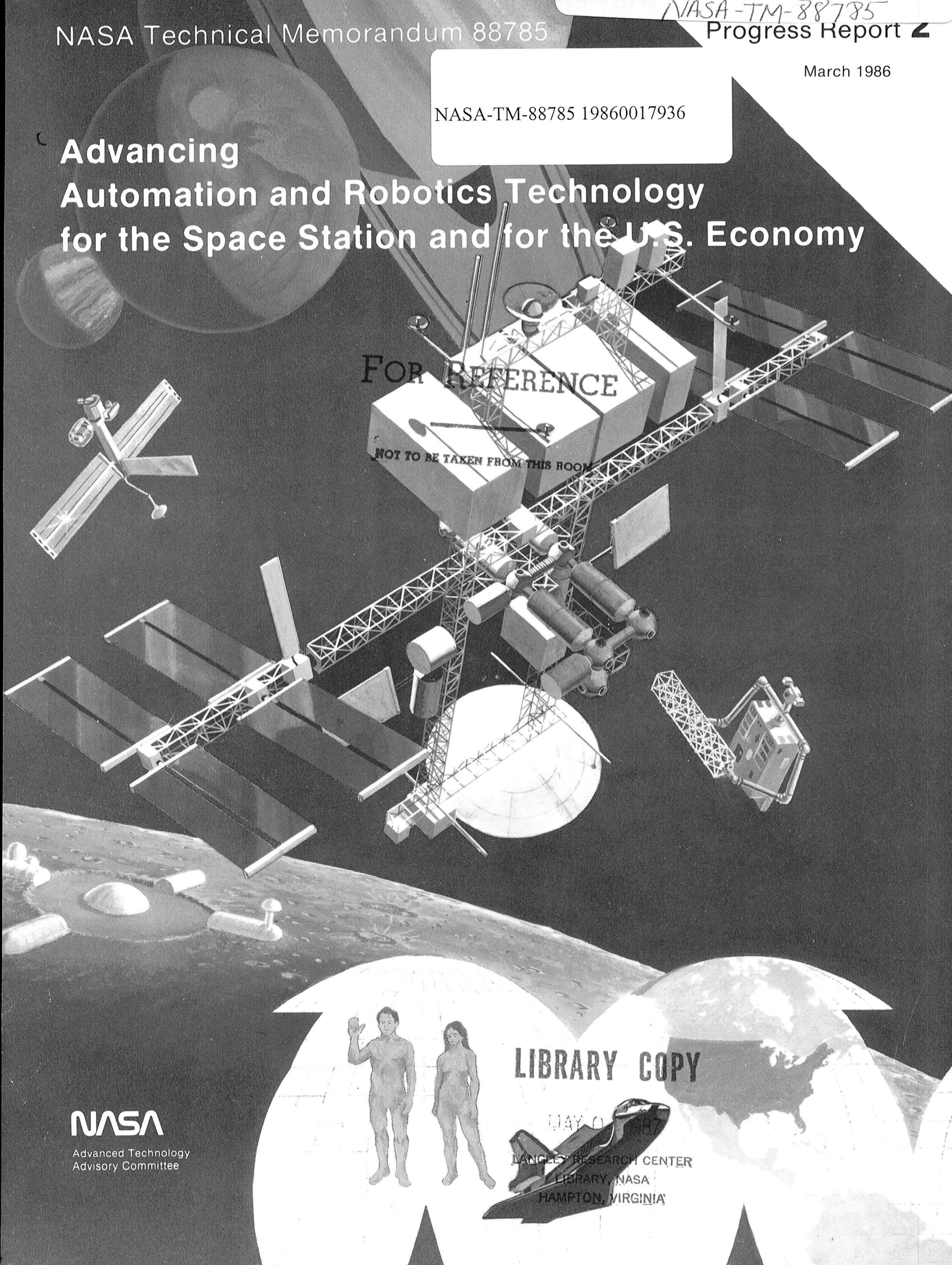
NASA Technical Memorandum 88785

Progress Report 2

March 1986

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



NASA

Advanced Technology
Advisory Committee

The cover painting captures the spirit of the machine intelligence and robotics policy described in this report. Prominently depicted are both the Space Station complex of platforms and core station in low Earth orbit 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 was created in the Technical Information Branch at the Lyndon B. Johnson Space Center; Raymond J. Bruneau did the artistic rendition from an original design by Roy L. Magin.

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NASA Technical Memorandum 88785

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

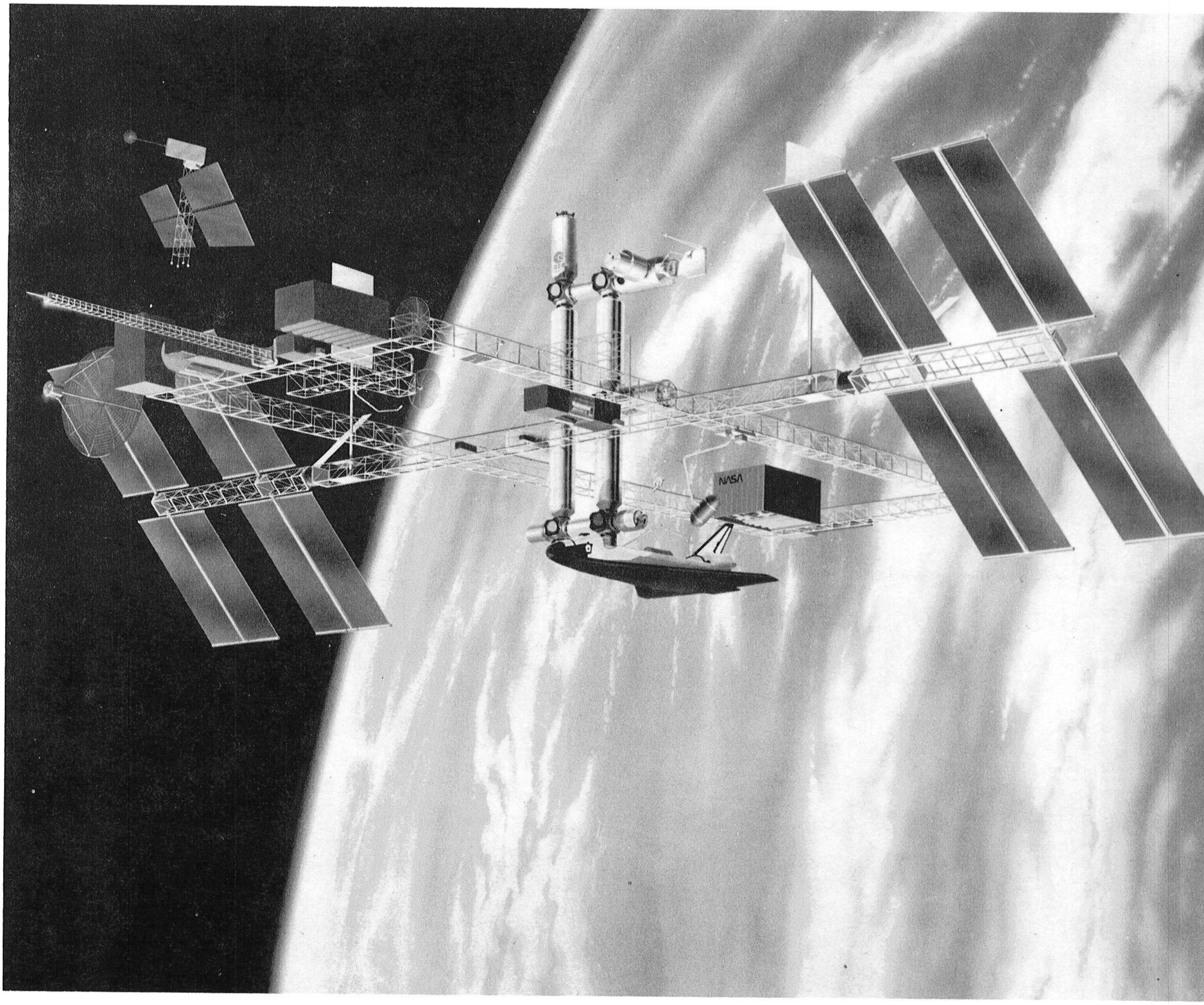
Progress Report 2 — October 1985 Through March 1986

Advanced Technology Advisory Committee
National Aeronautics and Space Administration

Submitted to the
United States Congress
April 1, 1986

NASA
National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas



The definition and preliminary design phase of the Space Station Program has resulted in many improvements to the initial configuration.

Synopsis

Congress recognized, in 1984, the merit of developing a new generation of general purpose automation and robotics technology using the Space Station as a stimulus. This technology would be efficient and flexible enough to meet not only the needs of the Space Station but also needs, as yet only partly specified, in the terrestrial economy of the United States.

In a NASA study mandated by Congress, recommendations were made and an approach to the implementation of advanced automation and robotics on the Space Station was outlined. This work was documented in the initial report of NASA's Advanced Technology Advisory Committee (ATAC), dated April 1, 1985 (ref. 1). The first 6 months of progress toward implementing the recommendations was assessed in ATAC Progress Report 1, dated October 1, 1985 (ref. 2).

During the second 6 months after ATAC made its recommendations, NASA, the phase B study contractors, and the Space Station international partners have continued to make major efforts in automation and robotics (A & R). ATAC has reviewed these efforts. The committee's assessment of progress can be summarized in five major points. These are

1. Good progress has been made on a number of fronts. This includes the definition of candidate A & R applications for the Space Station, the description of design accommodations for future A & R technology, the recognition of the need to capture design data, the consideration of measures for operational autonomy, and the expansion of a supporting research and technology development program.

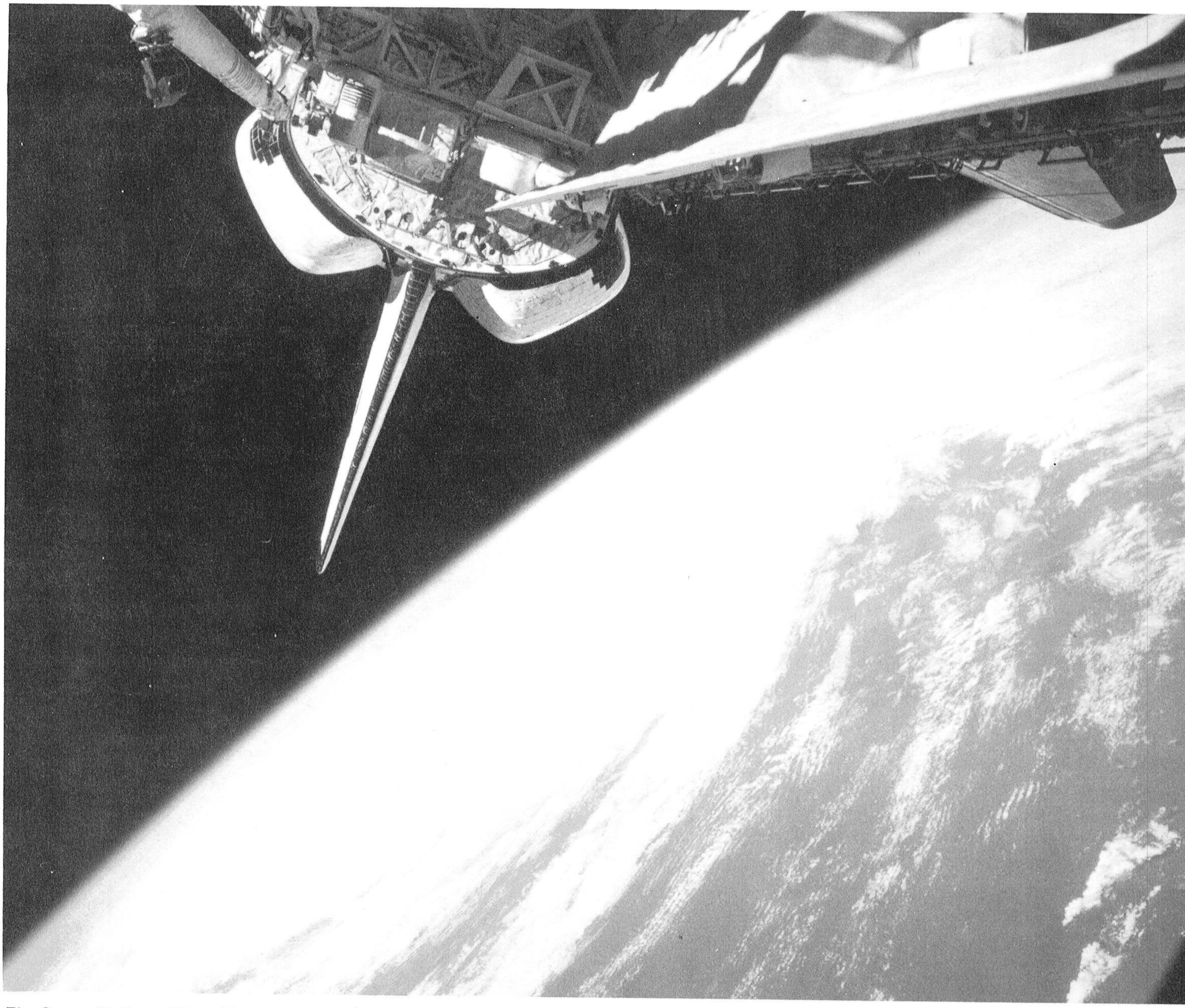
2. The most important single step that can be taken to stimulate the incorporation of advanced automation and robotics in the Space Station is to require the consideration of operational as well as initial costs in the design. NASA has espoused this "design to life cycle cost" methodology, and we encourage its prompt implementation.

3. The emphasis on developing a flight telerobotic capability for the initial Space Station is encouraging. The funding set aside specifically for this effort indicates the steadfast support of the Congress. NASA is preparing a plan to develop this much needed capability and will soon select a lead center.

4. Demonstrations, including flight demonstrations as appropriate, are very important to the incorporation of A & R technology in the Space Station. Not only do they drive the technology, but also they provide convincing evidence that the technology suits the application. The experiment in assembly of space structures which was conducted on Space Shuttle mission 61B is one of a series of planned technology demonstrations.

5. Important decisions are about to be made in the Space Station Program, decisions that will fix the nature of the station for decades to come. Proper tools for the assessment and costing of automation and robotics must be adopted programwide before the initiation of phases C and D.

ATAC believes that the intrinsic merit of automation and robotics technology for the Space Station will be realized by an ever-broadening number of program participants. With continuing attention to automation and robotics, the Space Station can fulfill its promise to be the "showcase" user and driver of this technology.



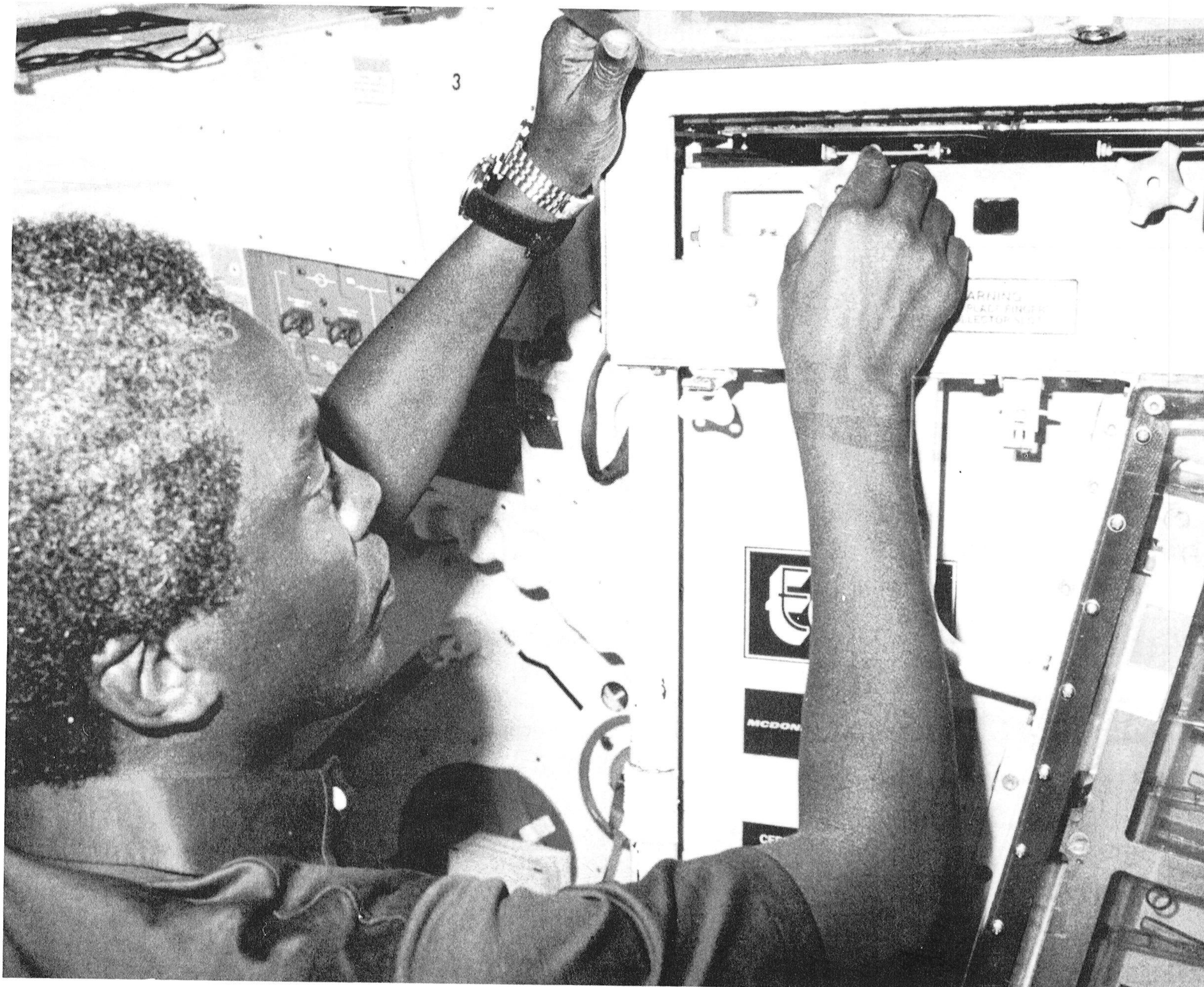
The Space Station will be able to make frequent observations of Earth features and thus help analyze resources and understand problems. Space views of hurricanes, for example, give information on their structure.

Preface

In April 1985, as required by Public Law 98-371, the NASA Advanced Technology Advisory Committee (ATAC) reported to Congress the results of its study of automation and robotics technology for use on the Space Station. A further requirement of the law is that ATAC follow NASA's progress in this area and report to Congress semiannually. This report is the second in a series of progress updates and covers the period between October 1, 1985, and March 31, 1986.

This reporting period has been a very productive one, with major program reviews and essential completion of the phase B "definition" period. The next period, in which the preliminary design will be developed, is expected to be similarly productive. However, ATAC expects to get fewer details from the contractors during the period beginning October 1986, because they will then be competing for the design and construction phases of the Space Station.

The drafts of this document were prepared by the Artificial Intelligence and Information Sciences Office at NASA's Johnson Space Center.



Automatic and robotic devices will make experimental and manufacturing work in space much more efficient.

Contents

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Introduction

The NASA Space Station Program has continued to work earnestly to implement the recommendations of the Advanced Technology Advisory Committee (ATAC) as documented in the study mandated by Congress (ref. 1). Other elements of NASA have also emphasized automation and robotics work, not only for their own programs but also for the benefits that can accrue to the Space Station. Furthermore, the international partners in the program have paid considerable attention to this area, and their work is expected to be complementary to that of the United States.

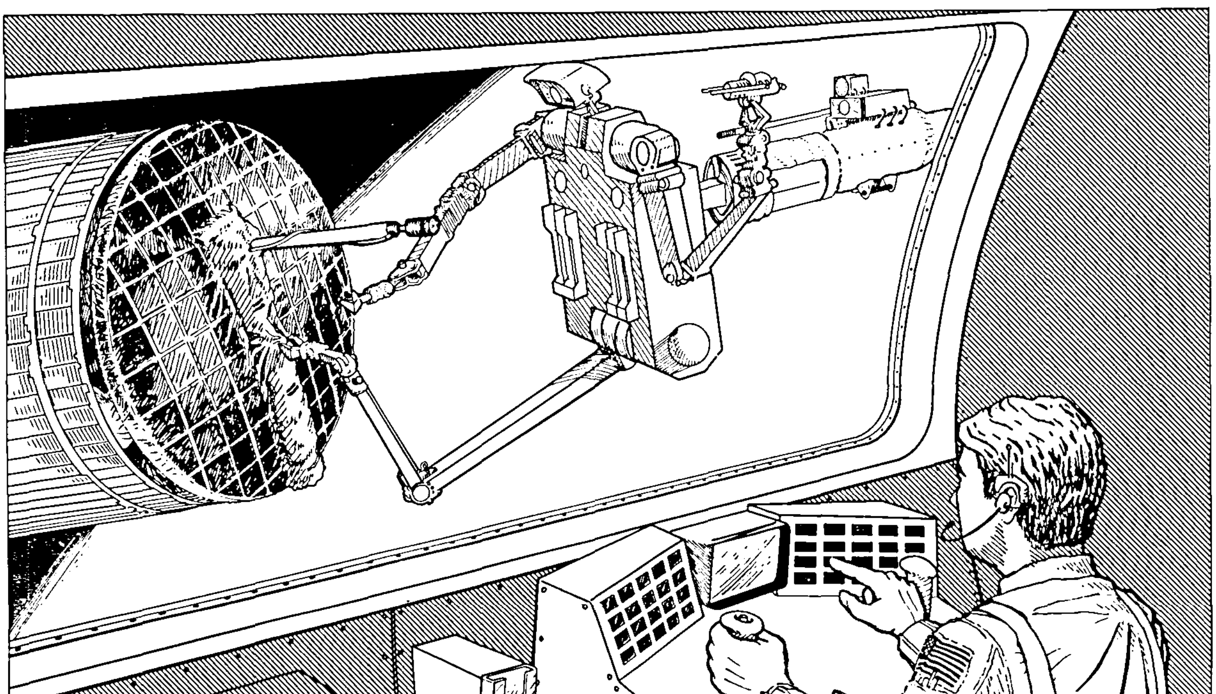
The progress reported herein has been assessed from Space Station Program reviews and from a Level B Program Office review mounted specifically to address progress with respect to the ATAC recommendations.

As we noted in the previous progress report, there is much to be encouraged about. We perceive good progress on many technical fronts, serious management attention across the agency, and continuing interest from Congress.

The most important single step that can be taken to stimulate the incorporation of advanced automation and robotics in the Space Station is to require the consideration of operational as well as initial costs in the design. NASA has espoused this "design to life cycle cost" methodology, and we encourage its prompt implementation.

An assessment of progress with respect to each of the ATAC recommendations is given in the next section. This assessment, along with the section on expenditures and the conclusions, provides a top-level view of progress for this reporting period.

Flight telerobotics will enhance the capability of the Space Station.



Progress With Respect to ATAC Recommendations

As in the first report, this section provides a summary assessment of the progress NASA has made toward fulfilling the recommendations originally made by the committee and adopted as policy by NASA. For convenience, each recommendation is stated before the assessment of progress.

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

NASA has made an earnest effort to implement this recommendation. People have been given responsibility for automation and robotics work at each level of the program. Directives (refs. 3-5) have been issued requiring program participants, including contractors, to study all Space Station systems and subsystems for applications of automation and robotics (A & R). And a broad program of supporting research and technology development is underway. These efforts are being made throughout the agency, not only in the Space Station Program but also in offices responsible for advanced technology development, the Space Shuttle, science and applications, and space tracking and data systems.

Clearly, those responsible for the A & R study tasks are giving serious attention to the application of automation and robotics. It is less clear that there is an adequate mechanism for incorporating the results of these studies in the station design. This concern arises not because of any lack of resolve or conviction on the part of the A & R advocates, but rather because the design focus appears to be on initial station cost rather than on a combination of initial and operating costs.

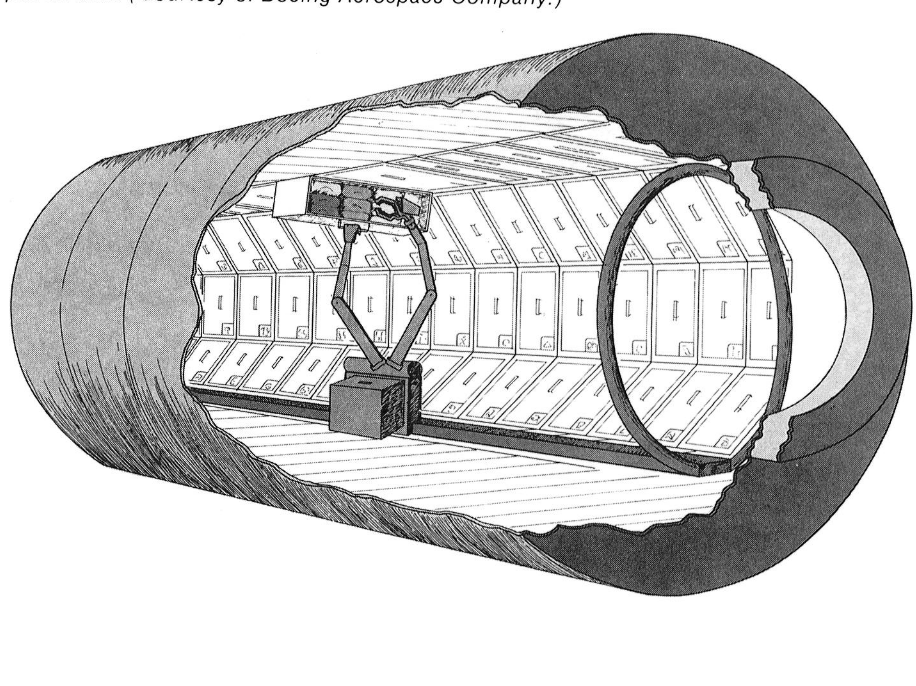
2. The initial Space Station should be designed to accommodate evolution and growth in automation and robotics.

As noted in the first progress report, NASA and the Space Station study contractors are addressing this top-priority issue in a serious way. The phase B study contractors have identified a large number of design accommodations that could benefit the station. Program guidelines, which are forthcoming from the Space Station Program Office, should stimulate a uniform treatment of the candidate design accommodations for the balance of phase B and for the rest of the program. We believe that it is still too early to tell, however, whether a sufficient number of the desired accommodations will be made in the face of very tight budgets.

Progress with regard to some of the specific suggestions connected to this recommendation continues to look good. In particular, the flexibility of the Space Station data management system, access to it, the use of standard programming languages, excess processing capacity, provisions for numerous sensors, and designing for operational autonomy are all sound. Furthermore, we are encouraged by planning that is underway to define test missions and to establish on the Space Station a test-bed for A & R devices and systems. Such a capability will promote the development and use of advanced A & R technology both for an evolutionary station and for station-related satellites, lunar and planetary missions, and other elements of the space infrastructure.

Noteworthy progress is being made on the committee's specific suggestion that design information and rationale should be captured in the Space Station computer data base. One approach has been developed and a mechanism proposed for implementation (ref. 5). Again we note that the practice of capturing such information is intended to apply to all station design matters, not just those presently thought to be related to automation and robotics. This

A robotic device to store and retrieve supplies will not get tired or bored or forget where it put an item. (Courtesy of Boeing Aerospace Company.)

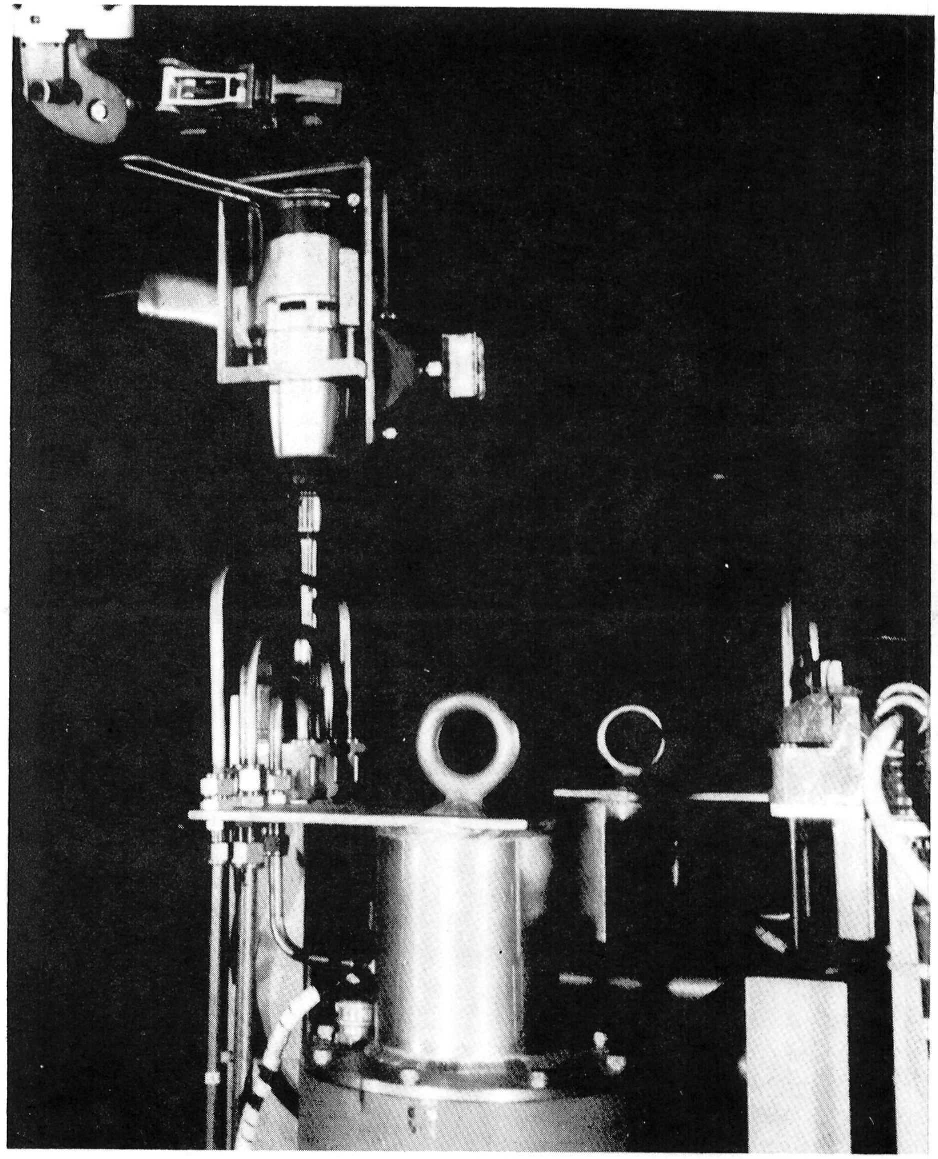


information is important to meet the usual needs of continuing engineering; it is mandatory to allow the application of A & R technology to an element of the station. And, again, this consideration must apply to all external systems with which the Space Station may eventually interact. This necessity appears to be well recognized by all program participants.

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

Since the last progress report, a very strong incentive for the early incorporation of A & R technology was provided by Congress in the form of a set-aside in funding specifically for a flight telerobotic capability to support initial station assembly and to serve as a smart front end for the orbital maneuvering vehicle. Planning is underway to implement this capability, which is described in some detail in section 6.

The list of possible applications of automation and robotics given in the first progress report has been refined, with some additions and some deletions. The process seems to be converging on a small number of highly beneficial applications, which will be further examined in the preliminary design phase.



Delicate operations require that forces be known and controlled. Appropriate sensing can be built into the manipulator itself. In this example, a force-reflecting manipulator is performing tasks at the Oak Ridge National Laboratory.

Stringent budget limitations may, however, inhibit actual inclusion of A & R technology unless proper account is taken of reductions in operational cost that it can bring about.

Progress is also being made in planning the type of demonstrations suggested by ATAC. We are convinced that these demonstrations are important to validate the technology so that it will be accepted for the initial station.

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

Criteria for applications of automation and robotics have been somewhat refined since the first progress report. While the various study contractors are still working to their own criteria, there is a high degree of commonality, and a consolidated set, at least in qualitative terms, should not be too difficult to achieve. Quantification of the criteria in a rigorous way will be a major task.

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

It is still too early to assess the program for test and verification of Space Station equipment. The concern over the lack of a plan for demonstrations, which was expressed in the first progress report, has been somewhat allayed in that the Space Station Program and other elements of NASA are planning experiments, including some on Space Shuttle flights, that will begin to demonstrate and qualify for space use knowledge-based control and telerobotic technologies.

These efforts are described in greater detail in section 4.

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

Effort toward fulfilling this recommendation is underway. Phase B study contractors have been instructed to perform surveys of existing and off-the-shelf A & R technologies. Specifically, they were required to update a list of A & R technologies expected to be available for the initial and evolutionary stations. The update is included in the documentation of the second requirements update review (RUR-2) and the Interface Requirements Review (IRR).

The Space Station Program has established a focal point for communication with industry in the form of a commercial advocacy group with the responsibility to assure transfer of technology. The transfer is seen as a two-way matter, with a mechanism for participation by industry in the building and operation of the station.

The formal review recommended in the first progress report of all study contractor work in automation and robotics has now taken place. A major series of presentations has been made to Space Station Program management by the study contractors and by the NASA centers. The results of these reviews were synopsized for ATAC. We now feel that we have a solid understanding of the work in progress.

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

The use of advanced computing technology to handle the problems of Space Station design and management is planned by NASA but is still far from fruition. The work on the Technical and Management Information System (TMIS) is moving ahead and shows promise of supporting Space Station well.

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

It is still premature to expect much progress in this direction. Just what constitutes advanced automation and robotics in the sense desired by Congress still needs to be defined. As we said before, this definition has two dimensions—

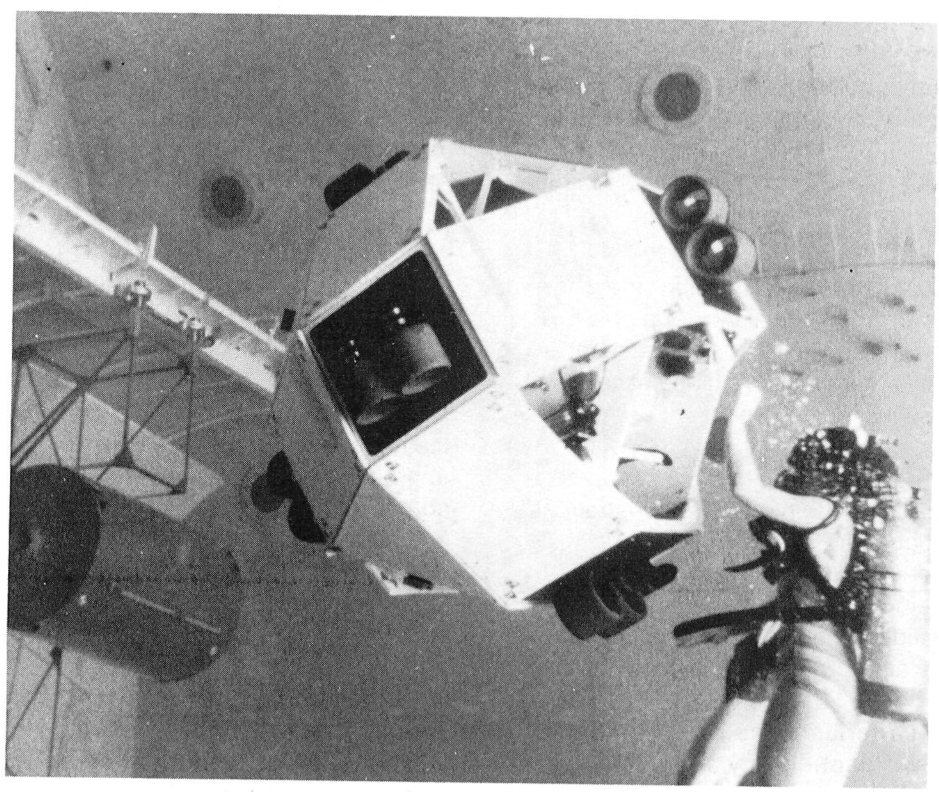
- Detailed performance measures quantifying the key technical characteristics
- Measures for the more generic characteristics, such as reliability, productivity, evolvability, maintainability, safety, speed, accuracy, and repeatability

Recommendations 9 through 13

Little has changed since the first progress report in regard to ATAC recommendations 9 through 13. These were made contingent on an augmented program that would enhance the technology base. This augmentation is still viewed as an important need.

One event of interest, however, bears on recommendation 13 that **satellites and their payloads accessible from the Space Station should be designed, as far as possible, to be serviced and repaired by robots.** NASA sponsored a workshop on satellite servicing (ref. 6), which covered the use of robotic devices. The committee finds it encouraging that NASA is attempting to stimulate a wide community to consider satellite servicing and to view robotic servicing as an important dimension.

Objects in the vicinity of the Space Station will need to be maneuvered carefully. Robotic devices for such "proximity operations" are being tested.



Overall Plan for Applying Automation and Robotics to the Space Station and for Advancing A & R Technology

Efforts to position the Space Station as both a "showcase" user and a driver of advanced automation and robotics have now been underway for a year. It may be useful at this time to examine the overall plan, the elements involved, and the participants active in it and to assess the soundness of these efforts.

TABLE 1.- LEVELS OF TECHNOLOGICAL READINESS

Readiness level	Definition
1	Basic principles observed and reported
2	Conceptual design formulated
3	Conceptual design tested analytically or experimentally
4	Critical function/characteristic demonstration
5	Component/breadboard tested in relevant environment
6	Prototype/engineering model tested in relevant environment
7	Engineering model tested in space
8	Full operational capability (incorporated in production design)

The basic philosophy adopted by NASA is to use advanced A & R technology for "people amplification." NASA encourages the view that the human/machine system is to be employed and that A & R devices do not replace people. In fact, the amplification that comes from automation and robotics will promote people from operators to supervisors and managers. ATAC endorses this view.

The plan for implementing A & R technology involves two major elements—the work on the Space Station proper and the building of a technology base. There is a categorization of technological readiness, McDonnell Douglas' The Human Role in Space (ref. 7), which is very useful in distinguishing between these two elements. Table 1 describes the eight levels of readiness. We will use this categorization throughout our report.

In the original NASA automation study documented in reference 1, ATAC focused on the first element—the work on the Space Station itself. This work is at technology readiness levels 5 through 8. The recommendations made by the committee pertained to the development and incorporation of A & R technology in the station and the provision for advancing the level of sophistication by introducing emerging technologies into evolutionary versions of the station.

The parallel work of the Automation and Robotics Panel (ARP) addressed the second element—the research and development necessary to build an adequate technology base. Such work is at readiness levels 1 through 4.

Each of these elements can be described in terms of several subelements and the level of detail can be elaborated considerably. We have attempted to diagram the interaction of these elements in the accompanying figure.

The experience of the past year leads the committee to conclude that the basic plan is sound. Clearly, existing technology can be adapted for the station. The enhancement of the technology base is vital for later applications. We will now examine each of the elements shown in the figure and relate the stage of the work to the technology readiness levels defined in table 1.

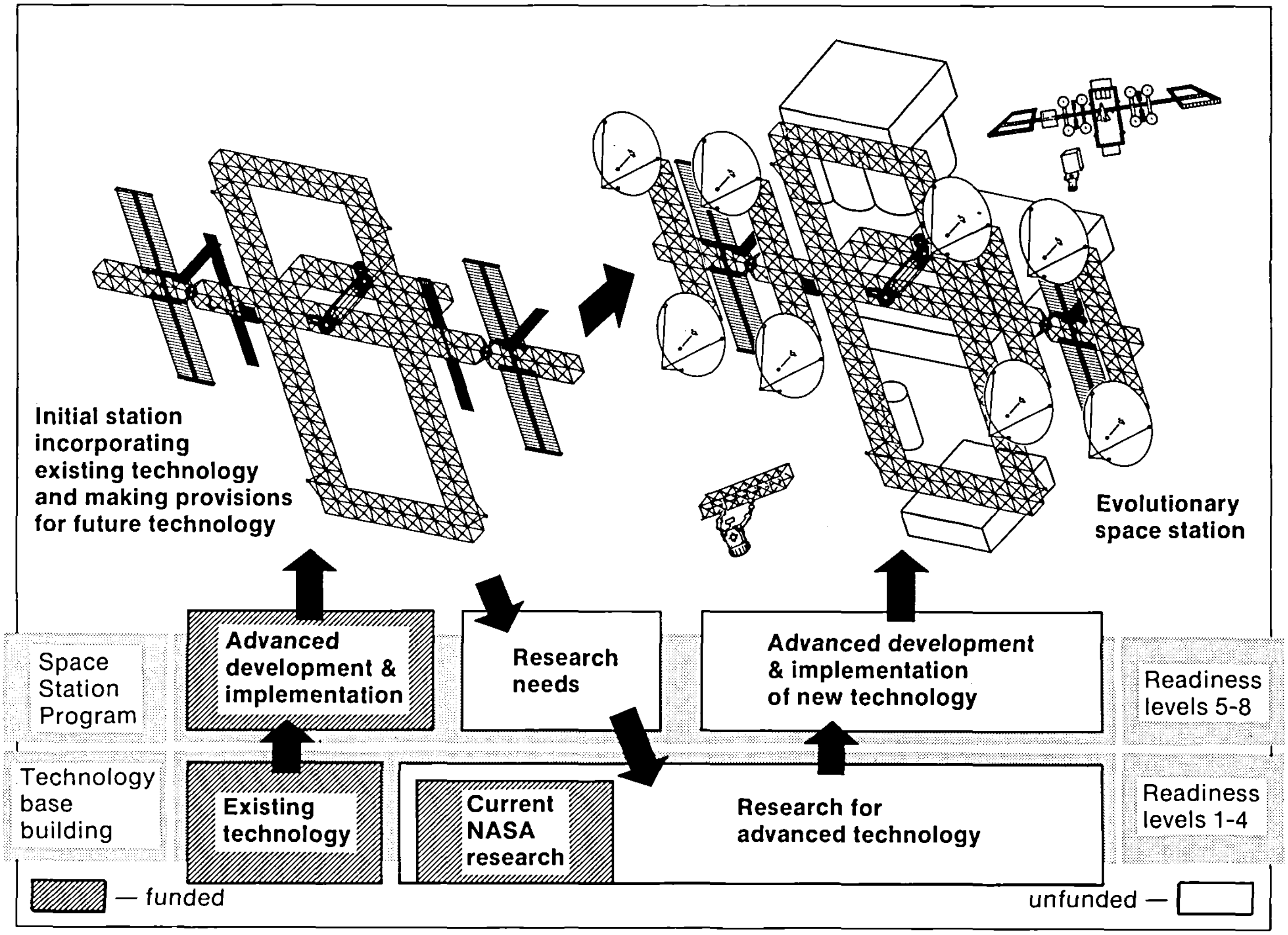
Technology Base Building (Levels 1 Through 4)

Existing Technology

There is a significant base of automation and robotics technology available at the present time. This, of necessity, will be the basis for most of the near-term implementations in the Space Station. We anticipate, of course, that the station design will accommodate later technology in a graceful way.

Several assessments have been made of the current situation. Some of these were a part of the original NASA automation study of 1984 and 1985 (refs. 8 & 9). Significant updates were provided by some of the phase B study contractors (refs. 10-17), and a recent summary is contained in the A & R Data Products Report for RUR-2 (ref. 5).

Many of these assessments have identified major deficiencies in current technology. These deficiencies will serve as problems for future research. The research areas that were identified in our original report remain top priorities.



A programmatic approach to the development of automation and robotics will lead to full implementation in the evolutionary space station.

Research for Advanced Technology

The basic scenario for the advanced work needed was established in the ARP report during the NASA automation study. ATAC endorses this approach. The ARP recognized that NASA must avail itself of any useful off-the-shelf technology, use as leverage the work of industry and other Government agencies where it can, and drive new research only where it must. Even with this economical approach, the panel concluded that resource commitments several times greater than those currently made are necessary to carry out this research scenario. ATAC responds that staying within the current program resources requires a judicious ranking of advanced A & R research projects.

Current NASA Research

Significant portions of the required work in advanced A & R technology are being sponsored by NASA. This work is concentrated in the Office of Aeronautics and Space Technology (OAST), which has greatly accelerated its efforts by reprogramming significant funding in response to the congressional initiative. Other offices of NASA, in the pursuit of their own programmatic goals, are also sponsoring technology that will be relevant to the Space Station. This work will be described in section 5.

Space Station Program (Levels 5 Through 8)

Advanced Development and Implementation

Within the Space Station Program, substantial effort—indeed the major work currently underway—is being devoted to examining just what current A & R technology is applicable to the station and to designing the station elements to accommodate such applications. This work will be described in section 4.

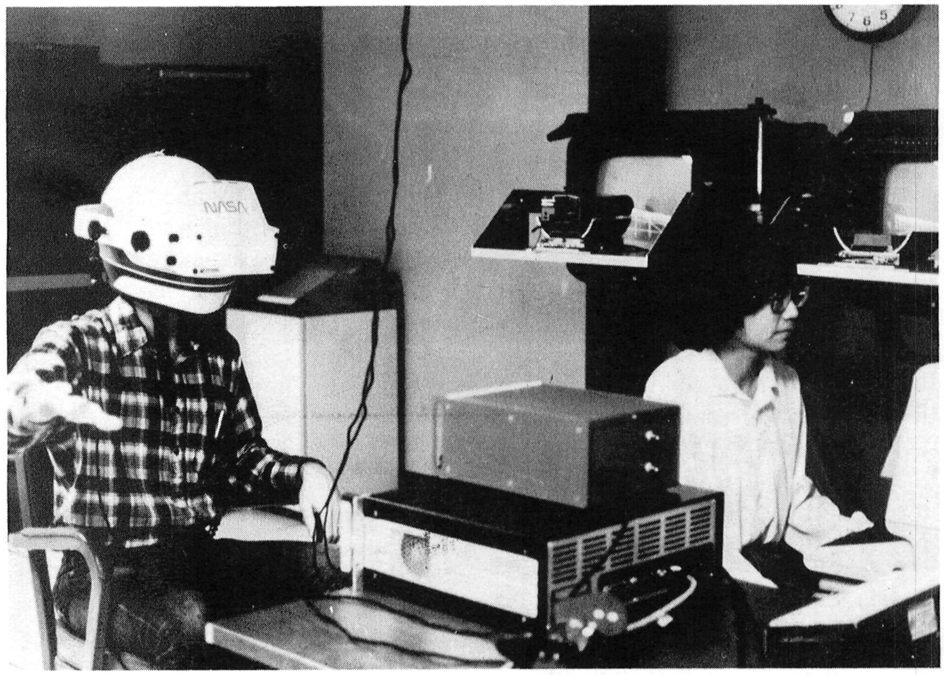
Furthermore, some advanced development work supporting automation and robotics is underway. This work is being pursued within the various "disciplines" (such as mechanisms, power, and extravehicular activity) and is not specifically identified as A & R work.

An encouraging recent development is the thrust, as specified by Congress, toward "the delivery of a flight telerobotic system at the time of initial Space Station operational capability . . . for station assembly and maintenance."

The notion is a good one. A dextrous telerobotic device not only could provide a "smart front end" for the orbital maneuvering vehicle (OMV) but also could be used on the mobile remote manipulator system (MRMS) or adapted to a free-flying vehicle.

Research Needs

The Space Station Program will span a very long time. As experience is gained during station operation and as subsystems are evaluated, needs will be identified for improvements or for new technology. These identified needs will provide important feedback from the operational program to the research community.



Information for telerobotic control can be displayed to an operator within a special helmet.

Advanced Development and Implementation of New Technology

The advanced development of new technology (at levels 5 through 8) and the incorporation of such technology into an evolutionary station will be an ongoing process with many cycles like the one shown in the figure.

Initial Station Provisions for Future Technology

A top-priority element in the design of the initial station is the provision of accommodations for future A & R technology. Such design accommodations* might include structural fittings that are adaptable to robotic manipulation or markings and lights that can be "seen" by computer vision systems. Extensive studies of such provisions are underway, as will be described in section 4. This, too, is an ongoing aspect of station design.

ATAC is in agreement with the general programmatic plan being pursued by NASA. Furthermore, we believe that NASA is attempting to carry out, within the limits of its funding, a reasonably balanced program.

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*In the jargon of the aerospace world, such design accommodations are often referred to as "hooks" and "scars." Hooks are software provisions on which to hang new capabilities as they come along. Scars are provisions in hardware to facilitate the later incorporation of new items.

Progress on Space Station Design for Applications of Automation and Robotics

Progress on the Space Station design will be treated in three parts: the detailed work of the phase B study contractors, the more general and operational work of NASA, and the work of the international partners.

The first progress report of the committee was based largely on the work of the first 3 months of phase B as documented in Requirements Update Review 1 (RUR-1) of July 1985 and on information from the Level B Program Office. In the intervening time, a second requirements update review (RUR-2) and the Interface Requirements Review (IRR) have taken place, and the committee has held its own reviews, as described in section 2.

The planned events by which progress can be assessed are those pertaining to automation and robotics in the Engineering Master Schedule. The relevant parts of this schedule are given in the following sections for convenience. Table 2 gives the events relating to the study contractors and table 6 those pertaining to NASA.

The Work of Phase B Study Contractors

As indicated in table 2, the A & R events defined in the schedule should have been completed by the time of the Interface Requirements Review. In general, the progress made by the contractors responsible for the various work packages has been satisfactory. The work package contractors have documented their work in a number of reports, some of which provide a great deal of detail (refs. 10-17).

The major work accomplished by the contractors since the first progress report has been in five areas:

- Description of provisions that would facilitate the incorporation of evolving A & R technologies in the initial and evolutionary stations
- Detailed definition of the characteristics of the various candidate applications
- Refinement and weighting of selection criteria
- Assessment of all the candidates against the selection criteria using one or more methods of multi-attribute decision analysis
- Recommendation of specific applications for the initial Space Station

TABLE 2.- AUTOMATION AND ROBOTICS EVENTS FROM THE SPACE STATION ENGINEERING MASTER SCHEDULE: WORK PACKAGE CENTERS (INCLUDING CONTRACTORS)

Define A & R application candidates for initial Space Station	
—RUR-1:	Describe candidate functions to be automated, with supporting rationale
—RUR-2:	Revise list of candidate functions to be automated, with detailed impact characterization
—IRR:	Define candidate functions, with quantitative impact characterization to support general automation guidelines
Define selection criteria	
—RUR-1:	Propose criteria (including supporting rationale) for selecting (1) Candidate functions to be automated (2) Candidate A & R technologies to be applied to selected functions
—RUR-2:	Define selection criteria, with supporting rationale
Select A & R technology candidates	
—RUR-1:	Update technology assessment to identify A & R technologies available for the initial station
—RUR-2:	Describe candidate A & R technologies for application to functions selected for the initial station
—IRR:	Recommend A & R technologies for application to the initial station, with supporting rationale
Define provisions to be made for A & R evolution	
—RUR-1:	Identify functional applications and available technologies for future automation and robotics
—RUR-2:	Characterize provisions to be made in the initial station to accommodate future technologies as identified in RUR-1
—IRR:	Characterize impacts (design, cost, etc.) of provisions for identified future A & R technologies

Progress in each of these areas will be summarized in the following paragraphs. While the committee does not yet take a position on the specific provisions, characteristics, criteria, assessments, or recommendations, we believe the work to be sound. It should provide a good basis for more detailed analysis and design.

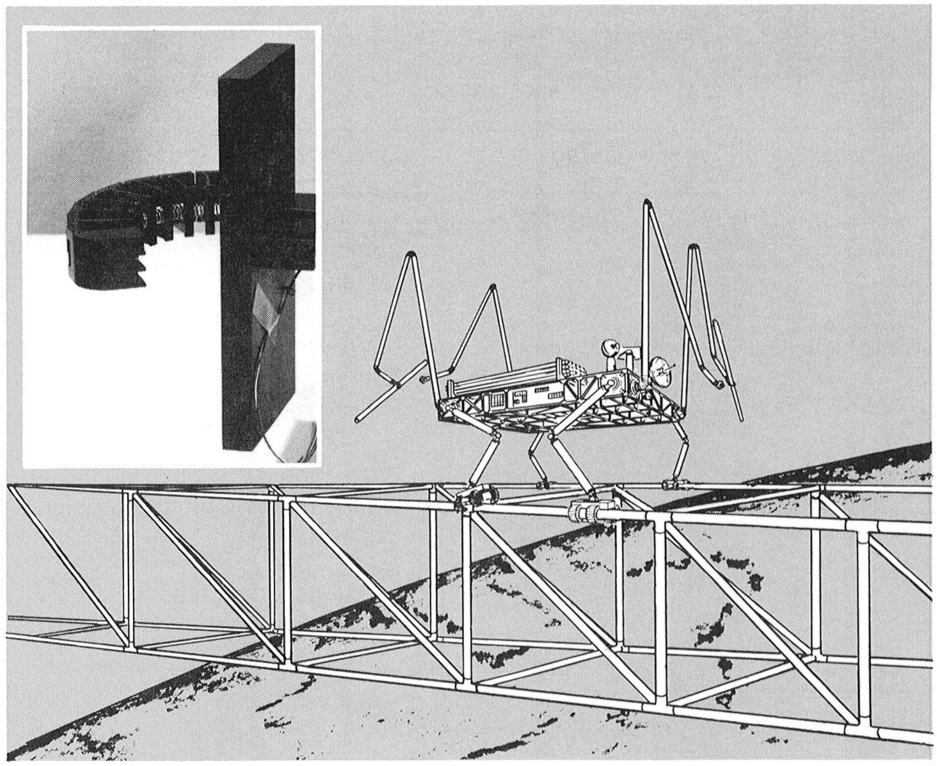
Provisions for Future A & R Technologies

The treatment of provisions for future A & R has been very good in some work packages. Categories of design accommodations have been suggested, as shown in table 3, and the accommodations needed to achieve certain capabilities have been described, some examples of which are shown in table 4. So far, only a rough, qualitative attempt has been made to describe the impact of implementing these A & R capabilities.

Detailed Definition and Characterization of Candidate Applications

The various studies addressed many candidate applications of automation and robotics. The initial possibilities were presented at RUR-1 and documented in the first ATAC progress report. Since then some candidates have been added and a few have been deleted, but the number and the nature of the candidates are substantially the same. We will not, therefore, tabulate in the body of this report all the candidates, as was done before. This detail is provided in appendix D.

ATAC was impressed with the level of detail and understanding developed by some of the contractors (refs. 10-17), especially in view of so many candidates (50 or more from some contractors). This work merits our giving at least a few examples; we will describe briefly three interesting cases.



Innovative concepts for mobility have been developed for future applications. In this example, an assembly robot is depicted moving along a truss on "legs" with special graspers (see detail). (Courtesy of McDonnell Douglas Astronautics Company.)

Space Station Coordinator

One potential application is a top-level, knowledge-based (i.e., expert) system for handling some important tasks of control and operation of the Space Station. The control of the station involves many tasks which are complex, concurrent, and often time-critical. Such control requires ongoing *coordination*, in the dictionary sense of the word—bringing things into the proper relationship with each other so they can work together efficiently and effectively. Such coordination includes

- Monitoring and controlling background tasks within the constraints of limited resources, a variable activity schedule, and a paramount need for safety
- Changing activity schedules to adapt to changing circumstances and modifying all related and interlocking schedules accordingly
- Detecting and circumventing faults promptly

TABLE 3.— CATEGORIES OF DESIGN ACCOMMODATIONS

Inherent	Basic design of Space Station should allow desired A & R evolution (bears watching)
Coattail	A & R applications can use provisions established for some other subsystem (bears watching)
Generic A & R	General Space Station guideline to ease A & R evolution
Specific A & R	Guideline to ease evolution of a specific A & R subsystem

TABLE 4.— EXAMPLES OF A & R APPLICATIONS WITH DESIGN ACCOMMODATIONS NEEDED FOR THEIR IMPLEMENTATION

(a) Robotic applications

Capability	Category	Design accommodations
More autonomy	Specific	Communication structure must provide for high-level, free-form commands (e.g., "release antenna lock"). Safe shutdown/freeze mode for teleoperator link loss must be provided.
Self-mobility	Coattail	"EVA" equivalency is required for handholds, slidewires, etc.; i.e., human scale for reach and grasp. Strategically located mounting fixtures, plugs for power and data must be provided.
Cooperation	Specific	Provisions for dealing with visual/force/tactile inputs of a fellow worker must be made. Collision avoidance is a top priority.
Vision	Specific	Readable (bar code or optical character recognition) labels for the location coordinates of ORUs, visual alignment marks, top/bottom indications, etc. must be provided.

(b) Other applications

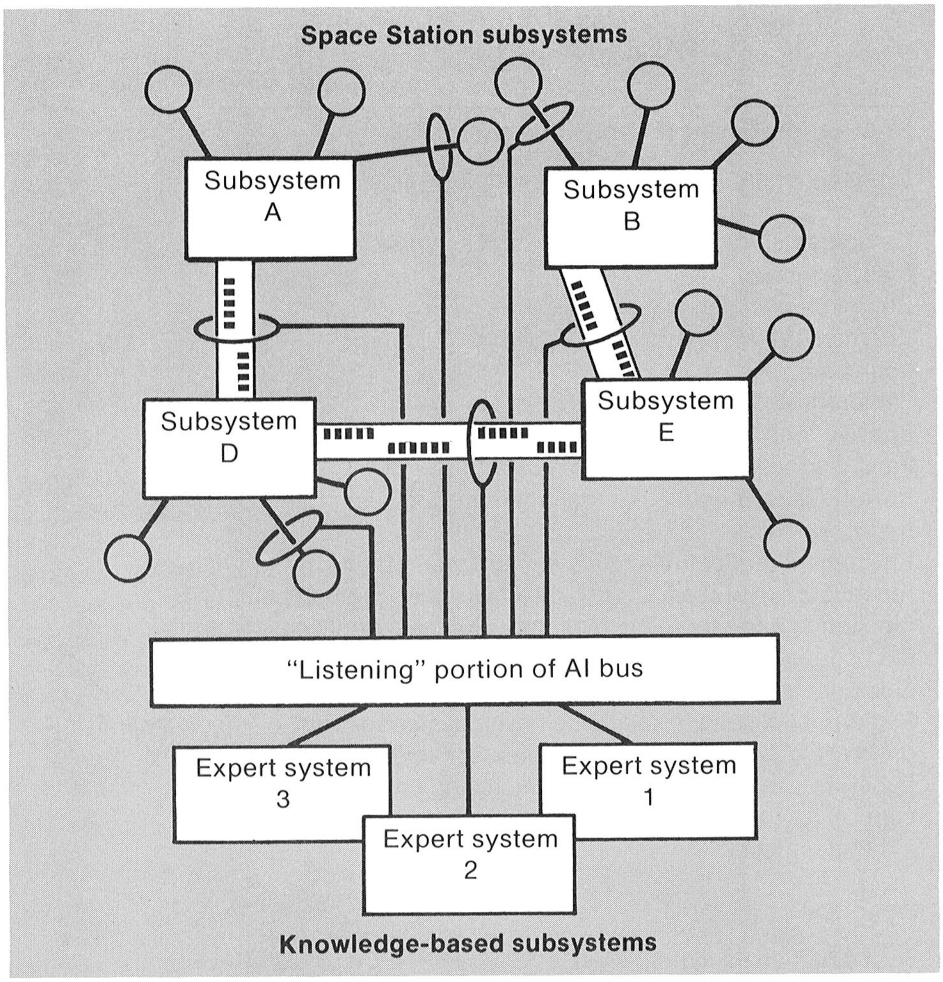
Capability	Category	Design accommodations
Voice input	Inherent	A means to make simple updates to the command interpreter, leaving the rest of the software the same, is needed. Extra vocabularies and equivalents must be provided if multilingual capability is desired.
Subsystem diagnosis	Generic	Provisions must be made for maintaining a history of component failure and redesign.
Symbolic processors	Specific	Network must allow free-form messages. Add-on processors must meet DMS interface standards.
Graphics	Coattail	Use general graphics technology improvements. Develop knowledge-based/reasoner links to a graphical data base.

Clearly, such a system would need to interact with the overall Space Station data management system and with the environment in which software is developed.

Once developed, such a system would, during orbital operations, amplify substantially the ability of the crew to run the station efficiently. The use of machine intelligence in an expert system application such as the Space Station coordinator would be a major step toward promoting the crew to supervisors rather than keeping them operators and technicians.

The Logical "AI Bus"

If, as may eventually occur, many of the subsystems of the Space Station have expert systems as part of their makeup, then communicating among these distributed systems becomes very important. One way of facilitating this communication would be to provide within the Space Station data management system a path (in computer jargon, a "bus") which is specially designed for artificial intelligence (AI) work. The figure illustrates how such an AI bus would support efficiently the vital interaction between expert systems and Space Station subsystems. If successful, this type of application should have wide applicability for interconnecting expert systems in any situation.



An "AI bus" could provide a standard interface between expert systems and Space Station subsystems. (Courtesy of Rockwell International.)

Refinement and Weighting of Selection Criteria

As is the case for the candidate applications of automation and robotics, the selection criteria themselves are little changed from the previous report. While there are some differences among the contractors, there is a high degree of commonality.

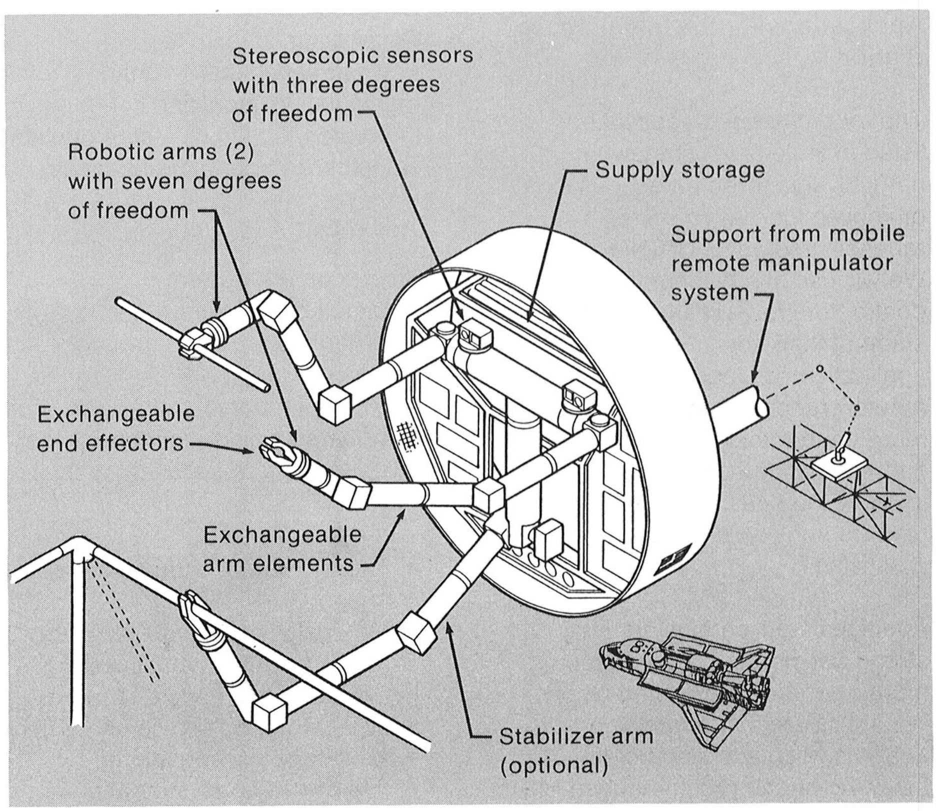
In addition to the refinement of the criteria themselves, substantial effort has gone into determining weighting factors to allow application of the criteria in a quantitative way.

A tentative synthesis of the proposed criteria has been made, which is presented in appendix E. Also given in this appendix is a sample weighting.

The Generic Robot

In the case of robotic applications, a generic approach has been proposed by several of the study contractors. In this type of application, one multipurpose robot is equipped with various end effectors to accomplish many tasks. Since the development and operating cost of the robot and its capabilities can be shared by many applications, the cost for each is much reduced. The figure illustrates one of the concepts proposed for such a robot.

A multipurpose robot with various end effectors could accomplish many tasks at a reduced cost per application.



Candidate Assessment

Assessments of the candidate applications have been carried out to varying degrees by the study contractors. Such assessments require, of course, at least a preliminary characterization of the application (cost, weight, power needed, etc.). Properly characterized, a candidate application can be evaluated against other candidates using the selection criteria, appropriately weighted.

Some contractors have progressed to the point of giving specific recommendations. Other contractors have just narrowed the list of candidates to ones deserving more detailed attention.

While the characterizations of the applications are preliminary and the cost estimates contain acknowledged uncertainties, we are encouraged that the winnowing of the candidates is being approached in a sound manner.

Recommendation of Specific Applications for the Initial Space Station

The recommended applications, listed in table 5, fall somewhat naturally into three categories:expert or knowledge-based systems, robotics, and advanced automation. We will use this taxonomy. Not all contractors have reached the same stage of their analysis, so this set of applications includes only those actually recommended by one or more contractors. A second list of strong candidates will also be given to show the additional applications that are considered to be most promising.

Additional applications are also strong candidates. Some of the more noteworthy are listed below. We anticipate that continuing analysis will place some of the following on the recommended list.

TABLE 5.— RECOMMENDED APPLICATIONS FOR THE INITIAL SPACE STATION

Knowledge-Based (Expert) Systems

Systems management—training and crew activity planning
Space Station coordinator
Data base management—subsystem assessment, trend analysis, fault management
Resource planning and scheduling
Thermal curvature control
Logistics
Onboard personnel training
Passive thermal monitoring
Fault diagnosis for communication and tracking
Power system control and management, including trend analysis and fault management
Environmental control and life support subsystem—trend analysis, reconfiguration management, data base management, built-in testing, monitoring and recording, fault detection and identification, and assuring atmospheric integrity
Guidance, navigation, and control—automated maneuver planning and control
Platform applications, including power system control, distributed data processing, and planners for guidance, navigation, and control
Laboratory module applications, including data management system and life support for experimental subjects
Experiment scheduling

Robotics

Space Station assembly
Inspection and repair of trusses and structures
ORU replacement
Utility run inspection and repair
Payload servicing—exchange, transport, resupply, fluid transfer, and manipulation, including interfaces compatible with both robots and humans
Laboratory functions—care of plants and animals, analysis of biological samples, and centrifuge access

Advanced Automation

Smart camera system
Automated power management (including automatic test and checkout) which incorporates fault-tolerant architecture and functions autonomously with ground override
Laboratory module automation, including cleaners for cages and plant growth chambers and a specimen-labeling device

- Interactive video/audio training support
- Materials technology laboratory (MTL) module layout system
- Experiment scheduler
- Laboratory module safety advisor
- Advanced conversational operator/system interface
- Logistics robot and inventory management system
- Teleoperated human emulator for MTL applications
- Robot to inspect before an extravehicular activity (EVA)
- Smart tape recorder system

Observations on Study Contractor Work

The committee has two concerns about the work of the study contractors. The first is that the work of the A & R advocates appears, in some cases, to be outside the actual design process. This situation arises, we believe, because the design work is being conducted so as to minimize initial cost in order to stay within the budget, and this consideration appears to be driving the decisions about the basic station configuration.

There are few, if any, applications of A & R technology that will reduce initial cost; i.e., the cost of design, development, test, and evaluation (DDT&E). We understand, however, that NASA has committed itself to considering operating costs in a forceful way (ref. 18). Furthermore, we understand that this commitment extends to taking life cycle costs into account and, indeed, to designing to minimize life cycle costs. This position is most fitting, and we encourage its prompt implementation. Until this management approach is widely publicized and implemented, there does not appear to be a strong mechanism to ensure the proper consideration of automation and robotics.

The second concern is that the designers may not be taking into proper account the importance of crew time. While various cost analyses using estimates of the cost of a crew hour have been made, this thinking seems not to have penetrated sufficiently into the design process. We suspect that each designer is assuming more crew time for his or her particular subsystem than is available. Such assumptions are likely being made both for the assembly of the station, for which the number of extravehicular activity hours is very limited, and for the routine operation of the station once it is built.

Preliminary studies indicate that as little as 4 crew hours per day may be all that is available for the monitoring and control of the entire station and its systems (excluding payloads and experiments). If this time were allocated across the various subsystems, then each would demand a significant level of automatic control. In abnormal situations, the allocation of time to a particular subsystem could be greatly diminished, increasing the need for an automatic approach.

A guideline might be that, in an emergency situation, the crew time allocation would be reduced to 1/10 the baseline allocation. For the subsystem undergoing the emergency, the allocation could be increased by a factor of 10 for a limited time. Some guideline of this sort should be developed and promulgated.

NASA's Work on Automation and Robotics

Many areas of importance to the program are the direct responsibility of NASA. These include systems integration, analysis methodologies, operations planning, training, and mission control.

The committee has had presentations by the various levels of program and project management on some of these topics and has reviewed the relevant documentation.

As indicated in table 6, the A & R events defined in the Master Engineering Schedule should have been completed either by the time of the IRR or within 2 months thereafter. In general, the progress made by NASA has been good.

The major elements of the NASA work are described in the following paragraphs.

Plans and Guidelines

Initial implementation plans have been promulgated (ref. 4), and further guidelines have been issued in the A & R Data Products Report for RUR-2 (ref. 5). These latter guidelines provide technology assessment and expository material that is a significant advancement over the material in the original ATAC report and its companion documents.

Integration, Evaluation, and Cost Analysis

The activity of integrating and evaluating candidate applications and analyzing costs for the work packages has only begun. A part of this work includes the promulgation of standard tools for analysis, and NASA is still in the process of establishing those tools. A vital aspect of this analysis is, however, the matter of considering operating costs, which requires a methodology for implementing the life cycle approach to costs, as NASA desires to do. This matter is of the utmost importance if the benefits of automation and robotics are to be included in the assessment of their value.

As an example of the importance of the life cycle approach, we will cite Space Station power system control. Space Station power will be derived by converting solar energy to electricity. The electrical energy will then be distributed to the various modules and subsystems. The power system requires sophisticated control to assure that adequate amounts of power are generated and apportioned to the elements being serviced. Furthermore, any faults in the system must be identified, located, and corrected very rapidly. A mature and competent technology exists to handle many of these functions and automation is an important aspect of this technology.

TABLE 6.- AUTOMATION AND ROBOTICS EVENTS FROM THE SPACE STATION ENGINEERING MASTER SCHEDULE: PROGRAM ACTIVITIES (LEVEL B)

Publish ATAC plan and implementation plan

—CSD: Distribute ATAC report and level B implementation plan to work package centers

Integrate and evaluate

—RUR-1: Identify requirements for system engineering and integration (SE&I) tools for A & R; define quantitative measures of progress; evaluate "nontechnical" program requirements, constraints on A & R implementation (e.g., congressional mandates)

—RUR-2: Evaluate preliminary work package data; develop initial guidelines on program A & R implementation

—IRR + 1 month: Recommend A & R implementation as to
- —Growth strategies
- —Application thrusts
- —Technology thrusts
- —Advanced development guidelines

Analyze costs

—RUR-1: Adopt tools to estimate cost of technology/application candidates

—RUR-2: Make preliminary analysis of technology/application candidates for initial and evolutionary stations

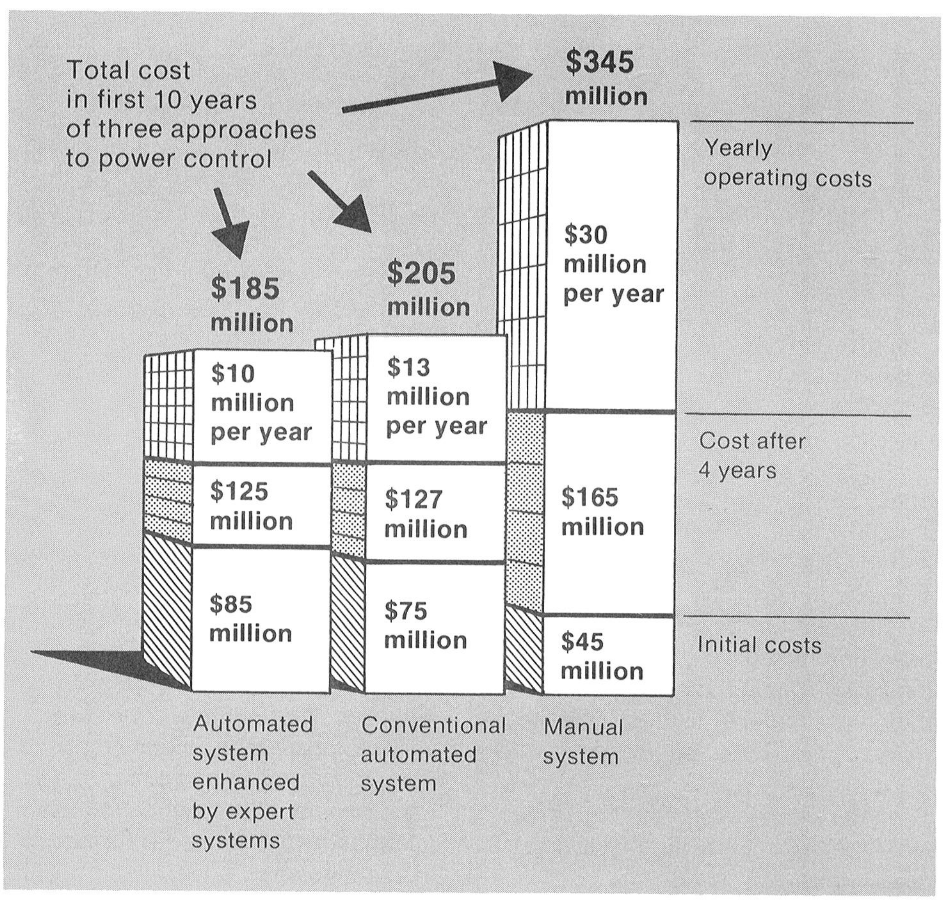
—IRR: Make final cost analysis of recommended technologies/applications

Update implementation plan

—RUR-1: Define scope of
(1) Work-package-specific automation
(2) A & R as an additional "discipline" in the Engineering Master Schedule

—RUR-2: Draft update of A & R implementation plan

—IRR + 2 months: Publish updated A & R implementation plan



For the Space Station, three levels of automation can be considered for the power system. We will describe as "conventional automation" the practices employed on previous spacecraft. The addition of a knowledge-based (expert) system could enhance the control capability but only at a greater initial cost. On the other hand, the initial cost could be reduced somewhat if major elements of the control were carried out manually on the ground. An estimate of the initial costs for each of these approaches is given in the accompanying figure.

While a highly automated system would cost more to build, it would cost far less to run. The difference in initial cost for a power control system, for instance, would be made up in 2-4 years' time.

The advantages of the more automated approaches come in the arena of operating costs. For these same three cases, annual operating costs have been estimated. The figure shows the level of such annual costs for each approach.

The most economical approach in the long run is, clearly, the one involving the expert system. We recognize that these cost estimates are rough, but we believe that the picture they paint is valid. In this particular example, the period over which the extra initial cost is recovered is very short. The expert system would allow recovery of its extra cost (over that of conventional automation) in approximately 3 years. Conversely, while the ground-based manual approach would save $40 million in initial cost (compared to the cost with an expert system), it would require an additional $20 million each year in operating costs.

ATAC is encouraged that NASA has committed to designing to minimize life cycle costs. We hope that ways will be found to do so even in the face of limited year-to-year budgets. If designing to life cycle costs can be accomplished, it will be the best possible incentive for the incorporation of automation and robotics technology in the Space Station.

A & R Implementation Plan

NASA has emphasized the release of an updated A & R implementation plan, due out 2 months after the Interface Requirements Review. A draft has been issued for comment, and the updated plan should provide definitive programmatic guidance.

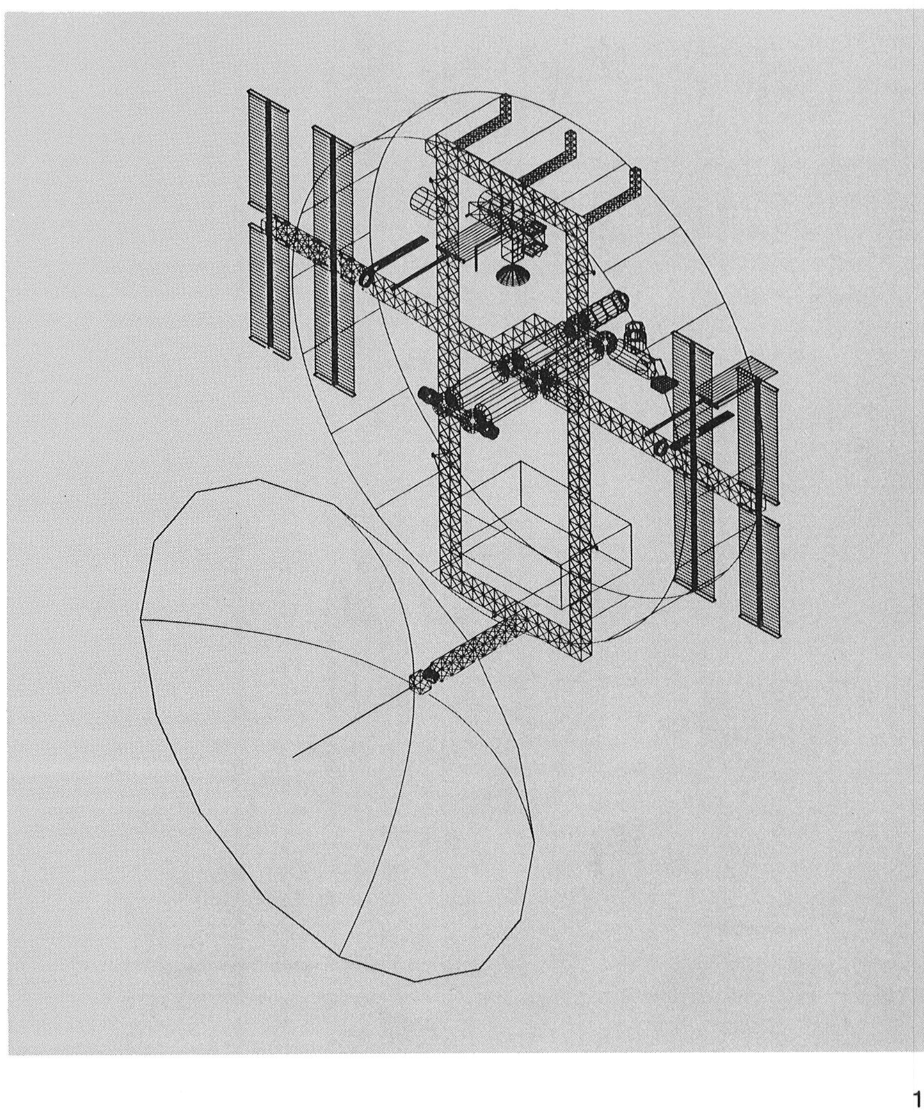
NASA has, in addition, prepared a manual for preliminary design (ref. 19), which will be released shortly. This, too, will provide useful guidance, including the important matter of design accommodations.

Capture of Design Knowledge

Good progress is being made in developing a methodology for capturing Space Station design knowledge. This is an area that the committee feels is very important and about which we have made specific suggestions. The need is to have in effect throughout the design phase provisions for capturing design information and rationale in the Space Station data base. Establishing these provisions early in the design process is particularly important. An approach has been developed and a mechanism proposed for implementation (ref. 5).

As we noted in our earlier report, the practice of capturing such information is intended to apply to all station design matters, not just those related to automation and robotics. This information is important to meet the usual needs of continuing engineering and to allow the eventual application of A & R technology to any element of the station. And, again, this consideration must apply to all external systems with which the Space Station may eventually interact. NASA appears to recognize this need well.

Capturing the details of Space Station design is vital to meet the needs of continuing engineering and to allow for the addition of A & R technology. Standard-format computer-aided design (CAD) data bases, from which this view of the evolving Space Station was generated, permit design information to be derived automatically for engineering analysis and robot plan generation. (Courtesy of Goddard Space Flight Center.)



Technology Demonstrations

Good progress is being made on a number of fronts in demonstrating technology that would support Space Station A & R applications. Some of these demonstrations have actually flown, such as the experiment on assembly of space structures which was conducted by the Shuttle Program Office on mission 61B. Other demonstrations are being planned.

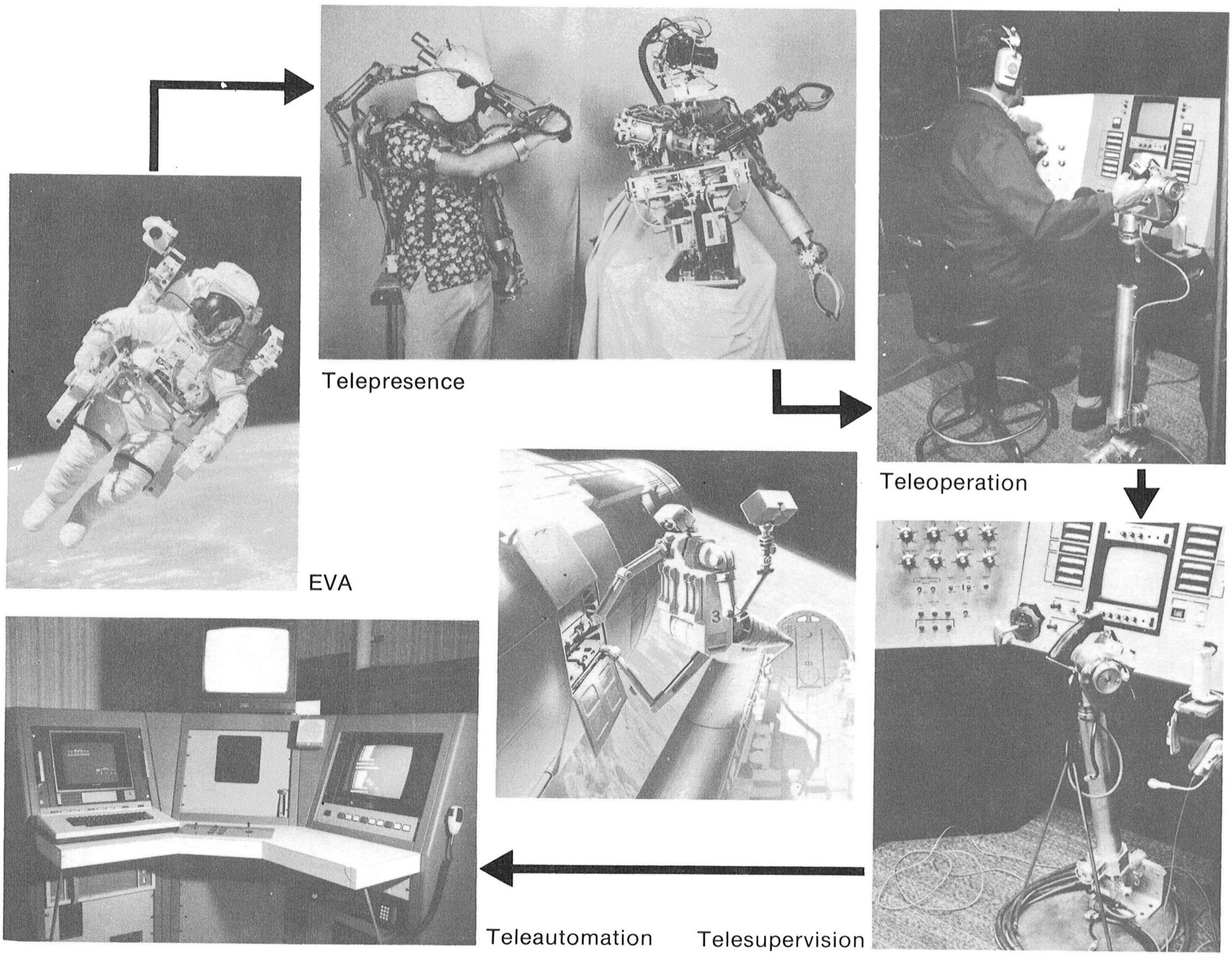
It is encouraging to note that there is wide sponsorship of this activity from several elements of NASA. Some of the more important demonstration activities are outlined in the following paragraphs.

Flight Telerobotic Capability

A significant NASA activity during this reporting period has been the development of plans to use the funding set aside by Congress and designated for "a flight telerobotic system at the time of initial Space Station operational capability." The available details of the plan are given in section 6. We commend this activity and suggest it be pursued vigorously.

Because teleoperated devices such as the Space Shuttle remote manipulator system (RMS) have flown in space for several years, it may be helpful to note the distinction between such devices and those called telerobots.

The basic notion of teleoperation is that a human operator is in full control at all times. A robot, on the other hand, has a degree of autonomy. A telerobotic device can be viewed as a hybrid between these two. Alternatively, it can be considered as an intermediate stage in the evolution toward a robot.

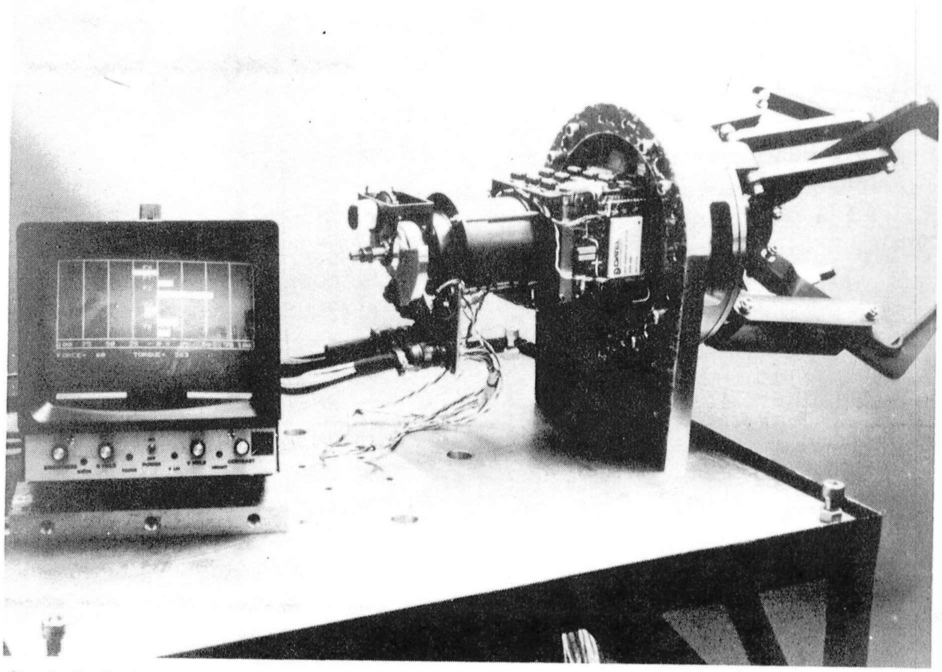


With the proper enabling technology, a flexible space robot could evolve from the current "astronaut-intensive" approach. (Courtesy of Martin Marietta Aerospace, Denver.)

Essentially, a telerobotic device can be operated by a human and much of the time must be. However, it incorporates some capability for independent action, typically the execution of simple, repetitive tasks which are part of a long procedure. For example, an operator may control the device through several steps and then come to a point where a set of fasteners needs to be removed. If this removal step has been provided for, the operator can switch the device to the robotic mode, let it remove the fasteners, and then resume control personally when the tedious task has been completed.

Robotic elements such as these, sometimes called "task primitives," are important in relieving the crew of the need for constant involvement. Without them, teleoperation would provide little gain over direct, hands-on manipulation.

The way in which flexible space robots might evolve is shown in the accompanying figure. The intermediate stages labeled "telesupervision" and "teleautomation" provide the capability we would expect of a telerobot.



Control of telerobotic devices requires novel methods for conveying information to the operator. In this example, methods are being developed to measure and display forces and torques experienced by end effectors. (Courtesy of the Jet Propulsion Laboratory.)

Force-Torque Sensor for the Shuttle Remote Manipulator System

A flight demonstration of a force-torque sensor for the Space Shuttle remote manipulator system (RMS) is planned for 1987.* A new form of feedback to the operator will be provided—a graphic display of the forces and moments (torques) experienced by the end of the manipulator. Awareness of these forces and moments should permit the operator to perform tasks, such as changing modules, that cannot be performed with the present system. The flight test will be an early experiment in the use of sensor data in a space teleoperation context as well as an enhancement of the Space Shuttle capability.

Expert System for Experiment Control

Planning is underway to conduct, on the Space Shuttle, a demonstration of an onboard, knowledge-based system to control experiments. This approved Space Shuttle advanced project is being augmented with funding from the Small Business Innovative Research program. We view this as another important piece of work that should be encouraged, and we are especially pleased at the involvement in automation and robotics of various NASA elements outside the Space Station Program.

Technology Development Missions on the Space Station

Further efforts that will lead to flight demonstrations are being sponsored under a program of technology development missions. One such effort is specifically aimed at advanced automation and robotics. The plan is to identify evolving A & R technology and then develop specific missions on the Space Station that will advance the technology for operational use in space.

Demonstrations in Telerobotics and Systems Autonomy

An extensive research and development program sponsored by the Office of Aeronautics and Space Technology depends heavily on demonstrations in the areas of its prime focus; i.e., in telerobotics and systems autonomy. These programs are covered in greater detail in section 5.

*Any impact on this plan by the hiatus in Space Shuttle missions has not been assessed.

Operational Plans

In its first progress report, the committee noted that NASA had a goal of operational autonomy in the first year of the Space Station. This goal has recently been affirmed by Level B, but concerns have been voiced as to its feasibility in light of budgetary constraints.

Work on operational autonomy has focused on incorporating into the station design an operations management system that would provide for centralized coordination of resources and facilities. The system would allocate onboard resources, schedule operations within the constraints of subsystem capabilities and crew availability, manage stationwide redundancy, authenticate commands, validate operational envelopes, and coordinate major events and targets of opportunity.

NASA recognizes that, even if all this capability cannot be provided initially, it is important to make provisions for its later application. Such provisions are stated to be instrumentation, data distribution techniques, and the ability to add data storage devices and upgrade onboard processing. We encourage thinking of this sort as just the type necessary to take advantage of the power of advanced automation and robotics.

Management Tools

The Space Station Program is in the process of establishing a Technical and Management Information System (TMIS) predicated on advanced automation techniques. This system will provide for information exchange among the various NASA centers and contractors involved with the design and construction of the Space Station. There are several ways in which TMIS can contribute to A & R work. Some of these are

- Assisting in the capture of Space Station design knowledge by providing networking, data standards, common interfaces, and compatibility between various data processing systems
- Providing data structures that support artificial intelligence communications; for example, semantic nets and frames
- Promoting the use of a common language for describing Space Station subsystems and components

Work by International Partners in the Space Station

Concerns have arisen over the potential impact on U.S. goals in automation and robotics of work by the international partners in the Space Station. Congress has put forth guidelines establishing the principle that participation in automation and robotics should be in proportion to overall participation. It is clear that the United States must be the principal beneficiary of the station's advanced technology.

Significant participation in the development of Space Station elements is anticipated from Canada, Japan, and Western Europe, as represented by the European Space Agency. In all cases, the partner countries will assume full technical and financial responsibility for the development of their elements.

Although all of the potential partners are examining the application of A & R technologies to their projects, steps will be taken to avoid the unwarranted transfer of technology between partners. At the same time, efforts will be coordinated to assure that the elements are compatible in operation. For example, agreement has been reached with the Canadians whereby they will study for the balance of the definition phase a mobile servicing center which will play a principal role in assembly of the station, transport of large masses, and servicing of attached payloads. This facility will complement the U.S. flight telerobotic system which will have the principal role in spacecraft servicing.

Compliance With the ATAC Guidelines

It is the committee's belief that the study contractors and NASA's Space Station Program are working earnestly to comply with the intent of the ATAC recommendations and the sense of Congress.While we believe the efforts to be generally well balanced, we would emphasize the importance of the following elements:

- Design accommodations for future A & R technology are even more important than the extent of automation and robotics incorporated in the initial station. Budget limitations may well constrain the initial applications, but we should not foreclose options to introduce new technology on an evolutionary station.

- Demonstrations, including flight demonstrations as appropriate, are very important. Not only do they focus the technology, but also they convince managers of the suitability of technology for use in a program.

- Designing to minimize the life cycle costs of the Space Station cannot be overemphasized. This is vital to provide incentives for the consideration of A & R technology and also has important implications for maintainability and operations in general.

- Decisions made on the station design should address A & R possibilities explicitly. For example, the truss structure appears to have been decided on without specific consideration of robot mobility. Truss size, configuration, method of assembly, protective coatings, and the like should all be arrived at in light of the needs and designs of robots. The truss design, in this example, could be influenced by whether the robot moves inside or outside the truss or both and whether it "walks" by grappling the truss members.

ATAC views the most critical needs for automation and robotics on the Space Station to be capabilities

- To assemble and build the station

- To operate it autonomously

- To service efficiently the station, payloads, and satellites

The efforts underway at NASA and in the contractor companies are addressing these needs, and the team should press on vigorously. Included in these efforts should be a quantitative examination of life cycle costs. ATAC believes that, as life cycle costs are quantified, the intrinsic merit of automation and robotics technology for the Space Station will be realized by an ever-broadening number of program participants and that, as important as this work has been in phase B, it will be even more important in phases C and D.

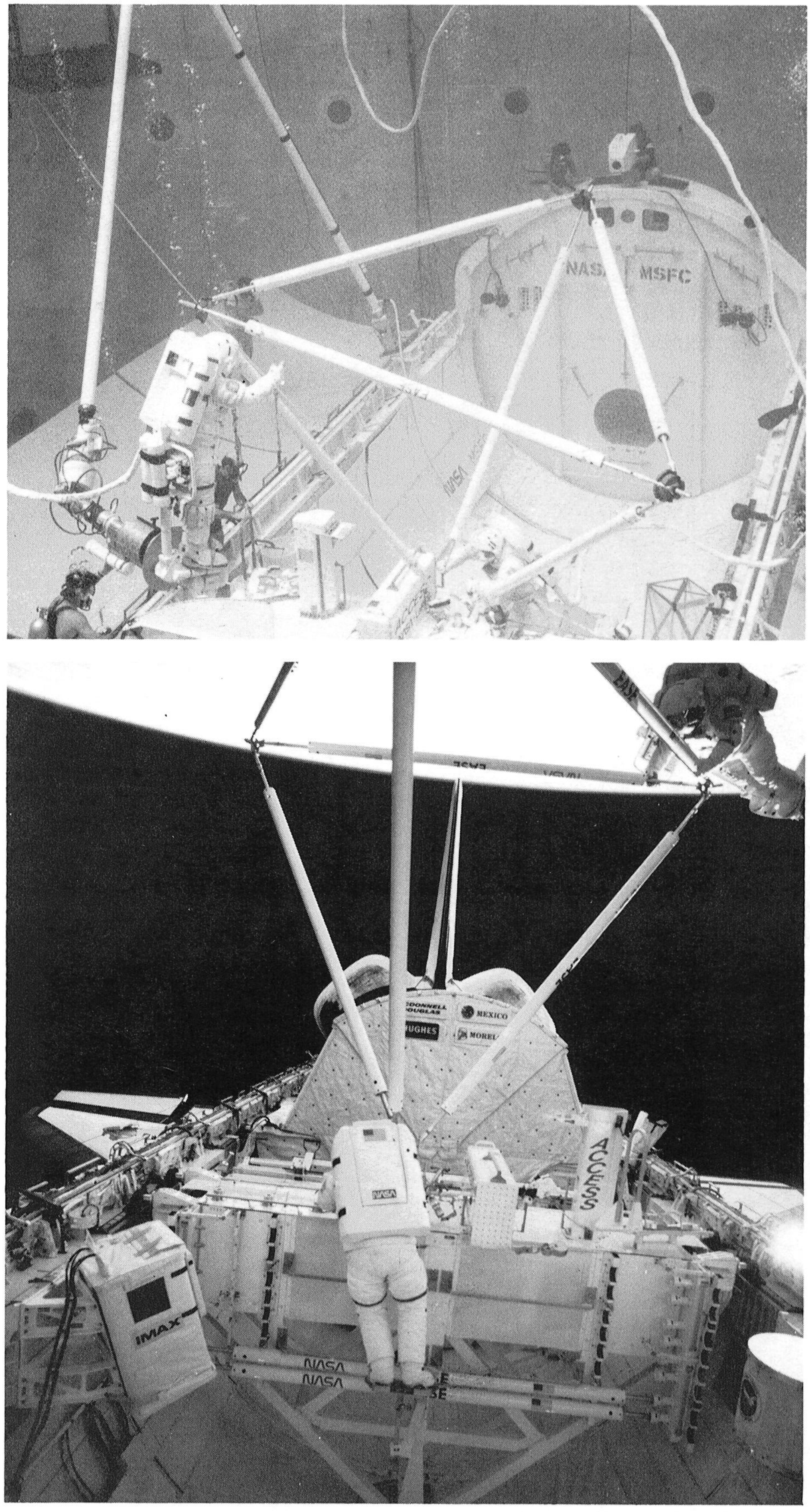
Progress in Research and Technology Base Building to Support A & R Applications

Space Station applications of automation and robotics are being built on a base of currently available technology. This area of technology is advancing rapidly. Several elements of NASA have A & R work underway for other programs, such as the Space Shuttle and the planetary program, but the work will benefit the Space Station as well.

Office of Aeronautics and Space Technology

The most extensive work within NASA is being carried out by the Office of Aeronautics and Space Technology (OAST). This office has been involved in automation and robotics work for many years and has had programs in artificial intelligence, robotics, and supervisory control of highly automated systems since 1980. The funding for work in this area has grown markedly since 1980 and, as a result of the congressional initiative, OAST will more than quadruple the support for this area between 1984 and 1987. Furthermore, a single, focused program has evolved which relies on close coordination with and leverage of the work done by the Defense Advanced Research Projects Agency (DARPA) in its strategic computing initiative and by the National Bureau of Standards in its robotics program.

The primary goal of the OAST program is to develop a generic technology base that can exploit the potential of artificial intelligence and of telerobotics to decrease the cost



Assembly of the Space Station, initially a manual task, will be facilitated by telerobotic devices. The weightlessness of space can be simulated in immersion facilities and a high confidence in procedures can be gained before such procedures are applied in space.

of ground operations and to increase the capability and flexibility of space operations. A related goal is to enable significant transfer to terrestrial automation.

The OAST program has two focuses: system autonomy and telerobotics. Integration of advancing technologies within each focus is to be achieved through a series of ground demonstrations scheduled from 1987 to 1996. Over this period, these demonstrations will cover a great increase in capability. In the area of system autonomy, the 1996 demonstration will consist of distributed control of multiple subsystems with the capabilities of fault prediction, real-time replanning, and learning. In the area of telerobotics, the 1996 demonstration will extend to repair tasks involving cutting and fabrication.

Underlying both sequences of demonstrations are five core technologies: sensing and perception, control execution, task planning and reasoning, operator interface, and system architecture and integration (ref. 20).

The good progress in automation and robotics made by the Office of Aeronautics and Space Technology was documented in the report of the ATAC workshop in May 1985 (ref. 21).

Office of Space Flight

The Office of Space Flight (OSF) is heavily involved in A & R work in support of the Space Shuttle, and much of this work is directly relevant to the Space Station as well. Efficiency of operation for the Shuttle itself and for the work it does for its customers in areas such as satellite servicing is a continuing objective. Advances in telerobotics and in expert systems for operations, planning, and control are major focuses of the OSF work. Current work includes the development of advanced components such as quick-change end effectors for robots and a force-reflecting end effector for the Shuttle remote manipulator system (RMS). Hazardous fluid loading methods and remote servicing methods using the orbital maneuvering vehicle (OMV) are also being studied.

Office of Space Science and Applications

The Office of Space Science and Applications (OSSA) will be a major user of NASA satellite servicing capabilities and will have a significant contribution to make to defining requirements and standards for such servicing. Studies of robotic servicing are currently being made for the proposed Earth observing system.

Office of Space Tracking and Data Systems

The Office of Space Tracking and Data Systems (OSTDS) is active in the important area of automation for ground operations. The basic motivation is to reduce the cost of conducting flight operations. Again, success in this work will have direct applications to the Space Station, for which a high degree of autonomy and efficiency in ground support are important to the containment of operating costs.

Summary of Progress

In the first progress report, we synopsized the results of the workshop the committee sponsored in May 1985. This workshop reviewed much of the work going on within NASA. An updated synopsis is shown in appendix G. As in the previous report, the synopsis shows the stage of the work in terms of technological readiness levels (table 1). It also categorizes each activity according to NASA's preliminary classification scheme for automation and robotics (appendix F).*

The committee is encouraged by the extent of effort that is being focused on automation and robotics both within NASA and in the associated contract and research communities. We are particularly pleased that steps are being taken to have all elements of NASA, whatever their programmatic orientation, aware of the Space Station needs and the congressional intent, and to have them provide leverage for the station's automation and robotics.

The Office of Aeronautics and Space Technology is particularly supportive of the congressional goals and has stretched its own resources as far as possible to address the building of a solid technology base.

We feel that NASA in general and OAST in particular have responded as fully as they can to the congressional initiative in automation and robotics.

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*This classification scheme is evolving, as it should. Some new items have been added, and the major categories have been aligned with the OAST research topics.

Plans for a Flight Telerobotic System Using Congressional Set-Aside Funding

In November 1985, congressional conferees directed (ref. 22) that a portion of NASA funding be set aside for a flight telerobotic system, saying

> . . . $5,000,000 which is available only for automation and robotics activities. Specifically, the Committee of Conference directs that the $5,000,000 be used for delivery of a flight telerobotic system at the time of initial Space Station operational capability for a mobile remote manipulator for station assembly and maintenance and a smart front end on the orbital maneuvering vehicle for remote operations and servicing.

NASA's Level B Space Station Program Office is devoting high-priority efforts to preparing a plan for this flight telerobotic system, and NASA is in the process of selecting a lead center to develop the system.

The preliminary plan developed by NASA in response to this congressional directive applies the $5 million of set-aside funding in fiscal year 1986 to the initial development of the telerobotic system and allocates $10 million of Space Station funding in fiscal year 1987 to the continued development of the system. The total cost to develop the flight telerobotic system is expected to be in the neighborhood of $100 million.

The plan is to develop what is essentially a teleoperated system. It provides simple robotic functions and is designed to facilitate evolution to greater autonomy. Advanced robotics technologies leading to a high level of autonomy could be incorporated at a later time if resources permit.

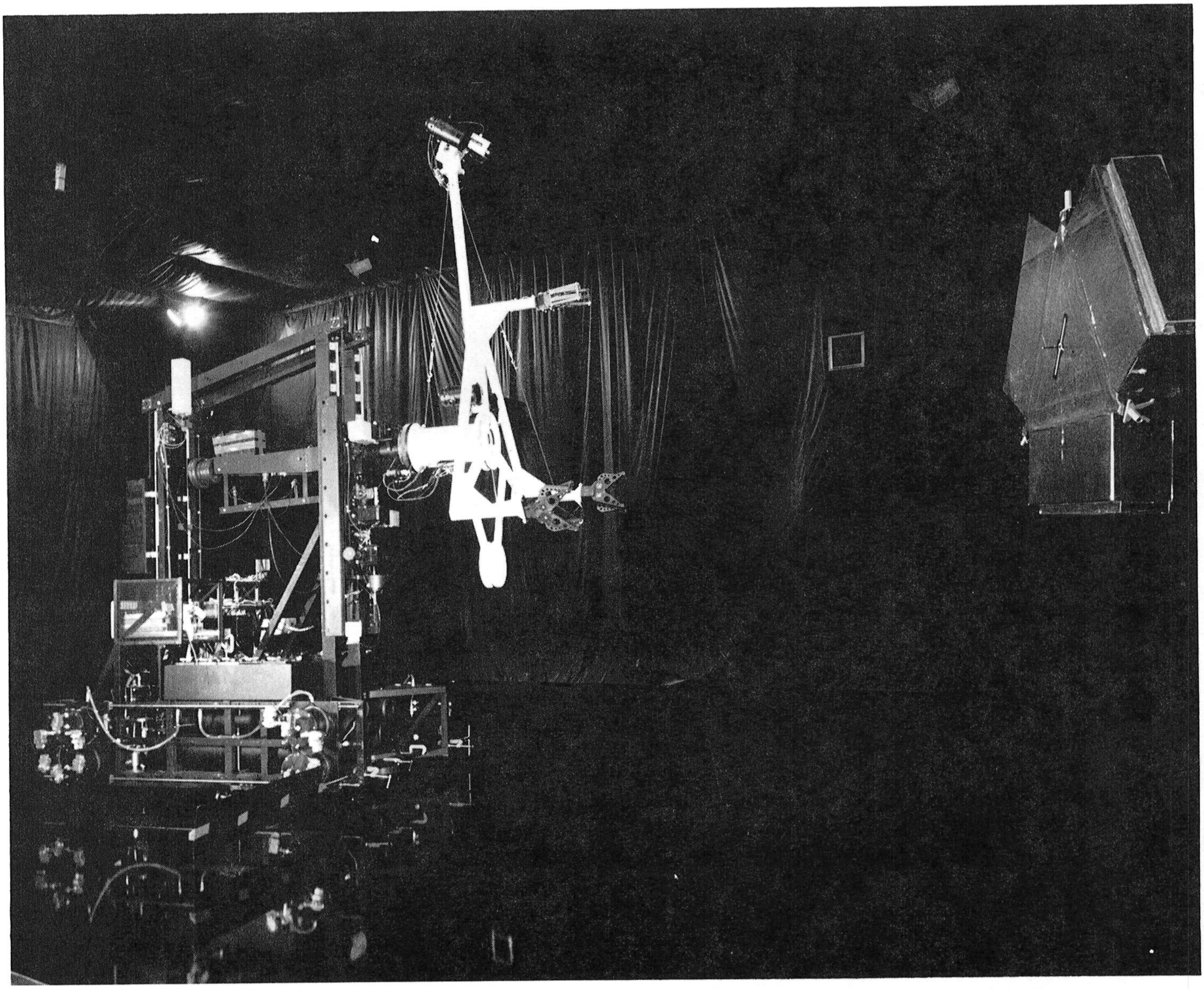
A planning workshop was held in late January 1986. The purpose was to identify what was necessary to implement the telerobotic directive. The workshop identified the following as tasks that need to be accomplished with the first 2 years' funding.

- Provide the work package centers with the facilities and expertise needed to define the required robotic functions and procedures.
- Identify the functions of the initial station which could be carried out by a telerobotic system.
- Evaluate the readiness of current technology to carry out the telerobotic functions.
- Define conceptually an integrated robot to perform the functions of assembly, maintenance, and servicing.
- Provide supporting elements, such as task mockups and simulations.

Development of a flight telerobotic capability such as that envisioned would provide benefits for the entire Space Station. Operation of the station relies heavily on various physical actuations and manipulations which, in the absence of such a robotic system, would have to be carried out by the crew. Many of these functions can be handled by a robotic system, thereby relieving the crew of heavy demands on their time and leaving them available to carry out higher order functions.

The characteristics of such a robot include

- Modular design exploiting orbital replaceable units (ORUs) for servicing
- Mobility provided by the remote manipulator system, the mobile remote manipulator system, the orbital maneuvering vehicle (OMV), and the service bay gantry
- Reach and strength at least equivalent to that of a suited astronaut on an extravehicular activity (EVA)
- Capability for the EVA tasks of servicing Space Station elements, the OMV, satellites, platforms, payloads, and tank farms
- Controllability from the Space Shuttle, the Space Station, or the ground
- Vision and force feedback for human operators
- Compliance (e.g., flexibility) in the robot's manipulator joints
- Adaptability to a pressurized environment
- Accommodation to increasing levels of autonomy
- Accommodation to attachment to and operation on co-orbiting and polar orbiting platforms

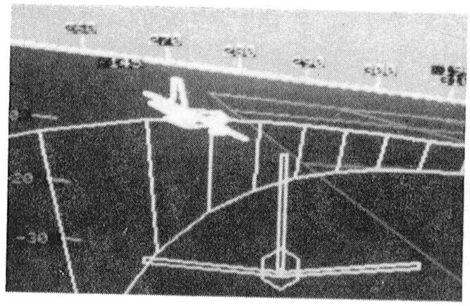


Simulations of the space environment are being used to develop systems and procedures for proper lighting, rendezvous, and docking. This example shows the orbital maneuvering vehicle simulator at the Marshall Space Flight Center.

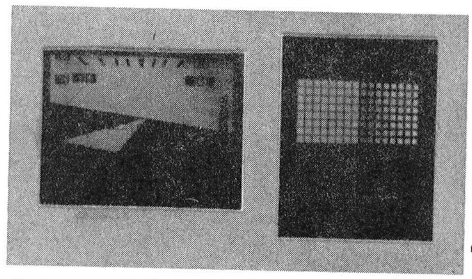
While we cannot describe the flight telerobotic system at this early stage, we anticipate that it will incorporate a number of advanced features. These include dual-arm cooperation; multiple light sources and multiple stereoscopic cameras; and force, torque, and position sensors. As a result of this effort, technology development in the areas of end effectors, sensors, evolvable architectures, and human/machine interfaces will be advanced.

This program is being closely coordinated with OAST to assure the timely transfer of technology. Formalized methods of transfer between the technology centers and the work package centers have been agreed on.

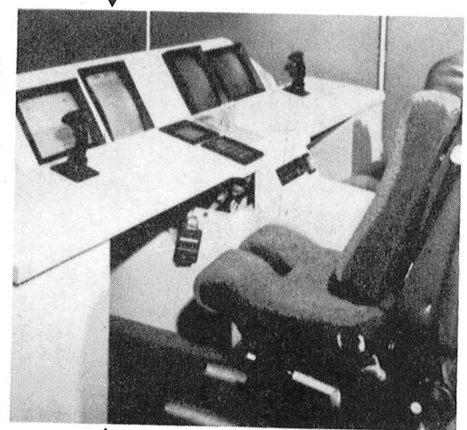
Expenditures for Advanced Automation and Robotics



Flight display graphics



Advanced display media



Just the right information, possibly produced by an expert system, will enable the interaction between human and machine. Novel technologies for display screens and work stations are being developed. (Courtesy of Langley Research Center.)

The committee recognizes that Congress wishes to be kept apprised of the extent to which the Space Station Program has complied with the suggested utilization of 10 percent of program funds for automation and robotics. We still believe, as we stated in the first progress report, that it is too early to form a useful judgment on the extent of compliance. Once the preliminary design has been completed (i.e., at the end of phase B), there should be sufficient information on which to base the desired assessment. The information yet to be developed is the actual extent to which automation and robotics will be incorporated in the station and the approximate cost of each element of the program.

Nevertheless, NASA has provided estimates of the Space Station expenditures devoted to automation and robotics for the current phase. This information is summarized in table 7; information is given for fiscal years 1985, 1986, and 1987, except in the case where the only estimate available is for the entirety of the definition and preliminary design phase.

TABLE 7.— SPACE STATION FUNDING FOR AUTOMATION AND ROBOTICS

Activity	Funding, in millions of dollars		
	FY 85	FY 86	FY 87
Advanced development	1.6	2.9	4.2
Systems engineering and analysis	1.1	1.0	0.9
Operations	0.1	0.8	0.9
Space Station utilization	0.4	0.8	1.7
Phase B contracts (22 months)	—	7.7	—
Total, all years			24.1*

*Excludes $5 million congressional set-aside.

We recognize the need for NASA to satisfy the spirit of the congressional mandate and show that the intended level of Space Station Program support is being provided. However, there is still a need for a sound method of estimating the projected cost of subsystems utilizing advanced automation and robotics, and NASA is working actively to devise such a method. We caution again that sensible methods are needed, ones that will not require undue (and perhaps unrealistic) accounting detail.

As has been described in the section on research, several elements of NASA outside the Space Station Program are devoting major amounts of funding to automation and robotics. While this work is being done only in part for the Space Station, virtually all of it is relevant to the station and needs to be included in any complete assessment of NASA's attention to A & R technology. The numbers we were given are current estimates for fiscal year 1986.

As was the case in fiscal year 1985, the Office of Aeronautics and Space Technology is funding the most A & R work, with lesser but substantial amounts provided by other offices. Table 8 gives a summary of the expenditures by funding office.

TABLE 8.- NASA FUNDING FOR AUTOMATION AND ROBOTICS

[Fiscal year 1986, millions of dollars]

Office and activities	Funding
Space Station	11.2*
Advanced development	
Systems engineering and analysis	
Operations	
Space Station utilization	
Phase B contracts	
Aeronautics and Space Technology	10.2
Ground demonstrations	
Telerobotics	
Systems autonomy	
Core technologies, such as	
Sensing and perception	
Task planning and execution	
Control execution	
Operator interface	
System architecture and integration	
Definition of user needs	
Space Flight	4.6
Robotics	
OMV servicing and refueling	
Automation	
Space Science and Applications	0.7
Definition of user needs	
Space Tracking and Data Systems	1.0
Improved flight operations	
Total NASA funding, approximately	27.7

*Includes $5 million congressional set-aside.

Key Events and Activities During the Current Reporting Period

Study Contractors Reported Their Progress at Two Reviews and Submitted Drafts of A & R Plans

Significant progress has been made by the phase B study contractors. This work was reported at the second requirements update review (RUR-2) in October 1985 and again at the Interface Requirements Review (IRR) in December 1985. Their draft A & R plans are references 10-17.

A Successor to the Automation and Robotics Panel Has Been Established

A contract has been awarded to the California Space Institute to continue to provide an independent review of Space Station A & R plans and progress from the vantage point of the research community. This effort is funded at a much lower level than was the original Automation and Robotics Panel (ARP). However, ATAC views this function as an important one that merits support.

Congress Voted Set-Aside Funding for a Flight Telerobotic System for the Initial Space Station

A significant amount of funding ($5 million in FY 1986) was designated by Congress for Space Station A & R work, specifically for a flight telerobotic system for the initial station. NASA has been working hard on a plan to utilize this money in a way that will satisfy the congressional intent and meet station needs.

The Importance of Robotics to Satellite Servicing Was Emphasized at a Major Workshop

NASA sponsored a major workshop—Satellite Services Workshop II—at the Johnson Space Center November 6-8, 1985. The workshop was well attended by representatives of organizations concerned with the building, launching, operation, and insuring of satellites. While much of the discussion centered around the current EVA approach to servicing, a strong theme of robotic servicing emerged. And, while the reception on the part of NASA was mixed, there was some recognition that robotic means are vital if servicing is to become routine and if the current "heroic measures" taken by the crew are to be minimized.

A Workshop Was Held on the Smart Front End for the Orbital Maneuvering Vehicle and Mobile Remote Manipulator System

A "smart front end" for the orbital maneuvering vehicle (OMV) and for the mobile remote manipulator system (MRMS) is a topic of great interest. A workshop to address various aspects of the smart front end was held at the Marshall Space Flight Center on January 13 and 14, 1986.

Guidelines for Program Use Were Updated and Issued

A data products report for RUR-2 (ref. 5) was issued. This report provided further definition of some of the assessment tools, a review of the current state of A & R technology, and additional guidelines for program participants.

A Workshop on Robotics and Advanced Automation Was Held To Present Tutorials and To Report Experience

A workshop was held at the Johnson Space Center December 6-8, 1985, at which both aerospace and industrial users of robotics and advanced automation provided a most informative set of tutorials, demonstrations of several robotic and teleoperated devices, and papers on experience in the field. This type of educational workshop should be encouraged.

A Level B Review of Automation and Robotics Activities Was Held

Work in automation and robotics going on throughout the Space Station Program, including relevant technology development work at the research centers, was reviewed by Level B at the Johnson Space Center February 4-6, 1986. Work package contractors and center representatives active in A & R research reported the status of their work. The essence of these presentations was provided to ATAC.

Plans Are Being Developed To Promote the Transfer of A & R Technology To and From NASA

In response to the requirement in the Space Station A & R Implementation Plan for a "vigorous program of technology transfer," the NASA Office of Commercial Programs and the Space Station Customer Integration Office are working together to plan technology transfer to and from NASA.

The Office of Commercial Programs is developing an industry technology transfer plan for automation and robotics. The transfer of A & R technology to the U.S. economy will most likely occur through three avenues: the NASA Small Business Innovation Research program; the dissemination of descriptions of commercial opportunities in automation and robotics; and application engineering projects conducted under the joint sponsorship of Government, industry, academia, and research associations.

To open this last avenue, the two offices are planning a workshop for late 1986. The purpose of the workshop will be to discuss roles and responsibilities and assess participant costs for the implementation of specific A & R technologies leading to either terrestrial or Space Station applications. Discussions have already been held at NASA Headquarters with the Society of Manufacturing Engineering, the National Bureau of Standards, and the National Academy of Sciences to determine the most effective way to conduct the workshop.

A Scenario for Training in Automation and Robotics Has Been Developed

During the workshop on NASA A & R activities held in May 1985, the issue of training in automation and robotics for NASA personnel was raised as a significant concern. The Office of the Chief Engineer has developed an approach to meeting this need. The approach involves graduate study for selected employees; special training sessions, demonstrations, and tutorials for larger numbers of employees; and the active support and recruiting of new employees currently in university or cooperative programs.

The Importance of Automation and Robotics to the Space Station Continues To Be Publicized

Efforts have been continued to make various communities aware of the NASA thrust in automation and robotics for the Space Station. This work has included writing articles for professional journals, giving presentations to various technical and professional societies, briefing audiences within the NASA family, and participating in general information exchanges in academic and community circles.

Computer-generated images of high fidelity are already an important aspect of training devices. Such images, supplied by a knowledge-based system, could provide information needed by astronaut-managers. (Courtesy of General Electric.)

Conclusions

The committee concludes from its review that there is broad compliance with the ATAC recommendations. A number of encouraging signs have appeared which indicate that advanced automation and robotics will be an important aspect of the Space Station, as desired by Congress. There is, however, no basis for complacency, since major efforts are still needed if the mandate from Congress is to be fulfilled and, indeed, if the Space Station is to perform as it must.

ATAC views the most critical needs for automation and robotics on the Space Station to be capabilities

- To assemble and build the station
- To operate it autonomously
- To service efficiently the station, payloads, and satellites

The efforts underway at NASA and in the contractor companies are addressing these needs.

Significant progress has been made in the definition of candidate A & R applications for the Space Station. Additional effort, including quantification of costs and benefits, is underway to refine the list of recommended applications for the initial station.

Design accommodations for future A & R technology have been described, and the supporting research and development program has been expanded. Attention is being given to capturing the design data and rationale for the Space Station. It is vital that this process begin early and continue throughout the life of the station.

Some recognition has been obtained of the extensive crew time required for Space Station functions, and we believe that advanced automation and robotics is becoming more widely appreciated as a requirement to alleviate this potential problem.

The emphasis by Congress on developing a flight telerobotic capability for the initial Space Station, as evidenced by the funding set aside, is highly encouraging. This capability directly addresses the most critical needs as ATAC sees them. A dextrous telerobotic device not only could provide a "smart front end" for the orbital maneuvering vehicle but also could be used on the mobile remote manipulator system or adapted to a free-flying vehicle. NASA is currently developing specific plans and will soon select a lead center to implement this initiative.

Demonstrations, both on the ground and on Space Shuttle flights as appropriate, are very important to the incorporation of A & R applications in the Space Station. The demonstrations serve to focus the technology and to convince managers of the readiness of the technology to support Space Station requirements. Demonstrations in systems autonomy and telerobotics have already been planned. The list will need to be expanded as candidate A & R technologies reach the demonstration stage.

The greatest concern of the committee relates to the impact of resource constraints on the incorporation of advanced A & R technology in the initial station. The primary cost benefit of automation and robotics is reduction in operational costs. The longer term savings in operational costs can far outweigh the increased initial costs. Therefore, inclusion of operational as well as initial costs is required for automation and robotics to be properly evaluated in the design of the Space Station. NASA has recently committed to designing to minimize life cycle costs and, if this can be accomplished in the face of limited year-to-year budgets, the incentives will exist for incorporation of A & R technology.

In spite of the encouraging progress, we note that very important decisions are about to be made in the Space Station Program which will fix the nature of the station for decades to come. As important as the work in automation and robotics has been in phase B, it will be even more important in phases C and D. Design accommodations for future A & R technology are even more important than the extent of automation and robotics incorporated in the initial station. Budget limitations may require us to rank the candidate applications for the initial station, but we should not foreclose options to introduce new technology on an evolutionary station.

ATAC believes that, as life cycle costs are quantified, the intrinsic merit of automation and robotics technology for the Space Station will be realized by an ever-broadening number of program participants and that, with continuing attention to automation and robotics, the Space Station can fulfill its promise to be the "showcase" user and driver of this technology.

APPENDIX A

NASA 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, Director of Engineering Division, Office of 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)

Lee B. Holcomb, Director of Information Sciences and Human Factors Division, NASA Headquarters

James E. Kingsbury, Director of Science and Engineering, Marshall Space Flight Center (MSFC)

Allen J. Louviere, Manager of Space Station Level B Systems Engineering and Integration

Henry H. Lum, Chief of Information Sciences Office, Ames Research Center (ARC)

Robert R. Nunamaker, Director for Space, Langley Research Center (LaRC)

Donna L. Pivirotto, Manager of Automation and Robotics Office, Jet Propulsion Laboratory (JPL)

Giulio Varsi, Automation and Robotics Manager, Engineering Division, Office of Space Station, NASA Headquarters

APPENDIX B

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APPENDIX C
Acronyms

A & R	automation and robotics
AI	artificial intelligence
ARP	Automation and Robotics Panel
ATAC	Advanced Technology Advisory Committee
CSD	contract start date
DMS	data management system
EVA	extravehicular activity
GNC	guidance, navigation, and control
IRR	Interface Requirements Review
MRMS	mobile remote manipulator system
MTL	materials technology laboratory
NASA	National Aeronautics and Space Administration
OAST	Office of Aeronautics and Space Technology
OMV	orbital maneuvering vehicle
ORU	orbital replaceable unit
OSSA	Office of Space Science and Applications
OSF	Office of Space Flight
OSTDS	Office of Space Tracking and Data Systems
RMS	remote manipulator system
RUR	requirements update review
TMIS	Technical and Management Information System

APPENDIX D

Candidate A & R Applications on the Initial Space Station

Part 1—Program Elements Addressed by ATAC

Subsystem/program element	Function/functional element	Source (work package)
Electric Power	System health monitoring, fault recognition	2
Generation, storage, and conditioning	Failure prediction	2
	Fault isolation and reconfiguration	2, 4
	Maintenance, repair, retest	2, 4
	Failure cause diagnosis	4
Loads and allocation	Scheduling and management	2, 3, 4
Common module	On-orbit checkout	1
	Trend analysis	1
	Fault management	1
	Load management	1
	Bus configuration management	1
Laboratory module, platforms, and attached payloads	Trend analysis	3
	Fault diagnosis	3
Guidance, Navigation, and Control	Maintaining the orbit	2
	GNC monitoring and maintenance	2
	Mission planning	2
	On-orbit checkout	2
	Mass properties validation	2
	Space traffic control	2
	Control of attached payloads	2
	Collision avoidance	2
	Deboost	2, 3
	Proximity operations	2, 3
Platforms, customer servicing/ accommodation	Rendezvous navigation	2, 3
Laboratory module, platforms, and attached payloads	Fault diagnosis	3
Communication and Tracking	External communications control	2
	Tracking control	2
Common module	Fault management	1, 2
	Video control	1
	Audio/video distribution	1
Laboratory module, platforms, and attached payloads	Data rate selection	3
	Communication scheduling	3
	Rendezvous tracking	3

Part 1—Program Elements Addressed by ATAC (concluded)

Subsystem/program element	Function/functional element	Source (work package)
Information and Data Management	DMS monitoring and diagnosis	2
	Fault diagnosis and performance prediction for external subsystems	2
	Continuity and opportunity planning	2
	Fault recovery	2
	Display interpretation	2
	Robot control	2
Common module	Module safety advisor	1
	Payload interface controller	1
	Inventory management	1
	System status assessment	1
	Fault diagnosis	1
	Redundancy and configuration management	1
	Resource and maintenance scheduling	1
	Trend analysis	1
Laboratory module, platforms, and attached payloads	Trend analysis	3
	Fault diagnosis	3
	Subsystem status assessment	3
	Redundancy and configuration management	3
	Data base management	3
Environmental Control and Life Support	Data base management	1
	Configuration management	1
	Statusing	1
	Water management	2
	Atmospheric management	2
	Fault diagnosis	1, 3
	Trend analysis	1, 3
	Hyperbaric chamber operation	3
Common module	Integrated controller	1
	Monitoring and statusing	1

Part 2—Program Elements Not Specifically Addressed by ATAC

Subsystem/program element	Function/functional element	Source (work package)
Thermal Systems	Inspection	2
	Assembly, repair, replacement	2
	Payload installation, servicing, and management	2
	Planning	3
Common module	Monitoring and statusing	1, 2
	Fault management	1, 2
EVA Systems	Customer service	2, 3
	Assembly support	2
	Rendezvous and docking	2
	EVA equipment support and servicing	2, 3
	EVA planning and monitoring	2, 3
Fluids	Storage and transfer operations	2
Structures and Mechanisms	Assembly of	2
	—Mounting plates	
	—Truss articulation control	
	Inspection of	2
	—Utility run	
	—Truss articulation control	
	—Lubrication	
	Maintenance and repair of	2
	—Utility run	
	—Bolt torque	
	—Remote manipulator	
	—Gimbal system	
	Thermal curvature control	2
	Station utilities management	2
	Medical assistance in airlock	2
Modules	Connect/interconect	2
	—Berthing assistance	
	—Utilities connection and verification	
	—Latch verification	
	—Inspection of seals	
	—Tunnel inspection	
	—Chemical decontamination	
	—Airlock actuation	
	Interconnect inspection and repair	2
Orbital Maneuvering Vehicle and Orbital Transfer Vehicle	Berthing and deployment	1, 2
	Navigation and control	1
	Fluid transfer	1
	Maneuvering	1
	Payload integration	1
	Maintenance and servicing.	1, 2
	—Checkout of orbital replacement units	
	—Inventory accounting	
	—Activity scheduling	

Part 2—Program Elements Not Specifically Addressed by ATAC (concluded)

Subsystem/program element	Function/functional element	Source (work package)
Logistics Module	Inventory management for items going to and from the Space Station	1
	Propellant transfer	1
	Spares relocation (inside and outside)	1
Laboratory Module	Experiment scheduling	1
Materials technology	Checkout of customer equipment interface	2
	Experiment monitoring	1
	Chemical and physical analysis	1
Life sciences	Experiment operation	3
	Exacting, specialized tasks	3
	Fetching of supplies	3
	Test protocol verification	3
	Experiment data processing and management	3
	Sample analysis	3
Operations	Crew training	2
	Station coordination	2
	Activity planning	2
	Shuttle proximity operations/berthing	2
	Shuttle interface inspection and repair	2
	Shuttle manipulator coordination	2
	Chemical decontamination	2
Propulsion	Propellant transfer	1
	Monitoring and statusing	1, 3
	Fault detection	1
Payloads	Checkout of attachment ports	3
User Interface	System monitoring and fault diagnosis	3
	Controller	3
	Servicing	3
General (Robotics)	Parts inspection and replacement	1
	Materials handling (satellite servicing and repair)	1

APPENDIX E

Criteria and Weighting Factors for Application Selection

Part 1—Criteria for Selecting Applications of Automation and Robotics

Tentative criterion	Considerations
Crew and station safety	Need for extravehicular activity Handling hazardous materials
Performance	System weight, volume, and power Accuracy and repeatability of operation Maintainability and reliability Contribution to mission reliability Adherence to customer-imposed requirements (user accommodation)
Productivity	Crew productivity, time saved, response-time improvements, extending performance beyond the capability of unaided crew Commonality among functions to be supported Ground operations productivity Compatibility of A & R hardware and software with other Space Station equipment and systems
Cost	Non-recurring development costs Operating—i.e., "life cycle" costs
Growth and evolvability	Potential for enhanced capability Flexibility Design accommodations ("hooks and scars")
Risk	Technology readiness Performance Cost sensitivity Schedule
General applicability	Commercial potential Application in other space contexts Benefits to the U.S. economy Terrestrial applications

Part 2—A Typical Set of Weights for One Contractor's Criteria

Factor	Weight
Safety	0.24
Productivity	.16
Initial station cost	.16
Cost risk	.08
Performance risk	.08
Technology readiness risk	.08
Spinoffs	.06
Flexibility	.06
Maintainability and reliability	.04
Commonality	.04

APPENDIX F

NASA Categories for Automation and Robotics Work

1.0 Basic functional capabilities and issues

1.1 *Knowledge (Task planning and reasoning)**
Representation and reasoning—surface and deep knowledge
Problem solving, control methods, search techniques
Deduction and theorem proving
Knowledge acquisition and learning
Diagnosis, monitoring
Planning, simulation, execution
Perceptual reasoning, object recognition

1.2 *Sensing (Sensing and perception)*
Force, torque
Proximity, range and rate
Tactile, kinesthetic
Visual, optical
Auditory, acoustic
Pressure, flow, temperature, dewpoint, speed, voltage, current
Integration and coding of sensor information

1.3 *Actuation and manipulation (Control execution)*
Control technology
—Coordination
—Collision avoidance
—Compliance
—Error recovery
Manipulators—arms, end effectors, propelling mechanisms
Actuation in dynamic and distributed expert systems

1.4 *Human/machine interface (Operator interface)*
Displays
Force/torque feedback
Controls and input mechanisms
Natural language processing
Voice synthesis and recognition
Interfaces and user interface management
—Users of knowledge-based or expert systems
—Users of management information systems
—Reprogramming and maintenance
—Options for levels of automation
Automation tradeoffs
Sensor fusion

2.0 System capabilities and system issues

2.1 *Supporting software and hardware (System architecture and integration)*
Fault-tolerant architecture
Specialized artificial intelligence architectures
Programming languages
Uninterruptable and distributed systems
Resource management
Design accommodation for automation and robotics

2.2 *System design and integration (System architecture and integration)*
Environments for automation
Verification and validation
Automatic test and checkout
Automated software development
Knowledge engineering
Shells for knowledge-based or expert systems
Engineering automation
Design, programming, and documentation aids

2.3 *Knowledge-based or expert systems (no equivalent)*
Control and monitoring
Fault management, servicing and repair
Executives and hybrid
Planning/scheduling/sequencing
Engineering and programming support
Data base management
Distributed and interacting expert systems

2.4 *Robotic and telerobotic systems (no equivalent)*
Assembly and construction
Parts handling
Servicing and repair
Computer vision systems, automatic inspection

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*The descriptions in parentheses are the corresponding categories used by the Office of Aeronautics and Space Technology (OAST) for their research.

APPENDIX G

R & D Activities Related to Automation and Robotics

Institution	Objectives of the research	Potential Space Station use	Level
Category 1.1—Knowledge			
Ames Research Center	Representational issues including —Time (duration and causality) —Actions and their effects —Spatial information (models, CAD) —Truth maintenance Decision-making under uncertainty Learning Fault diagnosis Integrated decision-making for distributed expert systems	Astronaut and equipment scheduling System operation Construction Autonomous robots	2-3
Goddard Space Flight Center	Geometric knowledge base Autonomous reasoning for assembly/ disassembly/replacement	Servicing and assembly	4
Goddard Space Flight Center	Development of standard formats	Autonomous robot servicing	5
Langley Research Center	Distributed artificially intelligent system for interacting with the environment (DAISIE): planner/ controller interaction	Control	3
Langley Research Center	Fault diagnosis expert system (for aircraft cockpit) including temporal reasoning	Fault diagnosis	3
Langley Research Center	Expert system development —Design optimization —Reducing search space for analysis programs and data bases	General applications	1
Marshall Space Flight Center	Intelligent robot servicing via task automation including —Sensor data fusion —World modelling —Task planning —Task sequencing —Conflict resolution	Automation of robot servicing, ORU replacement	2
Marshall Space Flight Center	Automatic development of time-optimal algorithms for robot manipulator control	Development of robotic system for Space Station and free-flying servicers	4
Category 1.2—Sensing			
Ames Research Center	Optical information processors	System operation	2-3
Ames Research Center	Information understanding and extraction (sensor fusion)	Autonomous robots	2-3

R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (continued)

Institution	Objectives of the research	Potential Space Station use	Level
Goddard Space Flight Center	Compliant force feedback and applications to use devices with such feedback	ORU replacement and assembly	4
Jet Propulsion Laboratory	Development of sensors—tactile, proximity, and torque Displays to enable teleoperation	Robotic and teleoperated grippers with force and moment feedback	3
Johnson Space Center	Development of TV systems for target recognition, identification, and attitude determination Voice command systems	Automated tracking	2
Johnson Space Center	Laser vision development Spatial positioning using controlled-position light beams Infrared remote control techniques	Robotic sensing and control	3
Langley Research Center	Laser-based image and rate/ranging systems	Autonomous robots	3
Langley Research Center	Focal plane preprocessing for improved sensitivity and speed		4
Lewis Research Center	Techniques for sensor-failure detection, isolation, and accommodation	System monitoring	4
Marshall Space Flight Center	Utilization of high accuracy charge injection device (CID) sensors in a hardware adaptive target-tracking system	OMV, orbital transfer vehicle (OTV), and Space Station docking, berthing, servicing	3-4
Marshall Space Flight Center	Vision sensor for a robotic system to remove solid rocket booster thermal protection during rework	Automated processes in the space environment	6
Marshall Space Flight Center	Optimization of lighting, video camera control, and transmission for OMV rendezvous and docking (through flat-floor simulation studies)	OMV and OTV operations and remote viewing	3
Marshall Space Flight Center	Development of vision system for automatic docking using TV box scan and syntax pattern recognition	Autonomous docking and servicing	2
Category 1.3—Actuation and Manipulation			
Ames Research Center	Real-time control of limber manipulators with end-point sensing	Manipulators, robotics, and servicing	2
Johnson Space Center	Robotic test facility for Space Station hardware interfacing requirements Actuator laboratory for advanced robotic and docking systems Programmable mechanisms for assisting the RMS in payload handling	Manipulators and robotics	2
Langley Research Center	Parallel-jaw end effectors with proximity detection Quick-change tool systems High-level command systems Six-degree-of-freedom force and torque sensors and displays	Generic robotics and teleoperation	3 5 4 6
Lewis Research Center	Smart remote power controllers and remote bus isolators for power limiting and fault detection and isolation	Autonomous electrical power system	4

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Protoflight manipulator	Servicing and construction	5-6
Marshall Space Flight Center	Intermeshing end effector for use on manipulator arms and capture devices	Servicing and construction	5
Marshall Space Flight Center	Intelligent robot servicing via task automation including —Active compliance control —Static and dynamic force limiting —Dynamic path compensation —Collision detection	Automation of robotic servicing, ORU replacement, berthing	2-4
Marshall Space Flight Center	Inflatible end effectors which expand inside large, irregularly shaped space structures, thereby distributing the force loads evenly	Assembly, maintenance, and repair of space structures	3-4
Category 1.4—Human/Machine Interface			
Ames Research Center	Telepresence information and environments Procedural aids for system automation Models of human vision, voice input/output, command language	Improved human/machine interface	2-3
Ames Research Center	Development and evaluation of AI technologies for autonomous systems	System and subsystem automation	3-4
Jet Propulsion Laboratory	Evaluation and analysis tools to assess the merit of automating various functions and decide where the human/machine interface should be	Optimal extent of automation and robotics utilization	4
Johnson Space Center	Development of virtual-image, helmet-mounted displays Anthropomorphic hand manipulator Automatic control of EVA cooling	More efficient extravehicular activity	2
Johnson Space Center	Advanced interface technologies—use of speech synthesis, voice recognition, and natural language integrated with expert system applications	Improved human/machine interface	3-4
Kennedy Space Center	Advancement of design capability by human/machine (CAD) interface	Improved human/machine interface	
Langley Research Center	Crew station design and evaluation —Real-time simulation —Expert system to handle human factors criteria —Integrated control and display Advanced display media—flat panels Advanced graphics —3-D displays —Multiple dynamic windowing —High performance graphic engines Advanced controls consolidation and work load reduction—voice, touch, keyboard, eye-slaved *Information management* —Concurrent processes monitoring —Intelligent automation criteria —Reconfigurable display concepts	More efficient use of crew time and work station space	2-4

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Reconfigurable remote operator station with stereoscopic video, graphics, and voice/touch control capabilities	Telepresence interface servicing and assembly More efficient use of crew time	2-4
Marshall Space Flight Center	Graphical simulation for predictive display, off-line auto-sequence display, and system checkout	Teleoperations and automated servicing and assembly	2-3
Marshall Space Flight Center	Expert system allowing non-simulation personnel to perform studies with complex simulation systems via a natural language interface	Reduced-cost Space Station simulations	4
Marshall Space Flight Center	Incorporation of 6-DOF hand controller used to operate manipulator arm	Control of remote servicer, OMV, MRMS	6
Marshall Space Flight Center	Use of force-reflecting hand controller to return force and torque information to operator	Telepresence control of servicing	6
Marshall Space Flight Center	Optimization of lighting, video camera position, and operator aptitudes for accomplishment of servicing tasks	Remotely operated servicing	3
Category 2.1—Supporting Software and Hardware			
Ames Research Center	Programming environments for expert, fault-diagnosis, and procedure-planning systems Real-time simulation and modeling Tradeoffs between human understanding and machine processing and intelligence Automated capture of design information Automated software validation and verification	Expert systems in general Optimal human/machine interfaces and task partitioning Fault-tolerant systems	2-4
Ames Research Center	A spaceborne very high speed integrated circuit (VHSIC) symbolic processor for "intelligent" processing	Advanced "intelligent" processing	2
Goddard Space Flight Center	Rapid prototype of "smart" telescience work station	Remote investigator display and control	5
Jet Propulsion Laboratory	Self-checking computer modules Autonomous management systems for redundancy maintenance Advanced high-speed computers	More reliable and efficient computing	2-3
Kennedy Space Center	Expert systems software for operational system diagnostics, test, and control embedded as firmware on system hardware	Automated diagnostics, test, and control of Space Station systems	
Kennedy Space Center	Expert system for scheduling, planning, replanning, and resource allocation	Automated system scheduling and resource allocation	
Kennedy Space Center	Higher order language for automated procedure development and systems communications	User friendly language for Space Station system operations and software maintenance	
Langley Research Center	Multiplexer with fiber optics and wavelength division to allow for high data rates and simultaneous channels of communication over a passive interconnect	Control, communication, data transmission	6

R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (continued)

Institution	Objectives of the research	Potential Space Station use	Level
Langley Research Center	VHSIC technology development —Multiplex interconnected processor to do asynchronous and spatial distributed data processing in a configuration that is fully self-testable —Algorithms to map tasks onto the processors (autonomous) —Strategic processor for joint and link trajectories —Coupling with sensor systems and image vision processing	Core processor (embeddable)	5
Langley Research Center	Multiplexer with wavelength division for a laser operating in free space to communicate over short ranges	Remote control and communication across robotic joints	2
Langley Research Center	Design and assessment methods for integrated, fault-tolerant flight control systems Methods for validating the performance and reliability of complex electronic systems A facility for research in advanced computer architectures	Fault-tolerant systems	2-3
Langley Research Center	Advanced information-network architectures —Integrated —Growable —Fault tolerant —Improved in capacity and speed of information flow	More reliable and efficient computing, data management, communications	4
Langley Research Center	Digital video that enables efficient and effective generation and reception/ display of high quality video for remote Space Station operations	Mobile remote manipulator system	2
Langley Research Center	Video image processing to enable complex decision-making for onboard human/machine interactions	Autonomous proximity operations and remote operations	3
Marshall Space Flight Center	Machine-vision system for more efficient and faster recognition of 2-D images	Higher speed remote applications	4
Category 2.2—System Design and Integration			
Goddard Space Flight Center	Test lab for robot techniques in ORU interchange	Servicing of platforms, spacecraft, and instruments	3
Johnson Space Center	Demonstration of a technique for automated control, being tested on air-revitalization components of the environmental control system	Automatic control and monitoring of Space Station subsystems	3
Johnson Space Center	Simulation, including visual displays, of docking and berthing activities among the Space Station, Shuttle, and orbital maneuvering vehicle	Development and training	2-4

Institution	Objectives of the research	Potential Space Station use	Level
Johnson Space Center	Computer augmentation/automation for integrating data formatting, computations, expert systems, displays, etc. in a distributed system	Orbital systems monitoring	2
Johnson Space Center	Support to definition of on-orbit assembly sequences and methods Berthing dynamics and simulation of orbital operations	Optimum assembly of the Space Station	2
Johnson Space Center	Expert system shells —Review capabilities of commercial tools —Pinpoint areas needing further development —Develop shells in conventional languages	Automation of Space Station functions	1-2
Kennedy Space Center	Development of a robotics test-bed to study the application of robotics to hazardous conditions such as refueling of rockets	Space servicing of satellites	2
Kennedy Space Center	Integrate distance sensing and robotic vision techniques to the control and movement of large structures	Mating, docking, and assembly activities	
Langley Research Center	Computer-aided assessment models —Space Station operations —Data management systems —Structural analyses	System design and operation	2
Langley Research Center	System validation techniques —System performance and reliability assessment methods —Emulation/simulation technology —Design-proof techniques	Validation tools	2
Langley Research Center	Acoustic environment qualification testing	Voice control systems	2
Langley Research Center	Simulation of robotic systems to define and analyze performance Test-bed for AI and robotics interfaces Intelligent control of robots, vision systems, sensors, graphics, etc. Design of a space manipulator	Improved robots and robotic control	2-6
Langley Research Center	Enhanced structural dynamics testing using artificial intelligence	Structure design	1
Lewis Research Center	Development of power system test-bed with network control to evaluate automation strategies	Autonomous electrical power system	3
Marshall Space Flight Center	Simulation, including video displays, of rendezvous and docking activities of OMV and OTV	Development and training	2-4
Marshall Space Flight Center	Simulation of teleoperator and robotic systems to define and analyze performance of manipulator test-bed for evolutionary automation, manipulator control systems, and sensor interfaces	Improved teleoperator and robotic systems	3-5
Marshall Space Flight Center	Autonomous management of large spacecraft power system	Electrical power system automation	4

R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (continued)

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Determining expert systems applicability and rapid prototyping for common-module electrical power system	Electrical power system automation	2
Marshall Space Flight Center	Flexible simulation of robot kinematics, dynamics, and control, allowing experiments in new manipulator designs, AI, and planning and control of robot paths	Reduce costs in evaluating new methodologies	6
Marshall Space Flight Center	Simulation and analysis of vehicle-contact dynamics using moving platform and force/moment sensors to determine vehicle interactions in space	Design, evaluation, and verification of berthing, docking, latching, and servicing mechanisms	6
Marshall Space Flight Center	Utilization of the intermeshing end effector to interface with EVA-compatible tasks	Servicing and assembly	4
Marshall Space Flight Center	Hardware system for autonomous docking utilizing high-accuracy solid-state sensors	OMV and Space Station docking and berthing	3-4
Marshall Space Flight Center	Expanded simulation capability to support studies of the OMV, free-flyers, the MRMS, and the common module	OMV and OTV payload berthing Space Station maintenance and inspection	3-5
Marshall Space Flight Center	Demonstration of intelligent robotic servicing including —Task automation —Reflexive manipulator control —Sensor fusion —High fidelity task simulator —Prototype hardware	Evaluation of ORU designs, servicing techniques, sensors, controllers	2
Marshall Space Flight Center	Neutral buoyancy simulation to provide EVA crew training and support for development of payloads requiring telerobotic or manned maintenance or servicing	Design of serviceable items for space Servicing techniques	6-8
Category 2.3—Knowledge-Based or Expert Systems			
Goddard Space Flight Center	Fault diagnosis for TDRSS communications	Automated Space Station monitoring and safety	5
Goddard Space Flight Center	Technology Development Mission (TDM) experiment—expert systems for planning and scheduling	Payload automation	2
Goddard Space Flight Center	Expert systems for planning satellite operations and for scheduling and managing the network control center	Payload data systems management	3-4
Goddard Space Flight Center	Fault diagnosis for local area networks	Automated fault detection and correction	5
Jet Propulsion Laboratory	Expert systems for forming and testing hypotheses, planning configurations of systems, and planning schedules	Operations	2
Jet Propulsion Laboratory	Expert system application of electric power management including interactive load scheduling	Onboard operations	2

R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (continued)

Institution	Objectives of the research	Potential Space Station use	Level
Johnson Space Center	Expert systems for designing simulation software for —Design of control systems for flexible structures —Rendezvous and approach planning —Task interpreter for intelligent end effector	Proximity operations Manipulator operations	3
Johnson Space Center	Expert systems for Space Station avionics	Power management Optical attitude reference Electric mate/demate for robotic applications	2
Johnson Space Center	Expert system prototyping	Navigation, flight analysis and orbit determination Monitoring mission control software Scheduling power use	3-4
Kennedy Space Center	Expert system for Shuttle cargo processing schedules and detailed "subschedules"	Logistics planning and support	2
Kennedy Space Center	Expert system for scheduling cargo directly from the manifests for each Shuttle flight	Logistics management	3
Kennedy Space Center	Expert systems for diagnosing liquid oxygen system faults and identifying candidate causes	Automated fluids management	5
Kennedy Space Center	Knowledge-based automatic test equipment that will design, execute and control tests and analyze results	Laboratory and station operation	2
Kennedy Space Center	Expert systems for weather forecasting for Shuttle launch and landing	Logistics planning	2
Lewis Research Center	Expert systems, simulators, and facilities for studies in power management	Mission planning and scheduling for power growth and loads Onboard power management —Generation —Storage —Load distribution —Access to power system —Configuration —System monitoring —Fault and trend analysis	2-4
Lewis Research Center	Expert system for structural analysis Robotic manipulators and positioners State-estimation methodology	Power system analysis and control	2-3
Lewis Research Center	Expert systems to increase productivity and provide aid to new employees at the center	Program management	2
Marshall Space Flight Center	Fault diagnosis expert system for the test-bed for Space Telescope battery power	Fault diagnosis for various subsystems	2
Marshall Space Flight Center	Fault isolation expert system for electrical power	Fault isolation for various subsystems	4

R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (concluded)

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Electrical load expert systems for the common module that match the use of dynamically changing resources with available/proper electrical loads	Both off-line and near-real-time planning and scheduling	2
Marshall Space Flight Center	Expert system that plans the use of shared resources for Spacelab experiments and operations	Mission planning and operations onboard Space Station	6
Marshall Space Flight Center	Expert system to aid in more effective utilization of the Spacelab payload crew training complex (PCTC)	Crew training and onboard operations	4
Category 2.4—Robotic and Telerobotic Systems			
Goddard Space Flight Center	Techniques for changing food cassettes, fixing specimens, drawing blood, and sampling and controlling wastes	Automated life science laboratory management	2
Goddard Space Flight Center	Design of ORUs, including tooling, manipulators, sensors, automatic control, and human interface Standardization of interfaces Uses of robotics	Servicing free-flying satellites, scientific payloads, and platforms	2
Jet Propulsion Laboratory	Three-dimensional computer recognition of moving targets made up of complex polyhedra	Robotic recognition of targets to be manipulated or serviced	3
Johnson Space Center	A telerobotic work station with capability equivalent to a suited astronaut	EVA servicing or repair activities	3
Langley Research Center	Systems-level research in robotics —Evolution from teleoperation to a goal-directed robot —Integration and analysis of the total robot system —Dual-arm coordination	Complete "integrated" robots	3
Marshall Space Flight Center	Robotic engine-welding system using off-line path planning and a vision sensor to correct the robot path in real time	Robotic use in manufacturing of propulsion systems and in on-orbit welding	3-6
Marshall Space Flight Center	Robotic system for removing solid rocket booster thermal protection during rework	Automated processes in the space environment	4-6
Marshall Space Flight Center	Integrated orbital servicer system for predefined ORU replacement	Automated servicing	5
Marshall Space Flight Center	Interchangeable tools for use by manipulator arm in servicing, assembly, and maintenance	Servicing, assembly, and maintenance	3-4

Notes

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16. Abstract

In April 1985, as required by Public Law 98-371, the NASA Advanced Technology Advisory Committee (ATAC) reported to Congress the results of its studies on advanced automation and robotics technology for use on the Space Station. This material was documented in the initial report (NASA Technical Memorandum 87566).

A further requirement of the Law was that ATAC follow NASA's progress in this area and report to Congress semiannually. This report is the second in a series of progress updates and covers the period between October 4, 1985, and March 31, 1986.

NASA has accepted the basic recommendations of ATAC for its Space Station efforts. ATAC and NASA agree that the thrust of Congress is to build an advanced automation and robotics technology base that will support an evolutionary Space Station Program and serve as a highly visible stimulator affecting the U.S. long-term economy.

The progress report identifies the work of NASA and the Space Station study contractors, research in progress, and issues connected with the advancement of automation and robotics technology on the Space Station.

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