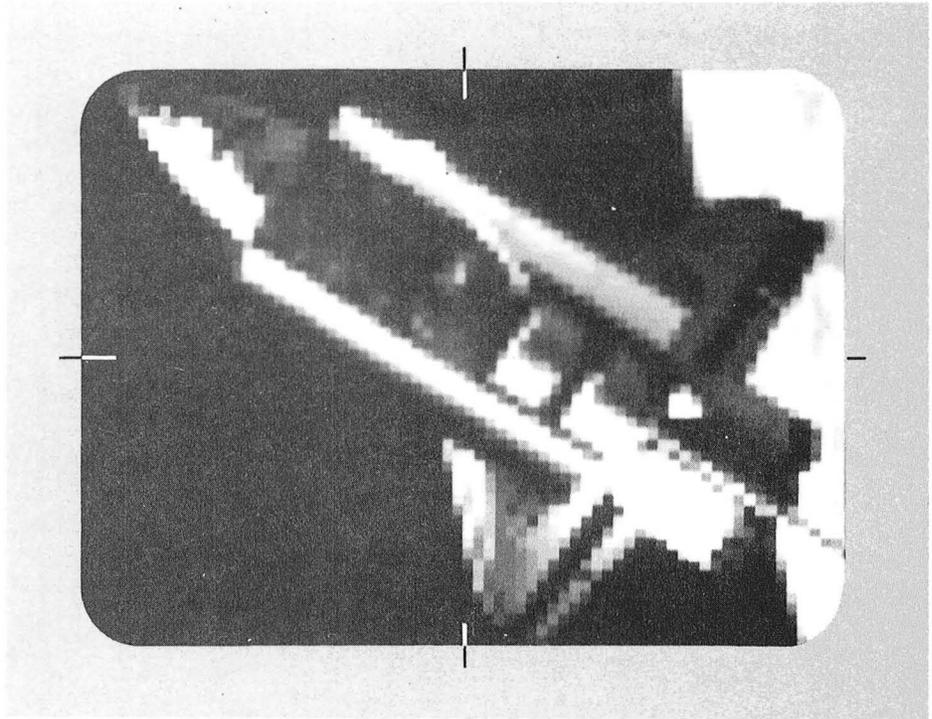


Automation, Robotics, and the Congressional Mandate

The United States Congress became convinced that the Space Station Program could be a logical user and a highly visible stimulator of new technological advances. A conference committee report suggested that NASA should examine existing systems "whose potential for enhancing automation and robotics technologies appears promising." The report also expressed the expectation that such technologies might not only "increase the efficiency of the station itself" but also "enhance the Nation's scientific and technical base leading to more productive industries here on Earth."

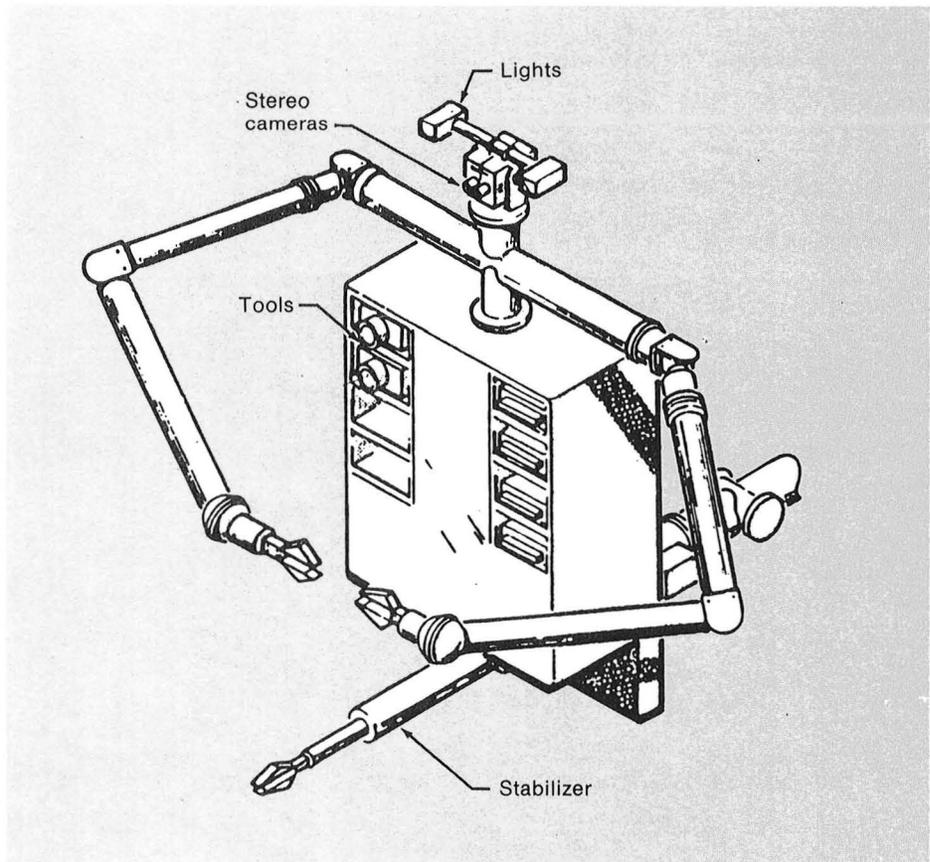
In April 1984, the Senate Appropriations Committee and NASA agreed to a congressionally sponsored study to produce an "Automation Report" for the Space Station. To that end, Public Law 98-371, dated July 18, 1984, and titled "National Aeronautics and Space Administration Research and Development, 98 Stat. 1227, Research and Program Management Report," provides that

The Administrator shall establish an Advanced Technology Advisory Committee in conjunction with NASA's Space Station program and that the Committee shall prepare a report by April 1, 1985, identifying specific space station systems which advance automation and robotics technologies, not in use in existing spacecraft, and that the development of such systems shall be estimated to cost no less than 10 per centum of the total Space Station costs.



Computer or machine vision will permit automatic recognition of objects such as a Shuttle coming in to dock.

Sophisticated manipulators can approach the dexterity of humans for specialized tasks.



As a result of its study, the Advanced Technology Advisory Committee believes that a key element of the "right" technology for the Space Station era is extensive use of advanced general-purpose automation and robotics. This could include many systems and devices (such as computer vision, expert systems, and dextrous manipulators) that have been made possible by recent advances in artificial intelligence, robotics, computer science, and microelectronics.

The exciting potential of automation and robotics, outlined in this document, can be realized only when the systems and devices are actually implemented in the Space Station. Such an implementation must follow an overall plan and be carefully integrated with station systems and operations. The details of the implementation in the initial station would be established during the definition and preliminary design phase. NASA should also produce during this phase a plan and requirements for additional implementation of automation and

robotics in later versions of the station.

Properly focused reliance on automation and robotics in the Space Station could free humans in space for the roles they fill best. That is, using their intelligence to perceive, to understand, to redefine continually what needs to be done on the basis of what has been learned, to take advantage of unforeseen opportunities, to solve unexpected problems, to save a mission (occasionally), to supervise machines, to adapt with minimal reprogramming, and to acquire, integrate, and interpret multisensory data to meet mission needs.

Automation and robotics could be an important factor whether the Space Station is initially inhabited or only tended by humans at intervals with permanent habitation deferred for several years.

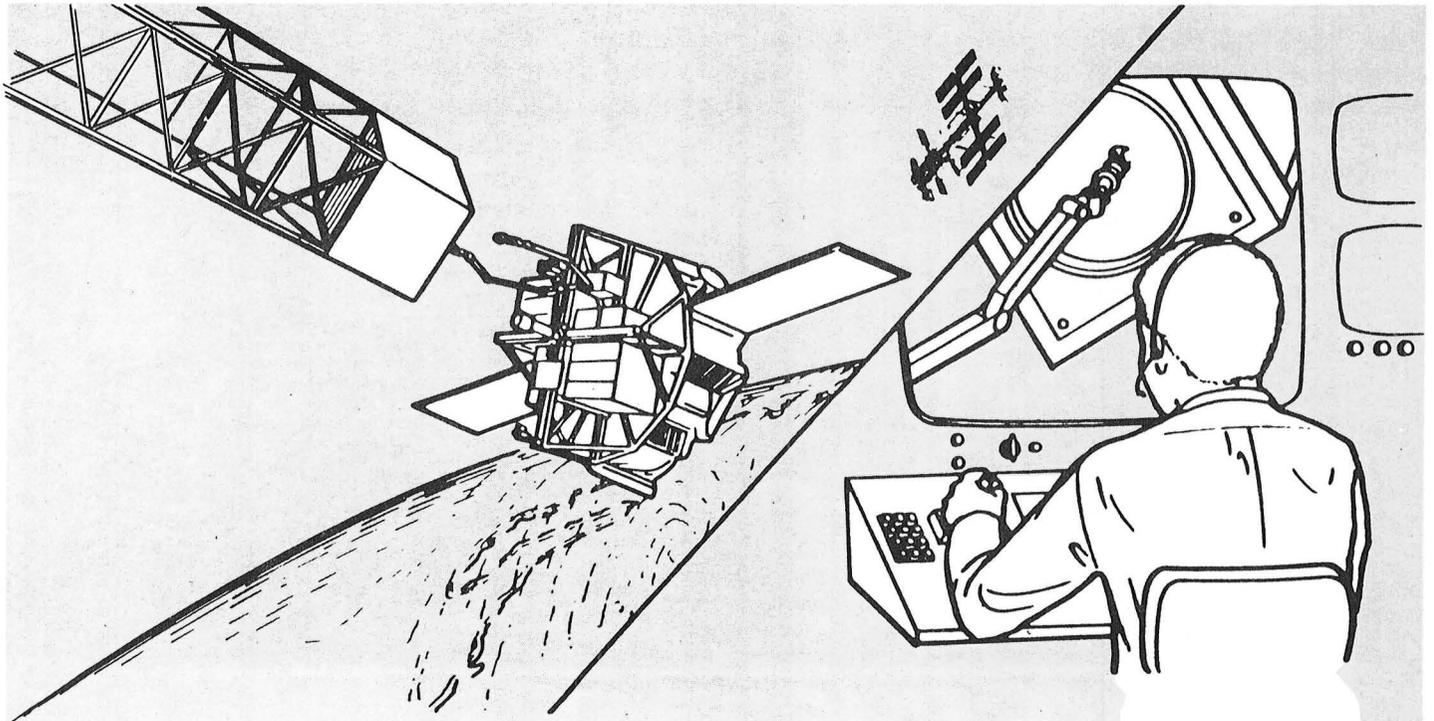
Automation in spacecraft has been important from the days of the earliest satellites. Current space systems incorporate a high degree of

automation, and plans for the Space Station have always called for the use of mobile remote manipulators and advanced control devices. However, the demands of a multipurpose facility like the Space Station are so great that major advances into the challenging territory of adaptable and general-purpose automation and robotics should be made if the full potential of the Space Station is to be realized.

The advances that will be required could come about in three ways. In some areas, NASA can be the prime mover in the development and application of new technology. In other areas, NASA can adapt for space use technology from terrestrial situations. And, in yet other cases, systems and devices from the commercial or the defense arenas can be taken and used directly.

In any event, the Space Station Program can provide a highly visible focus for advances in automation and robotics and be a stimulator or "driver" for the needed advances.

Remote operations (teleoperations) can be conducted under human control with the human operator feeling present at the worksite (telepresence).



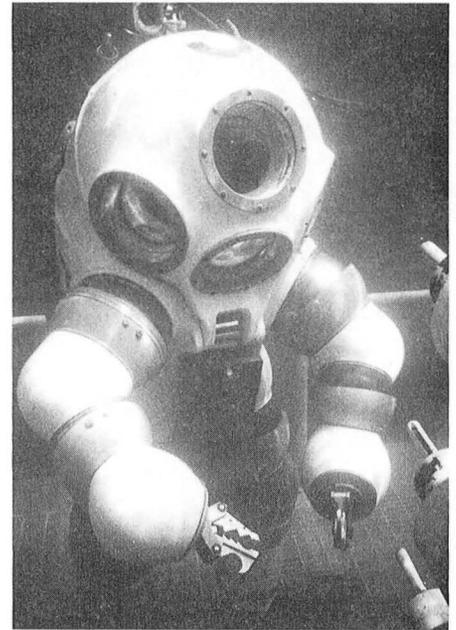
These advances could have benefits not only for space activities but also for U.S. technology in general.

For space activities, the benefits could be

- Increased productivity—with astronauts functioning as managers on behalf of station users rather than as operators carrying out routine functions
- Increased responsiveness to innovation—with the automated Space Station being more flexible and adaptable
- Lower cost of operations—with highly automated systems that can run at peak efficiency
- Improved reliability—with machine intelligence contributing to improved detection, diagnosis, repair, and recovery from abnormal situations
- Greater autonomy—with machine intelligence to support monitoring and control of station systems, thereby lessening reliance on ground support
- The ability to perform with robots and teleoperators tasks unsuited to humans alone—such as the assembly of large structures
- A reduced need, because of the use of robots and teleoperators, to expose humans to hazardous situations—such as extravehicular activities, fueling tasks, and servicing satellites in high orbits (where radiation could be harmful)

For the U.S. economy, the benefits will be

- A Space Station more suitable for commercial ventures with flexible and reliable systems and crew time for management actions
- The application of advances in automation and robotics stimulated by space ventures to terrestrial situations in settings ranging from the factory floor to the homebound elderly and on to the bottom of the sea



Manipulating devices can be improved for many applications.

(Courtesy of Oceaneering International, Inc.)



Devices to help the handicapped will come from advanced automation and robotics.

Recommendations to NASA for Advancing Automation and Robotics Technology

Because automation and robotics are so important, all Space Station Program elements (the "core" station, orbiting platforms, orbital maneuvering vehicles, and ground facilities) will make substantial use of these technologies as part of the basic program. However, much greater use could be made if research and development were accelerated in an augmented program. The Advanced Technology Advisory Committee has not evaluated the funding required to develop the technology base for such an augmented program. However, the Automation and Robotics Panel has addressed this matter and recommends a strong applications research program. The panel's desired level of additional funding is 13 percent of total Space Station costs; the minimum acceptable level for such a program is 7 percent. Additional funds would be needed for the adaptive engineering necessary to prepare the new technology for Space Station use. Such an augmented program would incorporate automation and robotics technology at a much faster pace than would the basic program. And the augmented program would result in somewhat greater productivity from the initial station, and much greater productivity from later versions of the station.

Recommendations for the Basic Program

To implement automation and robotics (A & R) in the basic Space Station Program, the Advanced Technology Advisory Committee makes the following

recommendations:

1. Automation and robotics should be a significant element of the Space Station Program.

The Space Station should be used as a medium for promoting automation and robotics within the nation.

Automation and robotics should be made a program-wide concern, equal in importance to safety or reliability.

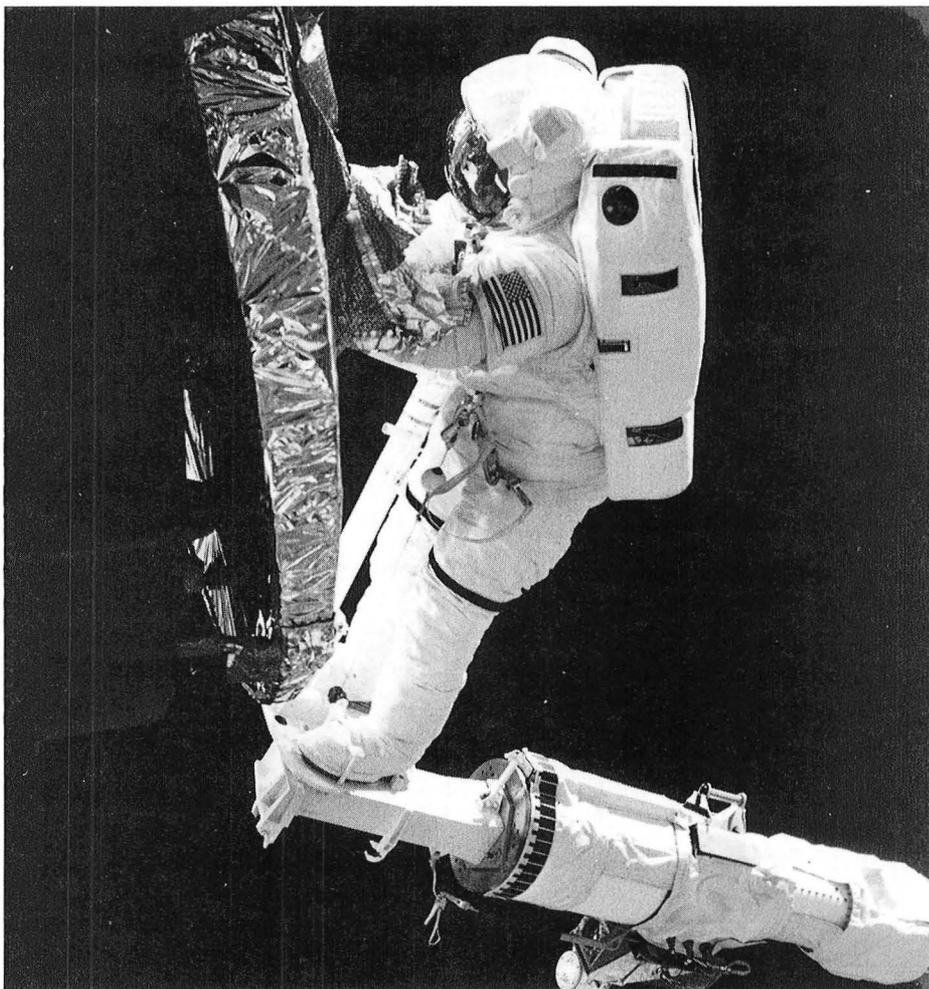
Research and development work should be focused specifically on automation and robotics.

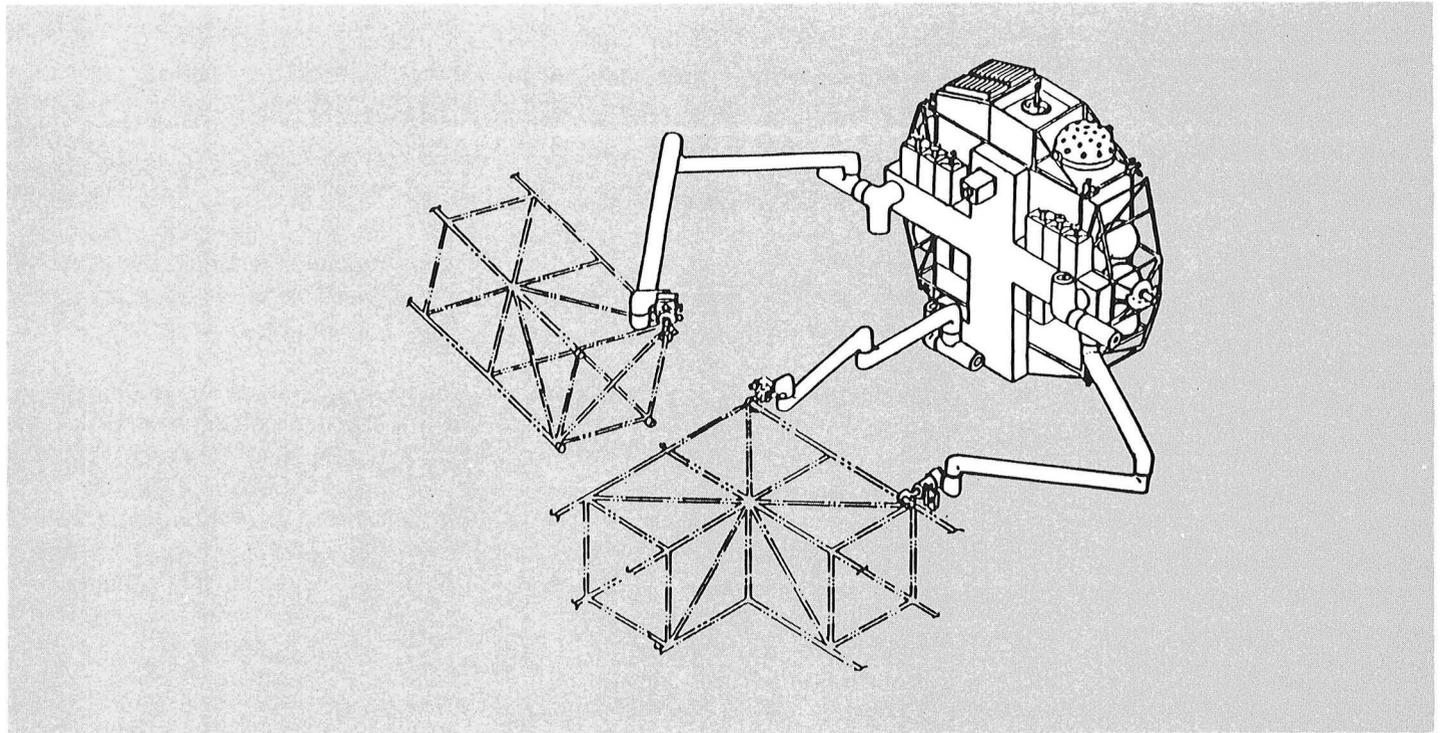
2. The initial Space Station should be designed to accommodate evolution and growth in automation and robotics.

Space Station system architecture should be developed to accommodate evolving A & R technology by

- Designing the Space Station data system to be supportive of artificial intelligence and robotics technologies and reserving the necessary capacity
- Capturing in the data base the Space Station design, including computer-aided representations and the *whys* or rationale thereof, to support later operations of expert systems (i.e., systems that simulate the behavior of human experts in certain specialized areas)

Initial station assembly will require astronauts aided by manipulators.





Robotic devices will aid in construction tasks.

- Maintaining, in the design process, the flexibility to incorporate new hardware as late as possible
- Using standard (yet evolvable) hardware, especially fittings and connectors, and standard marking techniques, such as bar codes
- Using standard programming languages
- Incorporating machine intelligence in the form of expert systems, first in well-defined and structured situations and later in more difficult situations
- Providing numerous sensors throughout the Space Station so that all elements can monitor their own well-being
- Providing ready access to the data base by station control systems, crew, and ground support staff under all station-operating and test conditions

- Designing the station to facilitate robot mobility, both within the station (intravehicular) and outside the station (extravehicular)
- Designing the station for eventual autonomy, with control by intelligent onboard devices and backup from intelligent ground-based systems, with human control as a last resort

Selection of contractors for detailed design and construction (phases C and D) should be influenced by the awareness of A & R issues displayed by the contractor during earlier work.

3. The initial Space Station should utilize significant elements of automation and robotics technology.

Applications of the A & R technology available at the time of the preliminary design review should be considered for the initial station. The initial station will include sufficient emphasis on automation and robotics to promote the accommodation of

future developments, especially in the area of general-purpose systems and devices.

NASA should conduct a set of progressive, experimental demonstrations/evaluations to determine what A & R technology can be incorporated into the initial station. Possible demonstrations are

- An intravehicular, voice-controlled inspection robot
- A mobile "go-fer" robot to assist in crew tasks
- A control device that uses artificial intelligence to enhance traditional automatic control

Specific goals are addressed in the next section.

Essential to the success of the demonstrations is that testing be done under realistic conditions. This requires that evaluations be conducted with the test item "embedded"; that is, functioning in an environment that resembles the eventual operational environment.

Because the Space Station crew would interact at every turn with the A & R elements, many of which have safety implications, the astronaut corps should be represented from the beginning and the design approach should incorporate manual means to override automatic systems. This way crew confidence in automated systems and robotic devices would be developed and safety would be assured.

4. Criteria for the incorporation of A & R technology should be developed and promulgated.

Criteria for Space Station use of the new technologies should focus on measurable issues such as productivity and annual operating costs and on potential benefits such as the merits of transferring space A & R technology back to terrestrial applications. Each application should be carefully selected and implemented according to these criteria to minimize overall system risks and costs and to improve system reliability.

5. Verification of the performance of automated equipment should be stressed, including terrestrial and space demonstrations to validate technology for Space Station use.

Many aspects of A & R technology are not yet well understood. Thus, applications would require careful verification before being used in life-critical systems. Furthermore, any implementation must recognize that, when subsystems interact with one another, the A & R aspects of those subsystems can lead to even more complex interactions.

6. Maximum use should be made of technology developed for industry and Government.

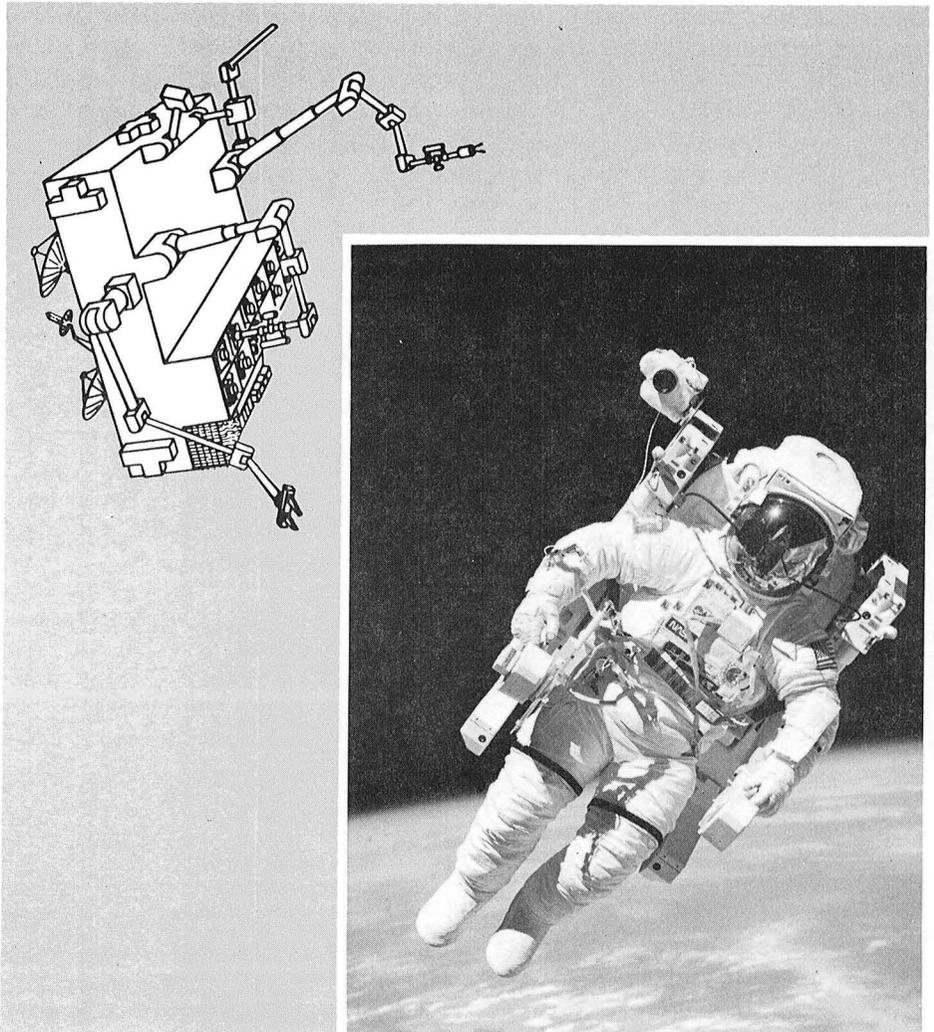
Extensive work in automation and robotics is currently underway in industry, academia, and Government agencies. Current and future technology from these activities

should be considered and used in the Space Station, provided the technology is applicable and has been qualified for space use. Examples might be

- Robots designed for terrestrial applications, modified as necessary for space applications in microgravity
- Products from the Strategic Computing Program of the Defense Advanced Research Projects Agency

A commercial approach to A & R hardware and software should be taken, as contrasted to a Department of Defense approach. However, NASA would remain cognizant of technology developed by the Department of Defense.

An "apprentice" astronaut can assist in many tasks.



7. The techniques of automation should be used to enhance NASA's management capability.

A major effort will be made to use automation technology in the management process itself. For example, a technical management information system is being developed to link all participating organizations. This will employ the most current office automation and computer-aided design, manufacturing, and engineering (CAD/CAM/CAE) techniques.

8. NASA should provide the measures and assessments to verify the inclusion of automation and robotics in the Space Station.

Quantitative goals should be established for various Space Station A & R technologies and appropriate measures defined to assess progress.

Recommendations for an Augmented Program

If research and development can be accelerated in an augmented program, then a great deal more automation and robotics technology can be incorporated into the Space Station. Not only will the initial station be able to make greater use of such systems, but the evolutionary versions of the station will be much more highly automated and approach autonomous operation.

Given such an augmented program, the Advanced Technology Advisory Committee would make the following recommendations:

9. The initial Space Station should utilize as much automation and robotics technology as time and resources permit.

Further research and an acceleration of development and testing would give much greater insight into what can be expected for later versions of the station. Thus, more complete provision could be made for accommodating such developments. Additional, important demonstrations would be conducted; notably, an extravehicular robot capable of replacing failed parts on orbit.

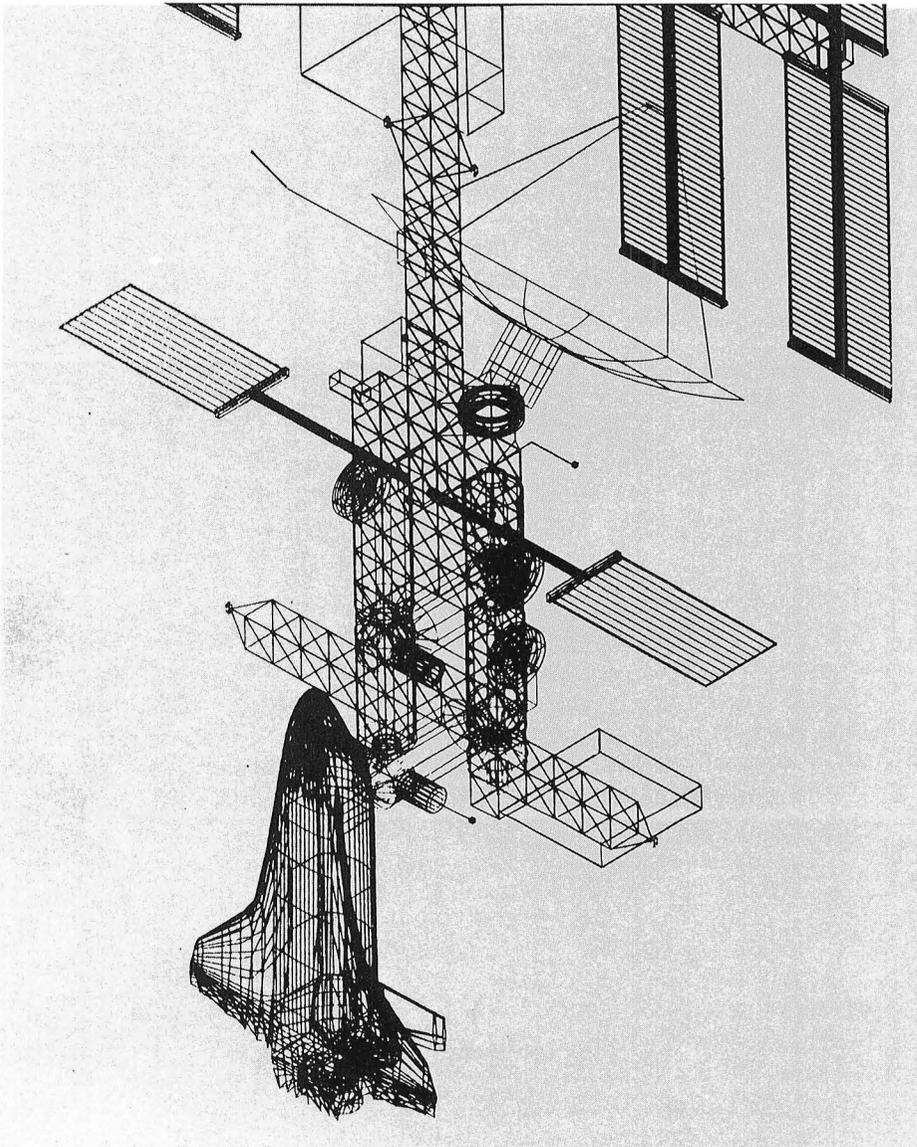
Also, early demonstrations of A & R applications, including flight experiments, would be planned and carried out before the end of phase B.

10. An evolutionary station should achieve, in stages, a very high level of advanced automation.

The Space Station will be evolutionary in nature; it should be developed in such a way as to allow facile introduction of future A & R technology advances.

Each Space Station function, element (such as a platform), and subsystem should be considered for A & R technology application.

Computer-aided design is vital to the Space Station.



At the levels of automation anticipated for an evolutionary station, autonomous operation would be the norm.

A primary thrust would be to minimize ground and crew involvement in fault isolation, redundancy management, and routine servicing of onboard systems and payloads.

The interaction between crew and system—the human/machine interface—should be as natural as possible; for example, voice control of an “apprentice” by a crewmember.

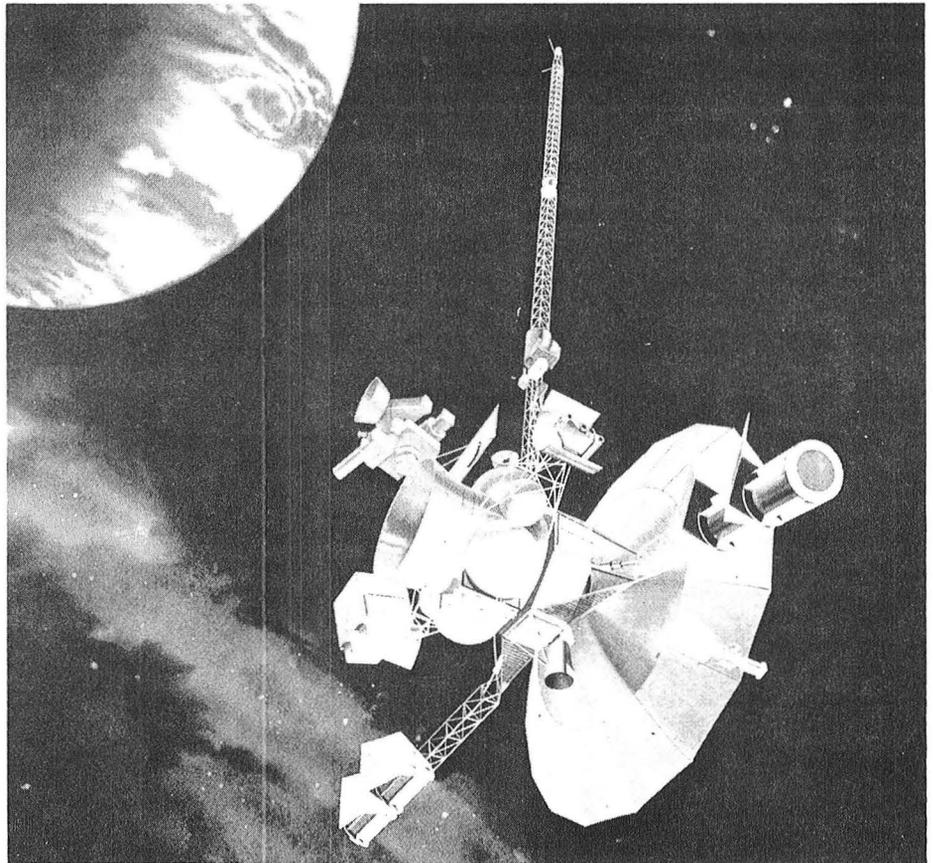
11. An aggressive program of long-range technology advancement should be pursued, recognizing areas in which NASA must lead, provide leverage for, or exploit developments.

NASA should try not only to promote advancements that are currently foreseen but also to stimulate improve systems and devices radically. Flexible, general-purpose systems are particularly important. Such systems could perform in situations not pre-planned by their designers and thus provide the adaptable and intelligent capabilities suitable for a space infrastructure that will serve a variety of needs.

NASA should solicit the involvement of entrepreneurs, especially those in small businesses, in Space Station automation and robotics for innovative ideas.

12. A vigorous program of technology transfer to U.S. industries and research and development communities should be pursued.

A Space Station Program pursued with an augmented effort to research and develop automation and robotics would be much more visible and attractive to potential terrestrial users of the technology. And there would be vastly more technology to transfer.



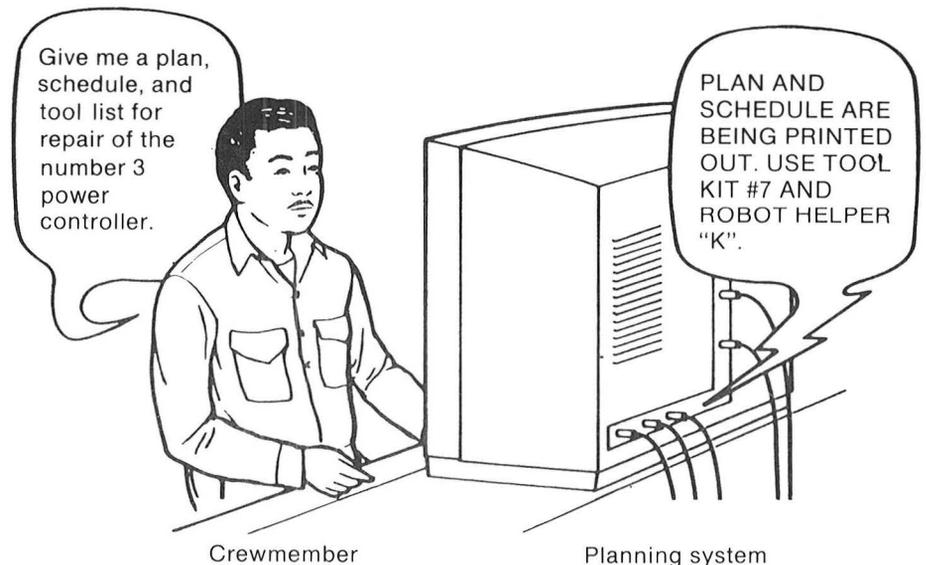
Future planetary spacecraft will be highly autonomous.

Major emphasis should be given to transferring the A & R technologies from the Space Station to private sector organizations contemplating commercial space activities.

sensitive to U.S. concerns about technology transfer that results in exporting jobs. NASA should use appropriate regulations to protect the A & R technology it uses and develops.

Potential international participants in the Space Station Program must be

A voice communication is natural and efficient.



13. Satellites and their payloads accessible from the Space Station should be designed, as far as possible, to be serviced and repaired by robots.

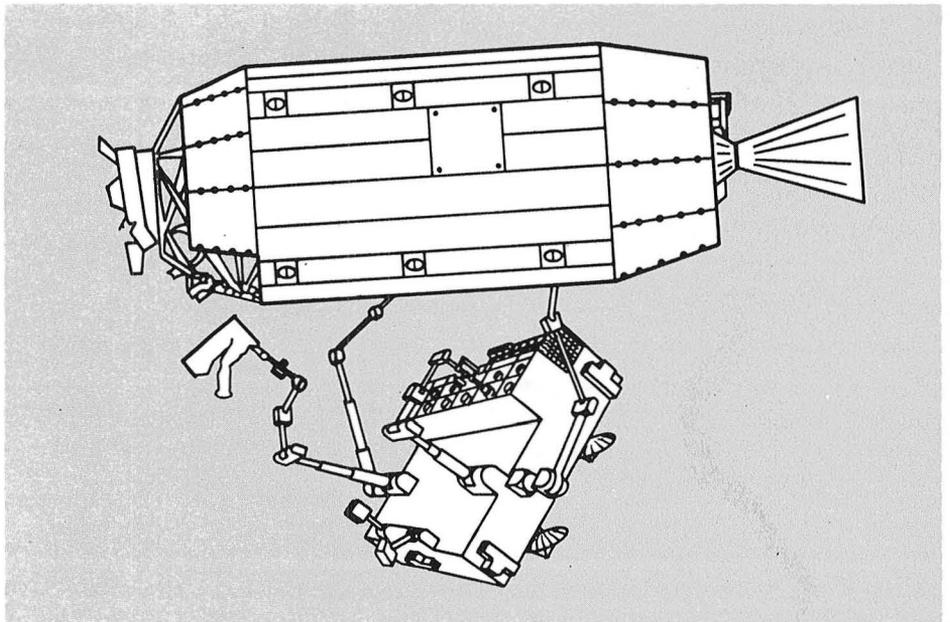
Management Approach and Schedule

NASA is concerned also with having an adequate mechanism to ensure that the intent of Congress is met and that A & R technology is appropriately used and advanced.

NASA should use the Space Station "definition and preliminary design" process (phase B) to define the automation and robotics to be used in the initial Space Station and to indicate the advances that will be needed as the Space Station evolves. An implementation plan using a systems approach and progressive, experimental demonstrations/evaluations is being prepared by the Office of Space Station. This approach will ensure that guidance from Space Station Program managers at all levels and innovative thinking from phase B contractors will be brought to bear on the evolution of automation and robotics.

The Advanced Technology Advisory Committee is in agreement with concerns expressed by the Automation and Robotics Panel that Space Station Program managers have a formidable job without having to be responsible for long term A & R development. NASA should supply a management focus that will provide the necessary visibility and thrust to this task. The Advanced Technology Advisory Committee will continue to follow A & R needs and report to Congress semi-annually.

A proposed schedule for phase B activities in automation and robotics is given in table 1.



In the future robots will service satellites.

TABLE 1.— PROPOSED AUTOMATION AND ROBOTICS MILESTONES DURING SPACE STATION DEFINITION AND PRELIMINARY DESIGN

Key Milestones	CSD	IRR	SRR	ISR	SDR																
Months after CSD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Send ATAC guidelines and Space Station Program A&R plan and design manual to phase B contractors	Initiate																				
Conduct early demonstrations/evaluations																					
Incorporate A&R changes, including time-phased requirements, into phase B study plan and advanced A&R development plan																					
Incorporate A&R changes into master data base and engineering master schedule																					
Establish A&R impacts on baseline configuration																					
Establish A&R impacts on interface requirements																					
Make level B decision on advanced hardware and software																					
Complete integration of A&R into preliminary design and estimate costs of systems advancing A&R																					
Develop supporting A&R technology																					
Formulate A&R time-phased requirements and technology development plan for evolutionary station	Initiate																				

CSD — Contract start date
 IRR — Initial Requirements Review
 SRR — System Requirements Review
 ISR — Interim System Review
 SDR — System Design Review

Goals for Advanced Automation and Robotics Applications

Automation would enhance all elements of the Space Station Program — the core station, orbiting platforms, orbital maneuvering vehicles, and ground facilities. There should be an evolutionary progression toward realizing an autonomous space station. However, all initial designs should utilize as much mature automation as

technologically feasible while not precluding eventual growth. Subsystem design should be targeted conceptually for a mature (year 2010) space station, and modifications should be made as necessary for the initial station, recognizing the readiness of the technology and the lead time required to achieve implementation.

The Advanced Technology Advisory Committee has distilled the results of its study, the findings of the Automation and Robotics Panel, and the results of contractor and SRI studies into a set of goals that should be pursued. Table 2 depicts proposed goals (by no means an exhaustive list) for advanced automation and robotics on the initial station.

Further, the committee believes that it is beneficial to suggest a path along which the evolution of automation and robotics could proceed. Thus, while we recognize that projections into a time as distant as a mature station (year 2010) are hazardous, we present a set of proposed goals, table 3, as an indication of our current thinking.

TABLE 2.— PROPOSED GOALS FOR AUTOMATION AND ROBOTICS APPLICATIONS, INITIAL SPACE STATION

- **Electrical Power**

Controllers enhanced by expert systems for

- Load distribution and switching
- Solar array orientation
- Trend analysis
- Fault diagnosis

- **Guidance, Navigation, and Control**

Expert systems for

- Station attitude control
- Experiment pointing
- Orbital maintenance and reboost
- Rendezvous navigation
- Fault diagnosis

- **Communication and Tracking**

An executive enhanced by expert systems for

- Communication scheduling
- Rendezvous tracking
- Data rate selection
- Antenna pointing

- **Information and Data Management**

An executive enhanced by expert systems for control of

- Subsystem statusing
- Trend analysis
- Fault diagnosis
- Redundancy and configuration management
- Data base management

- **Environmental Control and Life Support**

Controllers enhanced by expert systems for

- Trend analysis
- Fault diagnosis
- Crew alarm
- Station atmosphere monitoring and control
- Hyperbaric chamber

- **General**

Teleoperation of mobile remote manipulator with collision avoidance

Mobile multiple-arm robot with dextrous manipulators to inspect and exchange orbital replacable units

Systems designed to be serviced, maintained, and repaired by robots

Primary station control in space with appropriate backup

TABLE 3.— PROPOSED GOALS FOR ADVANCED AUTOMATION AND ROBOTICS APPLICATIONS, EVOLUTIONARY SPACE STATION

• Propulsion

An intelligent controller for

- Fuel distribution and management
- Leak detection and evaluation

• Electrical Power

An autonomous intelligent controller for

- Power management
- Fault detection and isolation
- Maintenance scheduling

• Guidance, Navigation, and Control

An intelligent controller for

- Fully automatic rendezvous and docking
- Space traffic control
- Remotely piloted vehicles
- Collision avoidance

• Communication and Tracking

An intelligent system for

- Automatic planning
- Tracking multiple vehicles
- Scheduling bulk data storage for communications blackouts
- Detection, identification, and characterization of general targets

• Information and Data Management

A intelligent system for

- Fault detection, isolation, and repair
- Natural language interface with crew

A data base manager for

- CAD/CAE bulk data storage facility
- Retrieval and routing to requestors

• Environmental Control and Life Support

An intelligent controller for

- Ensuring fail-safe/fail-operational modes
- Fault detection and isolation
- Chemical analysis of air and water
- Toxic gas analysis

• Habitability

An intelligent system for

- Health maintenance
- Speech interpretation and synthesis
- Physiological monitoring
- Automated medical decisions
- Trend analysis

• Structures and Mechanisms

Advanced work station
Intelligent actuators
Teleoperators

• Orbiting Platforms

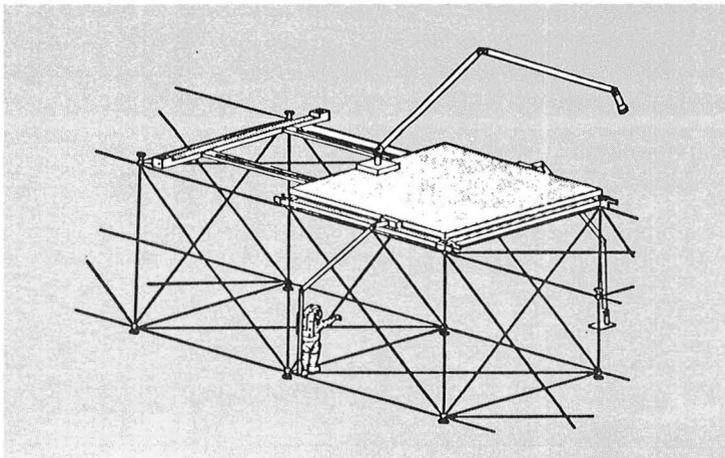
An intelligent system for

- Process control
- Maintenance control
- Planning and trend analysis

• General

Robots for

- Inspection, maintenance, refurbishment, and repair
- Fuel and materials transfer
- Detecting hazardous leaks
- Satellite retrieval and servicing



Major construction tasks will be aided by robots.

Case Studies of Automation and Robotics Issues

A number of case studies of advanced automation and robotics have been conducted recently by U.S. aerospace companies. These studies have provided very helpful insights into a number of representative situations. The companies and topics studied are

- Boeing
 - Operator/System Interface
- General Electric
 - Space Manufacturing Concepts

- Hughes
 - Subsystem and Mission Ground Support
- Martin-Marietta
 - Autonomous Systems and Assembly
- TRW
 - Satellite Servicing

The salient findings of each of these studies are summarized in the following paragraphs.

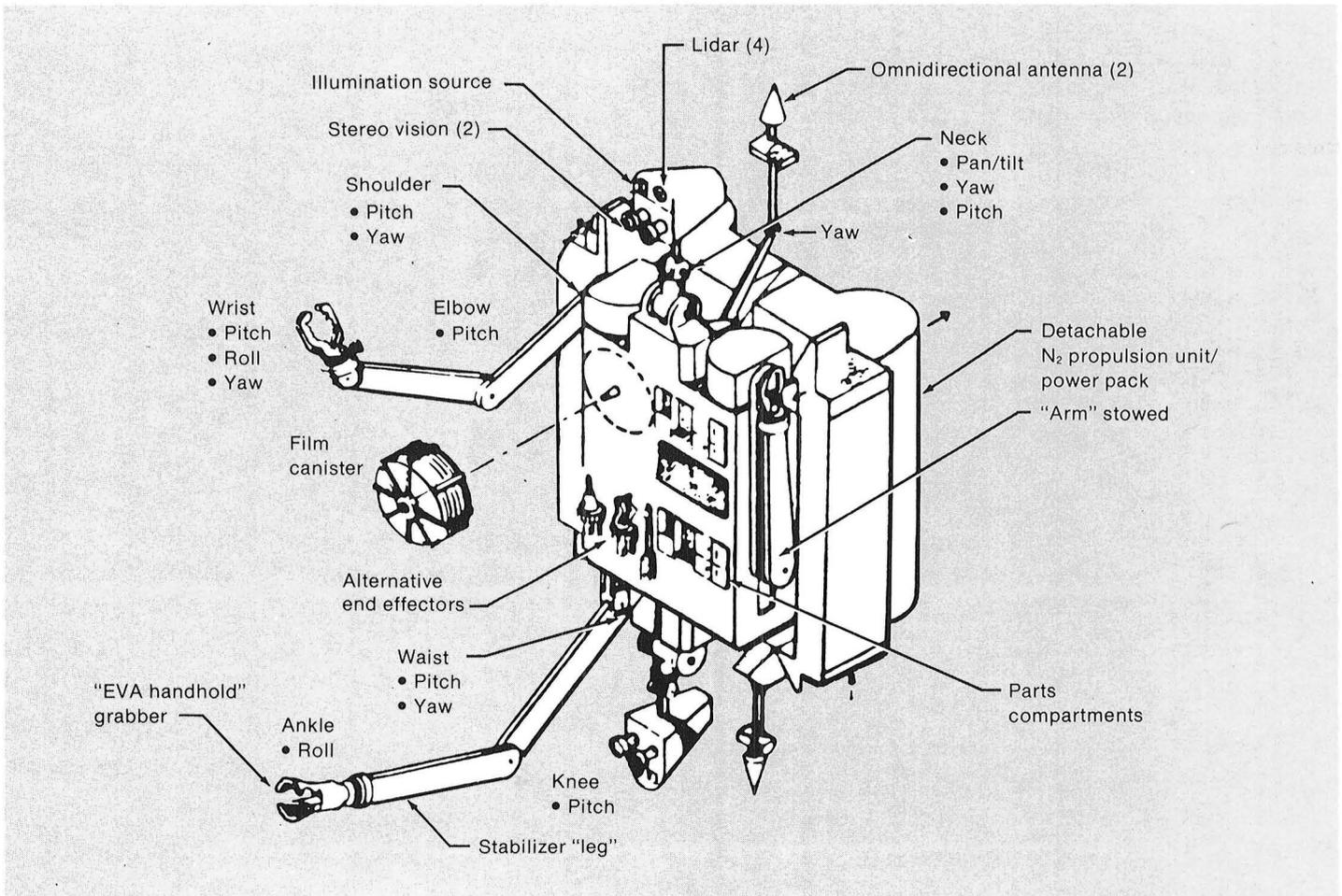
Operator/System Interface

Boeing studied the automation and robotics issues connected with the operator/system interface (OSI), sometimes called the human/machine interface, of the Space Station. This study, which was contributed by Boeing, drew upon a multimillion-dollar technology assessment carried out earlier by

Boeing which produced a model of the technology advances that could be expected for various investments.

The study focused on the functional requirements for the operator/system interface and the A & R technologies needed to meet these requirements. The specific topic was the interface for an extravehicular (EV) robot of the type which would move about the Space Station and perform physical tasks at various worksites. The operator/system interface for this robot would perform path planning, tracking and control, object recognition, fault detection and correction, and plan modification.

Free-flying robots can perform many extravehicular tasks, such as retrieving film from a photographic platform.



The major conclusions are these:

- It is technically feasible to develop an initial, fairly rudimentary EV robot and operator/system interface by the mid-1990s and a sophisticated, efficient, and convenient system by about 2010. The initial operator/system interface would have a limited supervisory capability and would be largely experimental in nature.
- An EV robot has great potential for relieving astronauts of routine and hazardous tasks and for increasing the level of extravehicular activity in support of the Space Station.

The following artificial intelligence technologies need to be emphasized in order to develop OSI capabilities:

Language representation
 Natural language understanding
 Analogical reasoning
 Nonmonotonic reasoning

Boeing recommended a program to develop the EV robot operator/system interface and described how such a program could be undertaken.

Space Manufacturing Concepts

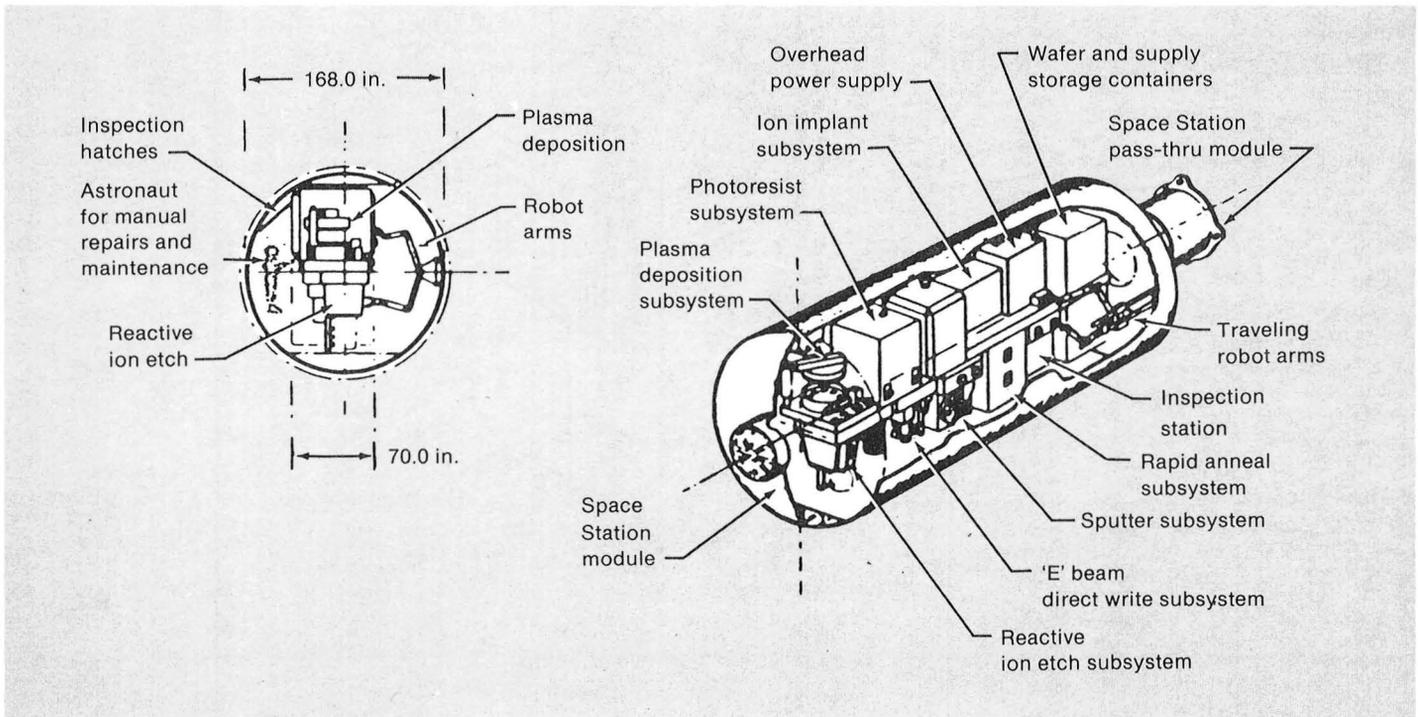
General Electric developed conceptual designs for two space manufacturing facilities to define factory automation requirements. The facilities studied were for the production of gallium arsenide (GaAs) crystals and for the processing of microelectronic chips from such GaAs material.

The major conclusions are these:

- The manufacturing concepts studied are representative of innovative, technologically advanced systems.
- The major challenge is how to maintain, repair, and refurbish the production equipment.

- Space manufacturing automation requirements and design approaches can be defined for process mechanization, teleoperation and robotics, sensors, and artificial intelligence.
- Teleoperators and robots can be based on present designs, but space versions will be very different. They must be lightweight, and they will have different kinematics and dynamics in the microgravity environment.
- Artificial intelligence and expert systems must evolve as each facility is developed.
- "Intelligent" tools needed for repairs, modifications, and fabrication of equipment in space will generally use teleoperation incorporating a high degree of telepresence.

Microelectronic components can be made in an efficient space factory.



- Many routine functions, such as removal or installation of standard retainers and replacement of expendables, will eventually utilize intelligent robots.
- Experiments in space must be conducted to prove A & R designs and capabilities.

General Electric recommended five near term A & R studies and experiments.

Subsystem and Mission Ground Support

Hughes studied the issues of automation in the areas of subsystem control and mission operations. The thrust was to develop concepts for autonomous operation and to assess the benefits and technology requirements of such concepts.

The study addressed electrical power, thermal control, and communications operations as representative subsystems, with emphasis on communications. The concept required automated capability to detect, isolate, and recover from failures.

Hughes recommends the following:

- Automatic speech recognition and synthesis should be considered a basic mode of *human/machine interaction* for Space Station command and control.
- The data management system and other subsystems of the Space Station should be designed to accommodate fully automated fault detection, isolation, and recovery.

Autonomous Systems and Assembly

Martin-Marietta asked what is the highest level of automation that could conceivably be accomplished by the year 2000 and what automation technology for assembly, construction, repair, and modification could be applied to the Space Station.

Martin-Marietta's major recommendations are as follows:

- Automation capability will grow rapidly and the Space Station needs to be flexible in design in order to accommodate this evolution.
- A cost-effective approach is to build in provisions for future modifications; for example, access corridors, berthing ports, and worksite "rest points" on which manipulating devices can be positioned.
- Status and warning capabilities for subsystems and for the total station should be provided.
- Human involvement in construction will start at an intensive level but decrease slowly until humans provide only a contingency capability.

Emphasis needs to be placed on the following technologies to support Space Station development:

- Teleoperation
- Proximity, touch, and force sensors
- Predictive displays
- Low-weight dextrous arm
- Dual-arm coordination
- Advanced activators
- Knowledge-based systems
- Planners, strategic and tactical
- Expert systems
- Machine vision
- Special and multifinger end effectors

Satellite Servicing

TRW addressed the issues of automated satellite servicing from the Space Station to determine benefits, methods, and best combinations of human/machine activities and to project needed technology advances.

The study considered four representative mission scenarios; i.e., low Earth orbit satellites, a co-orbiting materials-processing facility, payloads attached to the Space Station, and a geostationary satellite serviced by a recoverable orbital transfer vehicle (OTV).

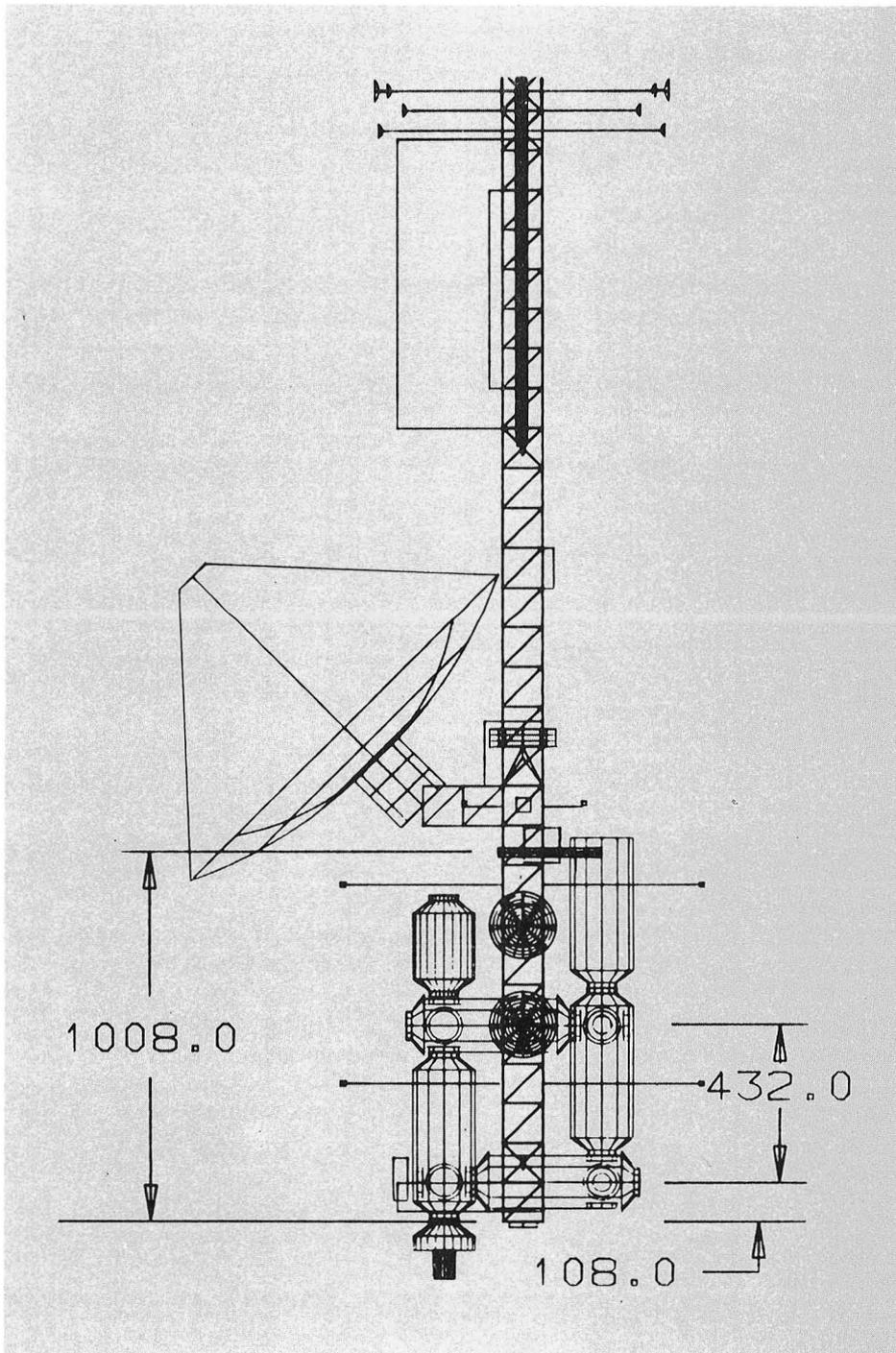
The major conclusions are these:

- Automation can make satellite servicing more productive, but accelerated development of automation hardware is needed.
- Servicing poses automation requirements significantly different from those of other Space Station orbital activities.
- Telepresence is the principal automation discipline required for servicing, with human operator involvement to handle task diversity and unforeseen situations.
- Geosynchronous satellite servicing demands more reliance on the full robotic mode, with human supervisory control and teleoperation preferably performed from a ground station rather than from the Space Station.
- Massive data system and artificial intelligence support is needed in planning, sequencing, and executing tasks.
- Major benefits to terrestrial applications will be in the area of flexible/adaptable automation.

TRW's recommendations for advancement of automation and robotics technology include emphasis on

- Robotic vision
- Standardized interfaces designed for automated servicing
- Intelligent servicing kits (e.g., for the OTV)
- Pressurized, movable work stations

An onboard data base can retain graphic details on the station design.



Benefits for the U.S. Economy

"The conferees both intend and expect that the technologies of Space Station automation and robotics will be identified and developed not only to increase the efficiency of the station itself but also to enhance the Nation's technical and scientific base leading to more productive industries here on Earth." So states report 98-867 of the Committee of Conference, a report that accompanies bill HR 5713, which authorizes funding for the Space Station.

The strength of the U.S. economy is closely linked to advances in technology. Keeping the economy robust requires a continuing injection of new technology of the type that can be developed in the Space Station Program. Indeed, we believe that the economy needs the same flexible, general-purpose machine intelligence and robotics. Thus the benefits expected by Congress can be realized if the technology advances described in this report are made successfully and then adapted to industries on Earth.

Contrary to popular fears, the application of A & R technology is not expected to decrease the number of jobs in the U.S. economy but may actually increase that number. Evidence from several studies, including studies by a congressional subcommittee and the Office of Technology Assessment, support this assertion. One summary statement concluded that, "in the long run, industrial robots should lead to improved working conditions, higher real wages and the creation of more jobs."

Technology Transfer

There are many possible applications of advanced automation and robotics to the terrestrial economy. Two of these are typical:

Expert Systems

Already beginning to come into use in the marketplace, expert systems model the performance of the best human experts in certain specialized areas. Notable success has been achieved in such tasks as determining what combination of components will make up the best computer system for a particular job, diagnosing problems in locomotives and suggesting repair procedures, and providing assistance in medical diagnoses.

Such systems figure prominently in the A & R advances that the Space Station could bring about. As indicated in tables 2 and 3, a large array of control and troubleshooting functions could be handled or enhanced by expert systems. Since many of these functions are equally important in terrestrial situations, the transfer of the technology should be very direct.

The transfer of advanced expert systems back to the terrestrial economy could, by the year 2000, result in major productivity improvements not only in industry but also in health care, transportation, communications, and many other sectors of the economy.

Adaptive Control for Robots

Critical needs exist in industry today for certain types of automation technology. For example, adaptive control for robots is needed to accomplish automated assembly tasks. Factors such as the requirement for autonomy, safety constraints, and productivity considerations will drive the development of adaptive control technology. The means exist within NASA to transfer such technology, if developed for the Space Station, to U.S. industry.

If adaptive control technology were available to large and small industries alike, the impact could be considerable. One preliminary estimate (Digeronimo) is that if NASA were to begin a vigorous development effort in automation and robotics in 1985 and continue through

Expert systems for diagnoses will aid greatly in health care.



2000, the annual sales of industrial robots for assembly applications alone would increase by \$600 million over currently projected sales.

There are many possible applications of intelligent robots. Some of these are depicted in table 4.

Commercialization of Space

Benefits will also accrue to the U.S. economy because of commercial activity in space. Some observers, in fact, see space as the next big industrial frontier. Commercial activity in space will result in the production of unique goods for sale to consumers and industrial customers on Earth. Automation would make the Space Station more flexible and adaptable and less costly to operate. Thus, by making station facilities more productive, it would make the Space Station a better environment for commercial applications.

An example of the benefits of such space commercial activity has already been cited in the case study on space manufacture of gallium arsenide crystals and microelectronic

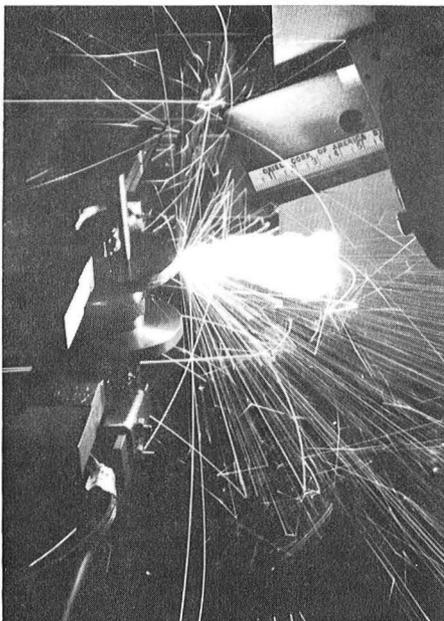
TABLE 4.— POTENTIAL INTELLIGENT ROBOT APPLICATIONS IN THE U.S. ECONOMY

Settings	Uses
Factories (manufacturing, light industry)	Welding, machining, painting, molding, assembly, inspection, repair, loading, packaging
Offices and institutions (hospitals, schools, prisons)	Distribution (mail, supplies, food), cleaning (floors, windows, trash)
Undersea	Surveying, search and rescue, cable laying, construction, extraction
Mining; oil and gas	Extracting, drilling, rescue (firefighting, boring), processing
Nuclear power plants	Maintenance, emergency operations
Agriculture	Harvesting, planting, irrigation, fertilizing, weed and pest control
Construction	Excavations, structure erection and demolition
Home	Aiding elderly or handicapped

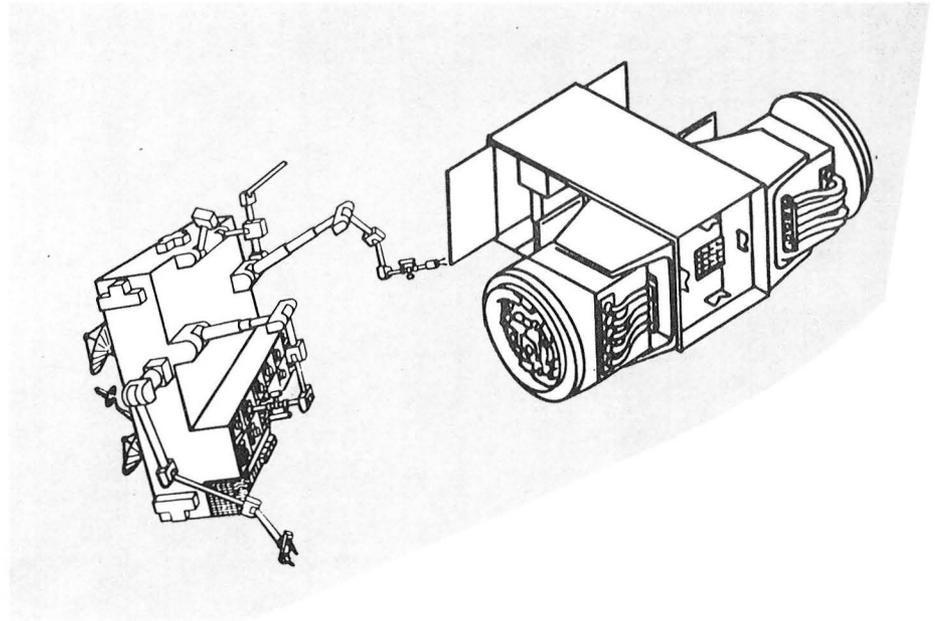
chips from such material. Such manufacturing could lead to more efficient electronic devices for terrestrial use. Automation is a key element in the successful commercialization of space, as described by General Electric in their study.

The commercialization of space in the sense of commercial satellites, such as for communication, is well established. Advances in automation and robotics could enhance the capability to support such satellites with space assembly, maintenance, and repair.

Industrial processes can be improved using advanced automation and robotics.



The technology underlying intelligent robots developed for space use can be applied to terrestrial tasks.



Closing Remarks

NASA must meet the significant challenges posed by the competitive, commercial era of the U.S. space program in its second 25 years. An important factor in meeting these challenges successfully should be the creation, adaptation, and application of a large array of automation and robotics technology to diverse situations in the Space Station. Equally important, NASA should promote the transfer of the new technology to terrestrial situations where it will benefit the U.S. economy.

The timely, successful generation and application of automation and robotics technology could have profound effects. When the technology is widely dispersed throughout our society, as the NASA technology transfer process allows, Americans could have a significantly improved capability to handle complex tasks that require the codification and mechanization of knowledge. The new technology could improve the capability of our industrial and political leaders to utilize the nation's pool of knowledge and to manage large enterprises effectively, flexibly, and with greatly increased productivity.

Successful incorporation of automation and robotics by the Space Station Program could lead to the deployment of a new generation of flexible and adaptable space systems. These systems could provide the United States with

important new methods of generating and exploiting space knowledge in commercial enterprises and thereby help preserve U.S. leadership in space.

Although there are difficult challenges to meet, ATAC believes that NASA can achieve the goals of a national program of such scope and complexity. A substantial return on invested resources in terms of increased Space Station productivity and increased economic strength can be expected.

Study Organization and Participation

In response to the mandate from Congress to address advanced automation and robotics, NASA undertook to enlist as much expertise as was reasonably available. A concerted effort was made to involve aerospace contractors, industry, and universities. The work was structured into three major elements, carried out by the Advanced Technology Advisory Committee, by the Automation and Robotics Panel, and by SRI International and aerospace contractors. The organizational methodology used for this Space Station automation study is depicted in figure A. The manager of the study is Dan Herman, NASA Headquarters, and the deputy manager is Victor Anselmo, NASA Headquarters. The chairman of the steering committee for the study is Robert A. Frosch, Vice-President, General Motors Corporation.

The Advanced Technology Advisory Committee was formed pursuant to PL 98-371. The members of the committee, listed in table I, were selected not only because of their professional experience and capability, but because the organizations they represent will be those responsible for assuring a high level of A & R accommodation in the initial Space Station and its associated platforms. The committee was tasked to consider the charge from Congress, the needs and limitations of the Space Station program, and the findings of the other studies and then to provide recommendations to NASA.

The California Space Institute (Cal Space) of the University of California formed the Automation and Robotics Panel (ARP), which included representatives of industry, academia, and Government (table II). The panel was to study available and prospective technology and to provide an independent set of recommendations to NASA.

The aerospace contractors involved studied automation and robotics in specific areas as follows:

Boeing	Operator/System Interface
General Electric	Space Manufacturing Concepts
Hughes	Subsystem and Mission Ground Support
Martin-Marietta	Autonomous Systems and Assembly
TRW	Satellite Servicing

Because of the limited time available, the contractors were directed to identify "drivers" for advanced automation. They were not asked to address all automation and robotics applications for an evolutionary Space Station but only those believed to be typical.

SRI International provided a technology assessment based on the contractor studies, their own knowledge of the technology, and their anticipation of technology readiness.

Figure A.— Methodology for the Space Station automation study.

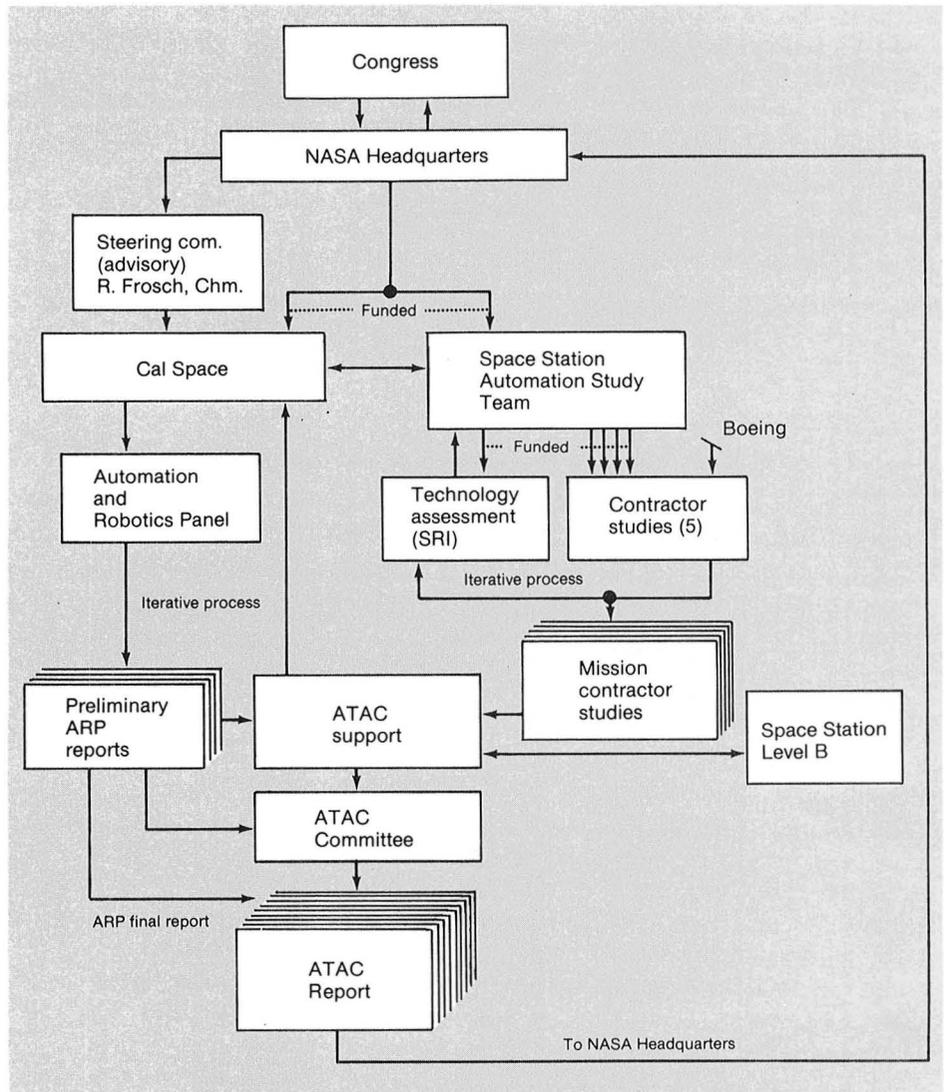


TABLE I.— SPACE STATION ADVANCED TECHNOLOGY ADVISORY COMMITTEE

-
- Aaron Cohen, Chairman, Director of Research and Engineering, Lyndon B. Johnson Space Center (JSC)
 - John H. Boeckel, Director of Engineering, Goddard Space Flight Center (GSFC)
 - J. Larry Crawford, Assistant to the Chief Engineer, NASA Headquarters
 - Lynwood C. Dunseith, Assistant to the Director of Space Operations, JSC
 - J. Stuart Fordyce, Director of Aerospace Technology, Lewis Research Center (LeRC)
 - Paul F. Holloway, Deputy Director, Langley Research Center (LaRC)
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 - Robert R. Nunamaker, Chief Engineer, Ames Research Center (ARC)
 - Donna L. Pivrotto, Manager, Space Station Office, Jet Propulsion Laboratory (JPL)
-

An ATAC support group (table III) was formed to assist in the effort. The members of the group functioned as a part of the Space Station automation study team, as observers at the ARP meetings, and as major participants in the support to ATAC. This support group assimilated the inputs from various contributors into this report.

The entire process of the Space Station automation study was an open and iterative one, with many information exchanges. All meetings, presentation documents, and so forth were open to all participants. This effort required and received extraordinary cooperation from the entire study team.

TABLE II.— AUTOMATION AND ROBOTICS PANEL

James R. Arnold, California Space Institute (Cal Space)
Robert Cannon, Stanford University
Roger Cliff, Defense Advanced Research Projects Agency (DARPA)
Aaron Cohen, NASA/Johnson Space Center
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Roger Perkins, Los Alamos National Laboratory
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TABLE III.— ATAC SUPPORT GROUP

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Program Office, JSC
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Ames Research Center

Acknowledgments

This report was prepared for the NASA Advanced Technology Advisory Committee (ATAC) by the ATAC Support Group and members of the NASA Johnson Space Center Artificial Intelligence Office. The support group, the members of which are listed in table III, provided guidance on the purpose, contents, and organization, as well as making vital contributions to the draft material.

The JSC Artificial Intelligence Office provided the initial draft of the report and integrated comments and revisions to produce the final version. The contributors were

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Several individuals, representing various NASA organizations, provided vital assistance and draft material in preparing this document:

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The technical writing was done by R. Bryan Erb, consultant, and the technical editing was done by Mary Fae McKay of JSC.

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Acronyms and Abbreviations

A & R	automation and robotics
AI	artificial intelligence
ATAC	Advanced Technology Advisory Committee
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacturing
CSD	contract start date
EV	extravehicular
GaAs	gallium arsenide
IRR	Initial Requirements Review
ISR	Interim System Review
IV	intravehicular
NASA	National Aeronautics and Space Administration
ORU	orbital replaceable unit
OSI	operator/system interface
OTV	orbital transfer vehicle
SDR	System Design Review
SRR	System Requirements Review

Glossary

[Many of these definitions are from Gevarter, 1983.]

A

Analogic reasoning: A type of reasoning that builds on analogies with related situations.

Artificial (or machine) intelligence (AI): A discipline devoted to developing and applying computational approaches to intelligent behavior. Also referred to as machine intelligence or heuristic programming.

Automation: The technology by which control of physical processes or devices can be exercised according to preestablished rules and, normally, without human intervention.

Autonomous: Capable of independent action.

C

Computer vision (robotic vision, machine vision): Perception by a computer, based on visual sensory input, in which a symbolic description is developed of a scene depicted in an image. It is often a knowledge-based, expectation-guided process that uses models to interpret sensory data. Used somewhat synonymously with image understanding and scene analysis.

Co-orbiting: Said of a satellite orbiting in an orbit close to and readily accessible to the Space Station orbit.

D

Data base: An organized collection of data about some subject.

Data base management system: A computer system for the storage and retrieval of data about some domain.

Dextrous manipulator: A mechanical device that can carry out physical tasks with a facility approaching that of a human.

E

Effector: The portion of a manipulator that causes the desired action, such as gripping or positioning.

Expert system: A computer program that uses knowledge and reasoning techniques to solve problems normally requiring the abilities of human experts.

F

Fail-safe/fail-operational: Said of a design approach for a spacecraft component in which a failure of the component will result in a condition that is operational if possible or at least safe.

G

Geosynchronous/geostationary: Of an orbit around the Earth at just the correct height so that a satellite in such an orbit will appear stationary with respect to a point on the surface.

H

Human/machine interface: The devices, programs, and procedures by which a human interacts with a machine.

Hyperbaric: Higher than atmospheric pressure.

I

Image understanding (IU): Visual perception by a computer employing geometric modeling and the AI techniques of knowledge representation and cognitive processing to develop scene interpretations from image data. IU has dealt extensively with 3-D objects.

Intelligent: Said of a machine capable of performing or planning actions for which it was not specifically designed; in effect, displaying characteristics which, if exhibited by a human, would be thought intelligent.

K

Knowledge base: An AI data base that is not merely a file of uniform content but rather a collection of facts, inferences, and procedures corresponding to the types of information needed for problem solution.

M

Microelectronics/microelectronic chips: Electronic devices or circuits which are very small and compactly packaged. Chips are very small, thin wafers that comprise many circuits and can carry out basic computing functions.

Multisensory data: Data from several sensors all simultaneously available. Sight, sound, touch, etc. provide human beings with a multisensory data set.

N

Natural language understanding : Response by a computer based on the meaning of a natural language input.

Nonmonotonic reasoning: Reasoning in which results are subject to revision as more information is gathered.

P

Phases B, C, D: Stages in implementing a space project; respectively, (B) preliminary design and definition, (C) detailed design, (D) construction.

Platform: A flight element of the Space Station Program which carries out special tasks in a separate orbit from that of the station and which is serviced in some way by the station.

Proximity sensor: A sensing device that detects when an object comes within a specified distance of the device.

R

Robotics: The technology and devices (sensors, effectors, and computers) for carrying out, under human or automatic control, physical tasks that would otherwise require human abilities.

S

Speech recognition: Recognition by a computer (primarily by pattern-matching) of spoken words or sentences.

Speech synthesis: Developing spoken speech from text or other representations.

Speech understanding: Speech perception by a computer.

T

Teleoperation: The execution of physical tasks by a manipulating device under human control.

Telepresence: The concept of remotely controlled manipulation in which the manipulators at the worksite have the dexterity to perform normal human functions and the operator at the control site has sensory feedback sufficient to provide the feeling of being present at the remote site where the action is taking place.

W

Wafer: A thin slice of a special material on which electronic circuits can be placed to create a chip.

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15. Supplementary Notes					
16. Abstract <p>In response to Public Law 98-371, dated July 18, 1984, the NASA Advanced Technology Advisory Committee has studied automation and robotics for use in the Space Station and prepared this report to the House and Senate Committees on Appropriations. The report is divided into two volumes:</p> <ul style="list-style-type: none"> ° The Executive Overview, Volume I (this document), presents the major findings of the study and recommends to NASA principles for advancing automation and robotics technologies for the benefit of the Space Station and of the U.S. economy in general ° The Technical Report, Volume II, provides background information on automation and robotics technologies and their potential <p>As a result of its study, the Advanced Technology Advisory Committee believes that a key element of technology for the Space Station is extensive use of advanced general-purpose automation and robotics. This could include many systems and devices (such as computer vision, expert systems, and dextrous manipulators) that have been made possible by recent advances in artificial intelligence, robotics, computer science, and microelectronics.</p> <p>Successful incorporation of automation and robotics by the Space Station program could lead to the deployment of a new generation of flexible and adaptable space systems. These systems could provide the United States with important new methods of generating and exploiting space knowledge in commercial enterprises and thereby help preserve U.S. leadership in space.</p>					
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