NASA Technical Memorandum 100777

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

Progress Report 5 — May 16, 1987 Through September 30, 1987

Advanced Technology Advisory Committee
National Aeronautics and Space Administration

Submitted to the
United States Congress
October 1, 1987

NASA
National Aeronautics and
Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

Synopsis

This report is the fifth semiannual progress report on automation and robotics (A & R) for the Space Station by the NASA Advanced Technology Advisory Committee (ATAC).

During this report period, as in previous report periods, ATAC's assessments were presented to the Associate Administrator for Space Station and his senior staff. The presentation described

- ATAC's background, including the Congressional mandate
- A change in the nature of ATAC from assessments of what A & R will be needed and what will be available for the Space Station Program to evaluations of the A & R applications included in the Space Station Program.
- Significant progress of the Space Station Program in the areas of automation and robotics
- Space Station Program needs in the areas of automation and robotics
- Recommendations for improvements in automation and robotics for the Space Station

In addition, ATAC provided a similar presentation to the National Research Council. We are also planning meetings with the other NASA Associate Administrators to further inform them of what the committee is attempting to accomplish.

The Space Station Program management has continued to be supportive of ATAC's efforts and has increased its own efforts to emphasize A & R and to implement the committee's recommendations. The principal deficiencies noted in our previous progress report were acknowledged by Space Station Program management and corrective steps have already been initiated.

As in previous progress assessments, the committee finds substantial areas of laudable progress and some areas requiring future attention.

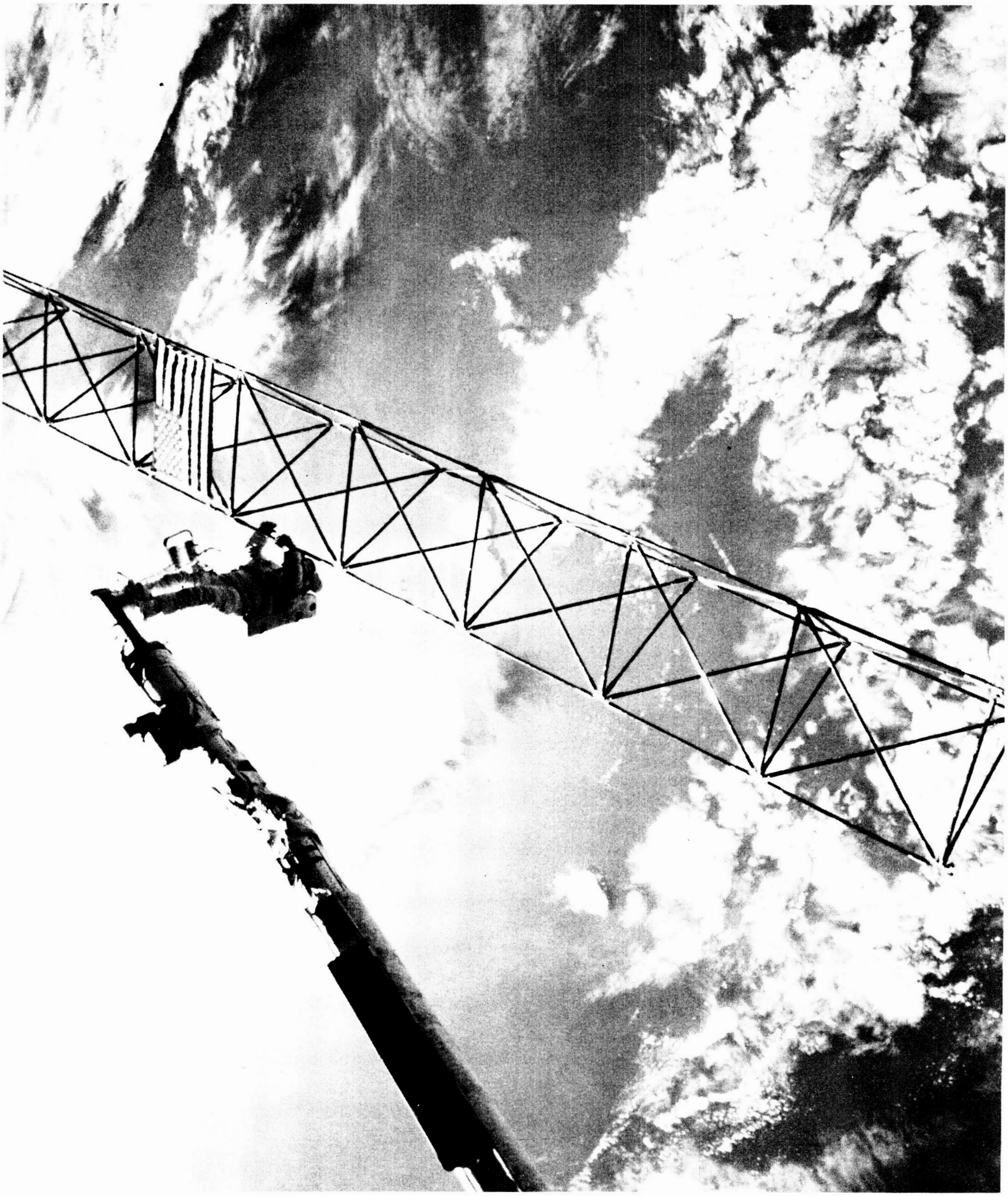
Areas of Progress

- The Space Station Program management is increasingly aware of the need for and the advantages of A & R. As evidence of this increasing awareness, the Office of Space Station sponsored a 1-day, "Managers' Seminar on Artificial Intelligence," which was attended by senior management at levels A, A', and C, including the Associate Administrator. The seminar was presented by Digital Equipment Corporation.
- There is an increasing responsiveness of Space Station Program management to the ATAC recommendations as evidenced by the following:
    - The Associate Program Director, reporting directly to the Program Director, has been established as the focal point for A & R in the Space Station Program.
    - Each of the operating groups, at level A', is in the process of appointing an individual to function as an A & R focal point. This person will support the Associate Director in the areas of A & R.
    - Priority has been given to staffing for A & R, including interim staffing with detailees. In addition, the Program Requirements and Assessment Office has been assigned to document Space Station A & R requirements and to assess the program's response to these requirements.
    - Priority has been given to the prime program support contractor, Grumman Aerospace Corporation, to support the development of the A & R plan.
- The requests for proposals (RFP's) for the Space Station design and construction phases (phase C/D) reflect a considerably stronger program motivation for A & R than was evident during phase B. Proposers are being asked to develop specific plans that address the whole implementation process for A & R. Requirements also include critical plans for design knowledge capture and data on life cycle cost benefits of A & R.
- Six competitive prime contractor proposals have been received for the Flight Telerobotic Servicer (FTS) phase B contract. The proposals include a broad spectrum of subcontractors representing an involvement of many universities and small, innovative companies that have entered the A & R fields.
- Plans for the FTS program include trade-off studies on mobility and on the levels of autonomy for the FTS.

- A memorandum of understanding between the NASA Office of Space Station (OSS) and the Office of Aeronautics and Space Technology (OAST) is being developed with the objective to facilitate the transfer of systems autonomy technology between the two programs. It will complement the memorandum of understanding on telerobotics described in our previous report.
- The prime contractor, Boeing Computer Services of Seattle, was selected to implement the Technical and Management Information System (TMIS). A work plan for the first phase of TMIS development is underway, pursuant to an early 1988 assessment. TMIS specifically addresses ATAC's recommendation number 7, that "The techniques of automation should be used to enhance NASA's management capability."
- The prime contractor, Lockheed Missiles and Space Corporation of Sunnyvale, was selected to implement the Software Support Environment (SSE) for the Space Station Program. The SSE will provide the environment for the development, delivery, integration, verification and validation, and the sustaining engineering of operational software for the Space Station Program.
- A special emphasis group for advanced automation has been established within the Space Station Operations Management System infrastructure.
- OAST has developed a Systems Autonomy Technology Program plan with a horizon of approximately 10 years. Approvals are in process. The plan includes core technology areas and demonstration projects in thermal control and electrical power systems.
- The Office of Space Sciences and Applications (OSSA) initiated a $2 million, 12-month Telescience Test-Bed Program to identify approaches for exploiting advanced information technology in the conduct of science in space.
- OAST, under the auspices of the Office of Science and Technology Policy (OSTP) Committee, is leading an effort to define a technology program for improving the reliability of large scale, real-time software. NASA provides special expertise in the areas of artificial intelligence, software engineering, and simulation.
- OAST's In-Space Technology Experiments Program received 25 Outreach and 6 Inreach proposals in the areas of automation and robotics.
- The Environmental Research Institute of Michigan has been selected by NASA as a Center for the Commercial Development of Autonomous and Man-Controlled Robotic Sensing Systems in Space. The University of Wisconsin had been selected in 1986 to establish a Center for the Commercial Development of Space, specializing in space automation and robotics.

Areas Requiring Future Attention

- Although the work package phase C/D requests for proposals reflect a considerably stronger motivation for A & R than was evident during phase B, the work package phase C/D requests for proposals, do not, in general, project a strong commitment to A & R. Automation and robotics, again in general, are not treated as an integral approach to building the Space Station. ATAC has recommended to NASA that phase C/D contract negotiations include, as a focus, the A & R content of the Space Station.
- Priority has been given to the development of the A & R plan for the Space Station Program. However, the workload required to fashion such a program by the Program Requirements Review (PRR) is staggering, especially considering the need to integrate across work packages.
- Due to the late start of the FTS, its functional integration with the rest of the Space Station is not adequate in the work package RFP's. The committee has recommended that the Space Station Program pay specific attention, early in phase C/D, to the design of the Space Station so that it will be "robot friendly" to the FTS.
- Although there is significant management attention to the need to minimize operations as well as design costs, criteria are not yet available for life cycle costs which would place A & R in a more favorable light. The committee has recommended that level A' and the work packages use the results of life cycle cost analyses as a factual basis for decisions on the inclusion of A & R candidates.
- The work package RFP's require proposals for the development of design knowledge capture plans. However, they will not be as timely as desired. Also, there are interfaces with the TMIS and the SSE to be specified. The committee has recommended that workshops and industry contracts be conducted to address this issue.



Astronaut Sherwood C. Spring, standing on the end of the remote manipulator system (RMS) arm, checks joints on the assembly concept for construction of erectable space structures (ACCESS) tower extending from the cargo bay of the Space Shuttle Atlantis. *(Photo taken November 27, 1985.)*

ORIGINAL PAGE IS
OF POOR QUALITY

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 studies on automation and robotics (A & R) technology for use on the Space Station. A further requirement of the law was that ATAC follow NASA's progress in this area and report to Congress semiannually. In this context, ATAC's mission is considered to be the following:

> ***Independently review the conduct of the Space Station Program and assess the integration of A & R technology. Based on assessments, develop recommendations, review the recommendations with NASA management, and discuss their implementation with consideration for safety, reliability, and cost effectiveness. Report assessments and recommendations twice annually to Congress.***

This report is the fifth in a series of progress updates and covers the period of May 16, 1987, through September 30, 1987. (However, progress and program changes occurring after August 31, 1987, are not reflected in this document.)

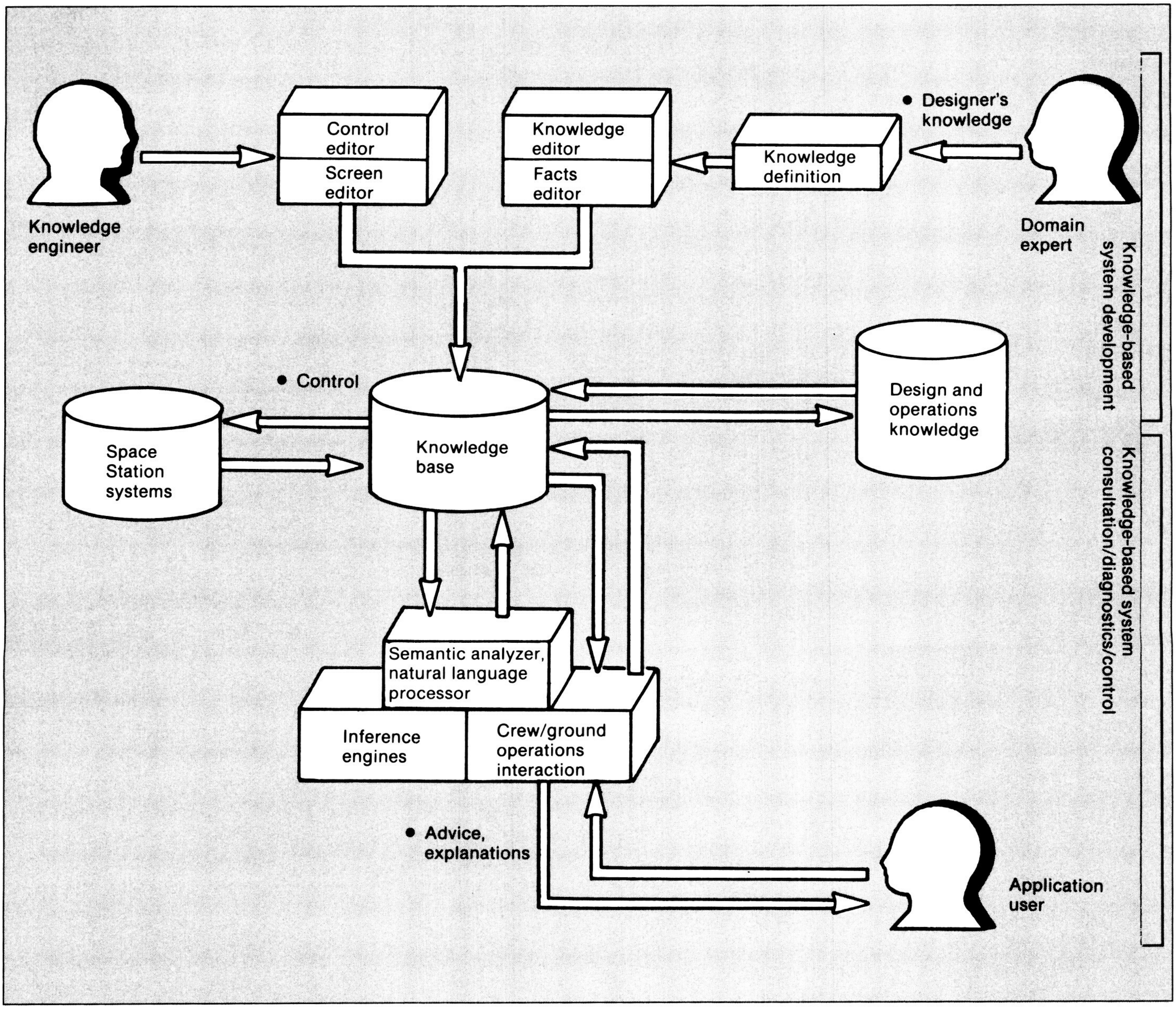
ATAC appreciates the cooperation of Space Station Program management and many organizational elements and personnel in providing presentations and background materials necessary for the committee to conduct its assessment and to prepare this report.

EVA STS-61A

Teleoperator ORNL M-2

A joint study of the capability of current telerobotics technology to accomplish realistic space assembly was conducted by NASA and the Oak Ridge National Laboratory (ORNL). The study demonstrated the capability of teleoperated assembly of the NASA ACCESS experiment truss. The teleoperated assembly used the dual-arm, six-degree-of-freedom teleoperated manipulator of the ORNL, shown on the right. The ACCESS truss had previously been assembled in space by Space Shuttle EVA astronauts on STS-61B in November 1985, shown in the photo on the left. In the ground-based repetition of the construction, the teleoperated system assumed the role and position of each astronaut (one at a time) during inflight construction. The investigations will continue, using other manipulator systems and more-representative Space Station hardware. Portions of the assembly will be automated, reducing the time required for direct operator control. (Courtesy of Langley Research Center.)

Contents



Knowledge-based systems have potentially wide application to Space Station operations. A knowledge-based system contains a body of knowledge, a means of interpreting that knowledge, and a means of making the knowledge available either for advice to an operator or for direct action with a Space Station system. The body of knowledge, called a knowledge base, contains English-like expertise, facts, and controls. The knowledge may be heuristic, i.e., rules of thumb gained from experience, or it may be causal conceptual models needed to handle the unusual or novel occurrence.

There are tools that, to an expert or knowledge engineer, are analogous to what spreadsheet software are to persons in business. These tools constitute a general-purpose system, sometimes called a knowledge-based system shell, for quickly and easily constructing and executing knowledge-based systems. During development and update of the knowledge-based system, knowledge acquisition is aided by the set of procedures in the shell into which knowledge is inserted. The knowledge representation in the knowledge base and the problem solving methods contained in the inference system are closely related.

During operations, which may be on a different processor, the inference system which contains the control knowledge uses the active knowledge to manipulate the facts and to infer new ones through its problem solving or reasoning strategy. User input may be to a natural language processor. An explanation facility may answer questions about how a conclusion was reached, how another alternative was rejected, why some information was rejected; or it may ask permission to take an action.

Introduction

In response to the mandate of Congress, NASA established, in 1984, the Advanced Technology Advisory Committee (ATAC) to prepare a report identifying specific Space Station systems which advance automation and robotics technologies. The initial ATAC report was submitted April 1, 1985 (ref. 1) and proposed ***goals*** for automation and robotics applications for the ***initial*** and ***evolutionary*** space stations. Additionally, ATAC provided ***recommendations*** to facilitate the implementation of automation and robotics in the Space Station Program. These recommendations were accepted as ***policy*** by NASA.

ATAC has continued to monitor and to report semiannually NASA's progress in automation and robotics for the Space Station, as additionally mandated by Congress. The first two years of progress is documented in ATAC Progress Reports 1 through 4 (refs. 2 - 5). In these semiannual progress reports, ATAC has documented progress, identified areas of concern, and provided further recommendations to NASA management.

As previously projected, this report covers a period of time in the Space Station Program during which there are relatively fewer reportable results of progress in automation and robotics (A & R). The report period covers a time frame between phase B and phase C/D of the Space Station Program. The focus of the Space Station Program during this period has been on establishing facilities and staff for future program management, completing and releasing the RFPs for phase C/D of the Space Station Program, and evaluating proposals and selecting contractors for phase C/D. During this period, funded contractual efforts are reduced, and communications are constrained for NASA personnel due to agency involvement in contract source evaluation boards.

ATAC has taken the opportunity to examine the Space Station work package requests for proposals, and in addition, the committee conducted a review of selected topics on June 25 and 26, 1987. The review topics included the following:

- The Space Station Program organization and its plans for automation and robotics
- OAST progress and its plans for systems autonomy and telerobotics
- The Space Station Operations Task Force Study
- The Space Station Operations Management System
- The progress of the Flight Telerobotic Servicer
- The NASA Technical and Management Information System
- The NASA/USAF Space Assembly, Maintenance, and Servicing Study
- The NASA Satellite Servicing Workshop
- The Evolutionary Automation Architecture Study by MITRE Corporation
- Langley Research Center activities in A & R
- Goddard Space Flight Center telerobotic systems demonstrations videos
- Activities of the Expert Systems Working Group

The committee review, along with the requests for proposals, are the primary sources of information for this report. An assessment of progress with respect to the ATAC recommendations is given in the following section. This assessment, along with the synopsis, provides a top-level view of progress for this reporting period.

In making its assessments, ATAC is mindful of key points relating the context of A & R to NASA's challenges in developing and operating the Space Station. These key points are listed below.

- Advanced automation and robotics are new fields that promise great benefits in manned space missions.
- The commitment to advanced A & R and the costs of development and implementation are all "up front", early in the program, while the cost benefits and increased technical performance will come later, during the operational phase of the program.
- Good management will not use a system as part of their design unless they have acquired confidence in it. Confidence can be obtained in advanced A & R systems only as a result of successful demonstrations and testing, because there are no "off-the-shelf" systems for advanced A & R.
- ATAC holds a firm belief that incorporating advanced A & R in the evolutionary Space Station is essential. An equally firm belief is that appropriate design accommodations must be incorporated in the baseline Space Station to allow the evolutionary Space Station to incorporate advanced A & R. The most important design accommodations are (a) all functions and all information necessary for control of the systems shall be accessible through the Space Station Data Management System (DMS), and (b) both the functions and the information will be accessible by both ground and spaceborne computers.

Progress With Respect to ATAC Recommendations/ NASA A & R Policy

As in the previous reports, this section provides a summary assessment of NASA's progress toward fulfilling the committee's original recommendations adopted as Space Station Program policy. 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.

Automation and robotics for the Space Station have received agency-wide attention. The requests for proposals for phase C/D of the Space Station Program all address automation and robotics. The phase B contractor studies indicate a wide ranging potential for A & R, starting with the initial station. Yet, the committee can not project the extent to which A & R will be incorporated into Space Station design and operations until phase C/D contracts are negotiated and the results are reported by the work package centers.

Staffing has begun and plans have been initiated for the level A' organization to perform integration studies and to provide A & R coordination across the Space Station Program. Importantly, the Associate Program Director, reporting directly to the Program Director, has been identified as the focal point for A & R in the Space Station Program. Individuals are being appointed as focal points in each of the operating groups at level A' to assist the Associate Director in executing his responsibility. ATAC is encouraged by this positive response to its previous recommendation that a strong management organization with authority at level A' be established. This is now being accomplished and should provide the top-level program-wide consideration required for A & R. Level A' has also initiated and placed high priority on the development of an integrated A & R plan as recommended by ATAC in Progress Report 4.

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

ATAC considers this the top-priority recommendation. This recommendation is especially critical because of the rapid advances being made and projected to be made in automation and robotics technologies and because of the projected benefits of these new technologies. Again, the content of the phase C/D contracts will be critically important.

Reviews of the Space Station data system requirements indicate their architectures should accommodate evolving A & R technologies. The Space Station Information System (SSIS) should provide access to the Space Station data bases by both flight and ground elements, according to current requirements. A special emphasis group on advanced automation is being established within the Space Station Operations Management System (OMS) to provide assistance to OMS development.

A continuing concern of the committee is in the area of design knowledge capture. The capture of design, design rationale, and operations data in electronic formats is required for integration, for sustaining engineering, and for evolution to knowledge-based systems that are necessary for systems autonomy and for use by intelligent robots. The timely development of a design knowledge capture process which could be implemented at the start of phase C/D by each program participant was not accomplished in phase B. Consequently, a set of requirements has not been levied upon the Software Support Environment (SSE) for the development and sustaining engineering of design knowledge data, nor have plans for analysis capabilities and the use of knowledge bases been developed. Neither have the requirements for relational data bases with regard to design knowledge been levied on the Technical and Management Information System (TMIS).

However, the general requirement for design knowledge capture was specified in phase B in the form of a design knowledge process requirements document, and it has been incorporated into each of the phase C/D work package requests for proposals. Each work package contractor will be required to develop a plan for design knowledge capture. It will be critically important for these plans to be funded and for the Space Station Program to integrate these plans early in phase C/D to establish compatible data structures for the various subsystems and to minimize the loss of important early design data.

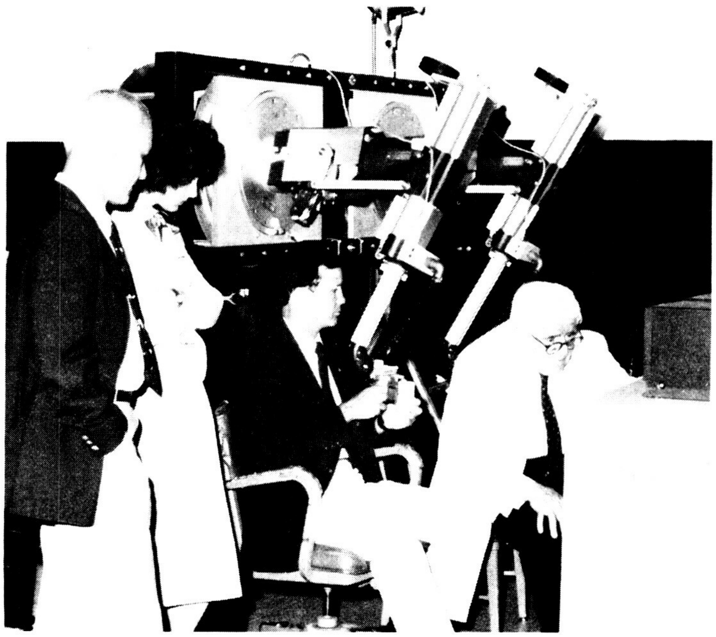
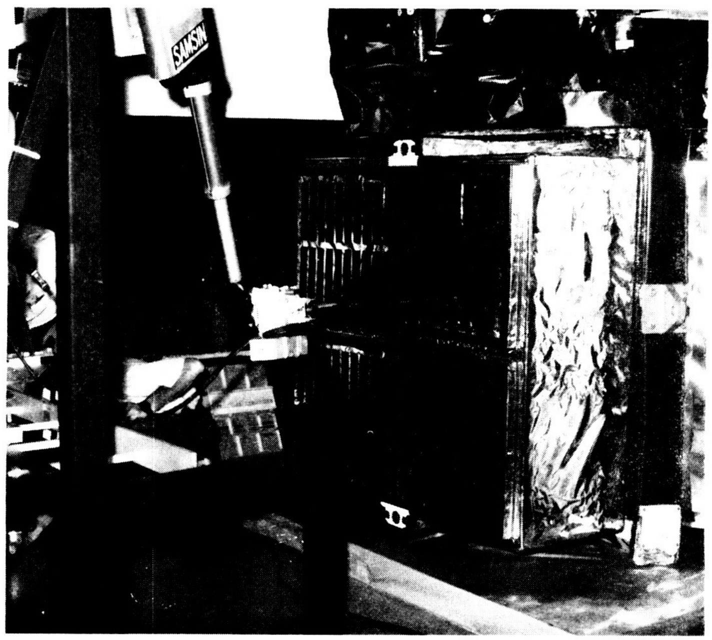
A second concern is that the Space Station Program did not adopt a set of design standards during phase B which would guide the Space Station design to facilitate systems autonomy and to be "robot-friendly" for the evolutionary station. Space Station compatibility with the FTS will be implemented by level A' when FTS performance characteristics have been established. A design guidelines manual (ref. 6) was prepared, based on phase B contractor studies, but it was not included as a reference document in the phase C/D work package requests for proposals. The Space Station Program needs to address the issue of design standards in an integrated approach early in phase C/D.

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

As previously reported, ATAC can not yet ascertain the degree to which automation will be incorporated into the initial Space Station. It is the committee's view, based on the Space Station baseline configuration, initial design costs, and the preliminary report of the Space Station Operations Task Force, that the initial Space Station will primarily use conventional automation and will be largely manual in its space operations with modest advanced automation in the ground elements. This may be temporarily acceptable if adequate provisions are made for advanced development and for future accommodations of advanced technologies.

Important research and development in A & R technologies is being carried out throughout NASA, as shown in Appendix F. This work is being conducted in-house and by universities, industry, and other government agencies. Progress continues to be made in the planning, research, and development supporting the Flight Telerobotic Servicer. Early ground demonstration tests of teleoperation concepts were conducted for truss assembly and for orbital replaceable unit (ORU) changeout. In addition, a commercial nuclear organization demonstrated the ability to accomplish remotely the three repair tasks performed on the Solar Maximum Mission satellite from the Space Shuttle.

The committee is cognizant that the movement of facilities into resource nodes and the deferral of many of the EVA-intensive activities will result in less demand on the FTS than was initially envisioned. The functional capabilities of the FTS to support assembly, maintenance, servicing, and inspection activities will be demonstrated during phase I operations, and therefore will provide the expected technology driver to benefit the U. S. economy. Extensive use of the FTS is projected for the evolutionary Space Station. FTS functional capability enhancements that are planned for the evolutionary Space Station will continue to act as a technology driver for the U. S. economy.

The Central Research Laboratory (CRL), a firm serving the commercial nuclear industry, demonstrated the ability to remotely perform the three repair tasks conducted on orbit from the Space Shuttle during the STS-41C Solar Maximum Repair Mission. The demonstration used the CRL's dual remote digitally-controlled bilateral force-reflecting master-slave manipulator system and adapted manual and battery-powered EVA tools. A subset of these tools was used by astronaut Captain Bruce McCandless to perform repair tasks, in order to gain insight into crew interaction with the robotic system.

The tasks consisted of the following: (1) the replacement of a 28-pound Solar Maximum Mission payload Coronagraph/Polarimeter main electronics box; (2) the replacement of a 4 by 4 by 1 1/2 foot, 450-pound, multimission modular spacecraft attitude control subsystem module; and (3) the installation of a 1-pound X-ray polychromator plasma baffle in a 2-inch by 3-inch hole. The main electronics box exchange involved performing a highly dextrous, 31 page EVA sequence, using 10 tools. Among the steps required were the removal and reinstallation of 14 cap screws (No. 10-32), removal of 22 slotted-head screws (No. 4-40), and the removal and reinstallation of 11 subminiature cable connectors, containing 362 active leads.

The photo on the left shows operation of the master-slave system. The photo on the right shows the removal of one of the screws. (Courtesy of Goddard Space Flight Center).

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

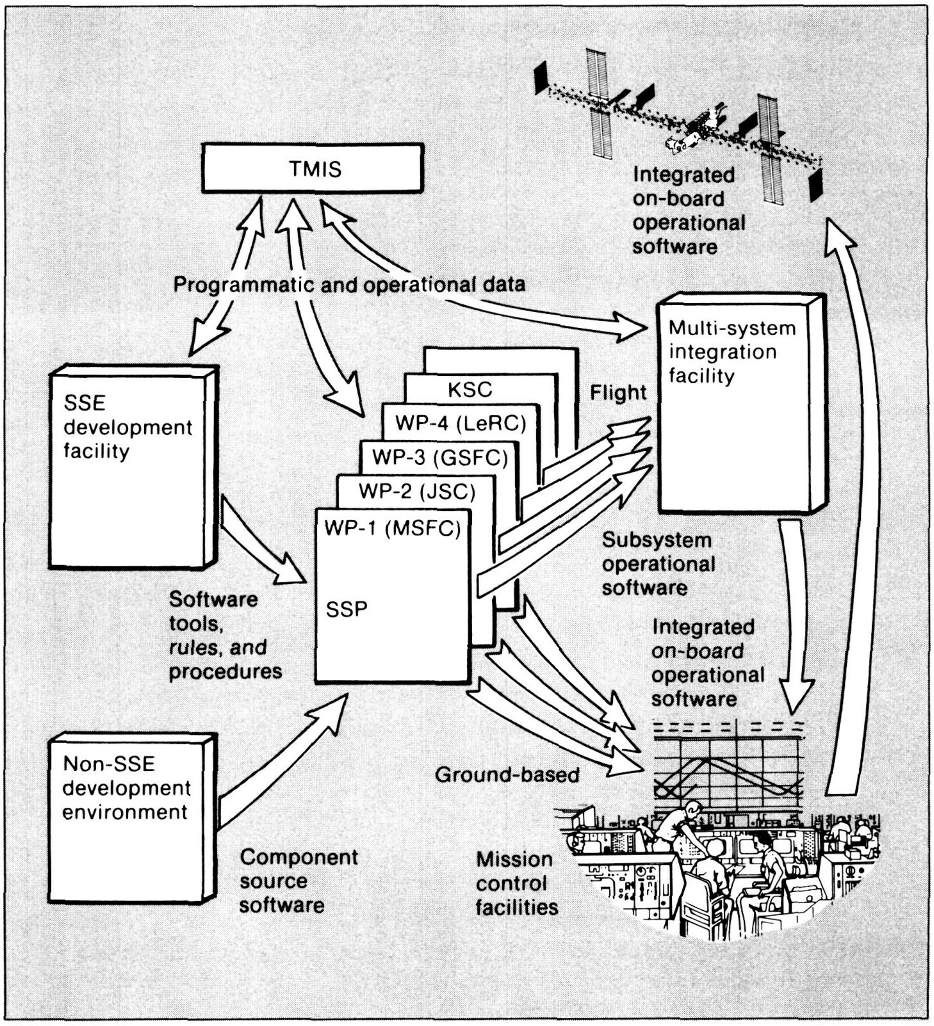
Criteria were developed during phase B and are cited in the phase C/D requests for proposals. The level A' organization has announced plans to conduct analyses, schedule and cost estimates, and priority ranking during phase C/D.

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

Plans for the FTS include both terrestrial and Space Shuttle demonstrations prior to first element launch of the Space Station. Joint OSS and OAST systems autonomy demonstrations are being conducted for the Thermal Control System and are planned for the Electrical Power System. A workshop which addressed the specific issue of verification and validation of expert systems was held at the Ames Research Center. Additional research is needed in this area.

During this report period, the contractor was selected for the Space Station Software Support Environment development. Lockheed Missiles and Space Corporation of Sunnyvale was awarded the prime contract. The Software Support Environment (SSE) System will play a critical role in development, delivery, integration, verification and validation, and sustaining engineering of operational software for the Space Station Program. The SSE System will be a wide-area network of computing facilities designated as the total resource for development of operational software for the entire Space Station Program. The SSE, as it is made operational in the SSE System, will include software, procedures, standards, hardware specifications, documentation, policy, and training materials to support software development. Therefore, the SSE will contain and support all software implementing automation technology.

For all software supported by the SSE, three important issues shall be addressed: (1) life cycle costs of sustained engineering of space mission software (seen to be increasing while the cost of hardware is decreasing); (2) the migration of mission control software from ground to flight; and (3) minimizing software integration issues between work packages while establishing one set of operational software to be sustained. There will be one SSE System facility, designated the Multi-System Integration Facility, used for integration, testing, acceptance testing, and delivery of flight operations software prior to transmission to the onboard Data Management System (DMS). Should



The Space Station Software Support Environment (SSE) System will play a critical role in the development, delivery, integration, verification and validation, and the sustaining engineering of operational software for the Space Station Program (SSP). The SSE is an integrated set of tools, rules, and procedures which will govern the entire life cycle of all SSP operational software. The SSE System will be established through a wide-area network of commercial hardware and software facilities in the Space Station Program. Operational software will originate in and will be sustained by the SSP production facilities. Flight software will be passed through the Multi-System Integration Facility prior to delivery to the Space Station onboard Data Management System (DMS). Non-SSE production facilities will implement software through the SSP production facilities. All SSE System elements will interact with the Technical and Management Information System (TMIS) for programmatic and operational data.

ORIGINAL PAGE IS
OF POOR QUALITY

the need arise for an additional integration facility for other elements of the Space Station Program, any SSE System facility could serve in this role.

At the present time, there has been no specific requirement levied on the SSE to support unique requirements of advanced automation such as knowledge-based systems. However, the proposed SSE design utilizes knowledge-based systems and other advanced automation concepts (e.g. automated project management/configuration management, project object data bases/management, software qualification for reusability) that require unique advanced automation implementation methodologies.

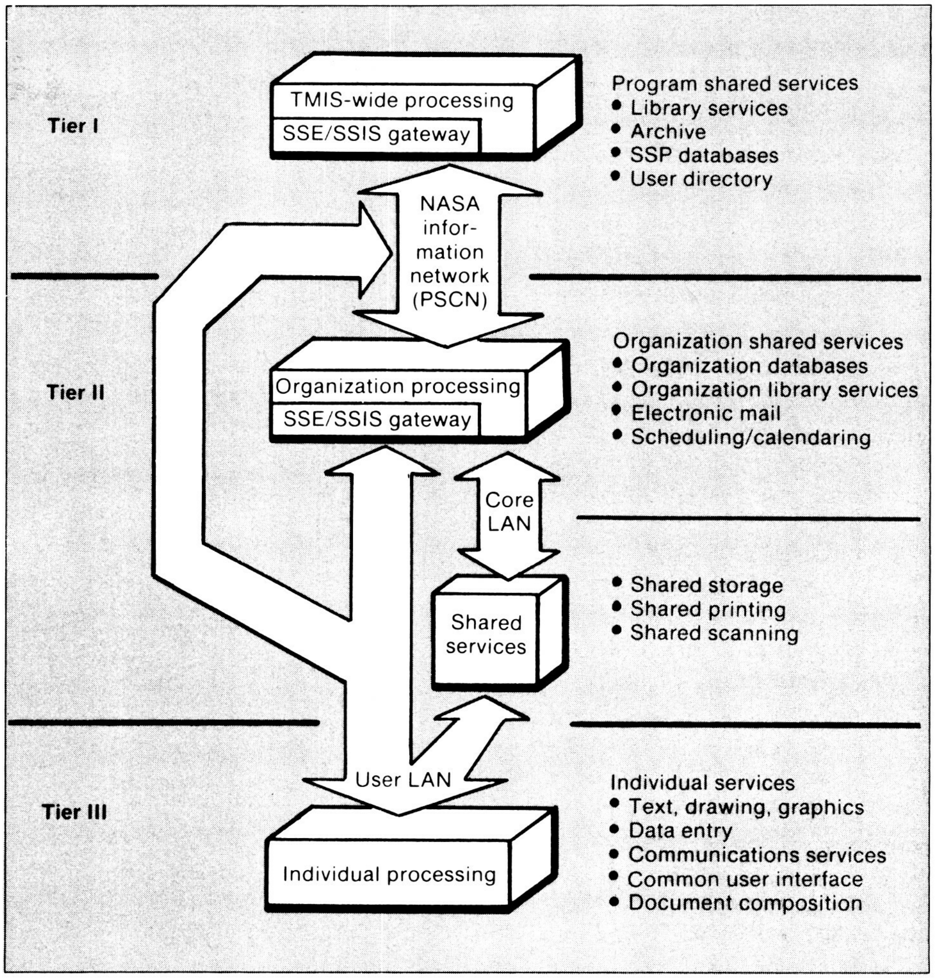
6. Maximum use should be made of technology developed for Industry and Government.

As noted in our previous report, we believe the Space Station Program enters phase C/D with the background understanding required for effective use of technology developed for industry and government. However, the Space Station Program may need to consider special incentives to provide for incorporation of new technologies as the Space Station design and operations mature.

NASA has selected the Environmental Research Institute of Michigan as a Center for the Commercial Development of Autonomous and Man-Controlled Robotic Sensing Systems in Space. This Center will develop technology for commercial use in space and will facilitate the transfer of technology between NASA and industry.

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

The NASA Administrator has given approval to the first phases of



NASA's Technical and Management Information System (TMIS) will provide integrated data processing communications services for the management of Space Station information. The conceptual design of TMIS is a 3-tiered architecture that will provide these services at the program, organizational, and user levels. Both hierarchical (vertical) and pier-to-pier (horizontal) services are provided to facilitate information access. Electronic communications are provided through local area networks (LAN's) and the NASA Program Support Communications Network (PSCN). The Space Station Software Support Environment (SSE) and the Space Station Information System (SSIS) will also access TMIS. (Courtesy of TMIS-Boeing Computer Services, Seattle.)

implementation of the Technical and Management Information System. Boeing Computer Services of Seattle has been selected as the prime contractor and it has initiated the effort indicated in the accompanying illustration. The TMIS objective is to provide the following, agency-wide:

- An information system which will provide a repository to store and secure data and which will provide a conduit to move data from the producer to the user
- A set of tools (hardware, software, networks) to assist in the generation and use of data
- A service which complements existing NASA resources (data systems and procedures) in order to provide Space Station Program level information integration

The concept is considered to be responsive to the committee's original recommendation by

- The use of CAD/CAM/CAE
- The use of office automation
- The implementation of an electronic technical and management information system

It is critically important for TMIS to support the management of design knowledge data. However, the requirements have not been levied on TMIS by the program.

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

The committee has not noted any significant activity in this area during this report period but anticipates this will become part of the A & R plan to be developed by the Space Station Program level A'.

Recommendations for an augmented program

Recommendations 9 through 13 were made contingent on an augmented program that would enhance the technology base and accelerate research and development. Augmentation has been provided for development of the FTS as described in previous reports. This augmented effort directly addresses aspects of Recommendations 9 and 13. Recommendation 9 is that *"The initial Space Station should use as much A & R technology as time and resources permit,"* and Recommendation 13 is that *"Satellites and their payloads accessible from the Space Station should be designed, as far as possible, to be serviced and repaired by robots."*

Progress on Plans for A & R in Space Station Operations

In April 1985, at the request of the NASA Associate Administrator for Space Station, an independent industry panel of respected operations experts met to obtain an evaluation of and to provide advice on Space Station operations. In their report (ref. 7) the panelists recommended that the Space Station Program should be operations driven and that the operations should be customer driven. The panel recognized that the operations baseline is at the top of the Space Station Program hierarchy and should drive the design. The panel suggested a task team be established for the purpose of providing a comprehensive operations baseline. The importance of the "use of robotics, automation, and artificial intelligence", together with judicious use of ground support and reliable systems as "means for reducing crew workload" was emphasized. It was also recommended that "consideration should be given to the use of automation to minimize the requirements for ground controllers." Subsequent phase B contractor studies have indicated that significant safety, productivity, and cost benefits can be derived from automation and robotics applications.

Space Station Operations Management System

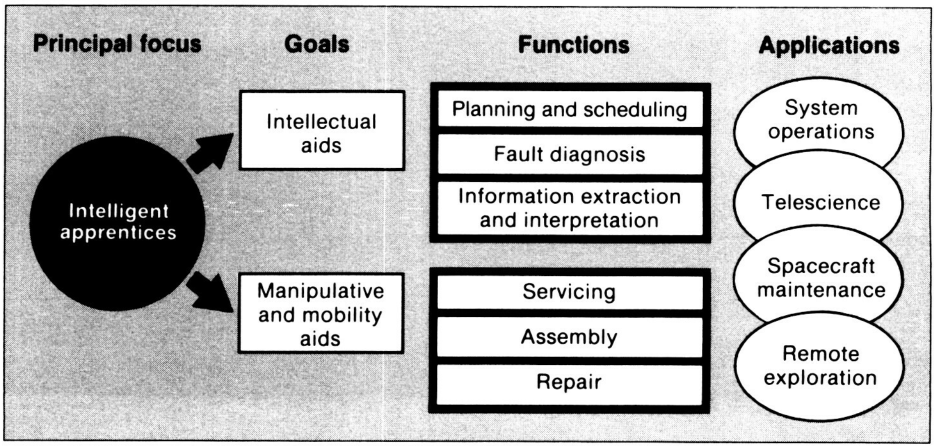
One key provision in which operations has influenced the Space Station design is the Operations Management System (OMS). The OMS will account for the distributed nature of the Space Station by providing the Space Station base with selected real-time and near real-time operations management services which will require coordination between Space Station subsystems and flight elements. The Space Station subsystems and flight elements will provide information to the OMS and will respond to directions from the OMS, using the monitoring and control capabilities of the subsystems and flight elements. The OMS functions are listed below.

- Manage and update the short-term plan
- Coordinate systems, elements, payloads, and crew operations in the execution of the short-term plan
- Monitor system, element, and payload status
- Manage inter-system, element, and payload testing
- Maintain and log station-wide configuration, activity, and state information
- Detect and manage resource conflicts
- Manage station-wide caution and warning
- Perform station-wide fault management and reconfiguration
- Support transaction management (supporting telescience)
- Provide a station-wide inventory and maintenance management system
- Support onboard training and simulations

The OMS concept provides for a mix of machine processes and manual procedures distributed both in space and on the ground. The OMS onboard software is referred to as the Operations Management Application (OMA) and the ground software is referred to as the Operations Management Ground Application (OMGA). The avionics interfaces with the subsystems and flight elements are provided by the Data Management System (DMS). The DMS also provides standard DMS services, including processing capacity and mass storage.

The plans for the OMS at Space Station phase I operations are for a largely manual operation with modest reliance on automation and artificial intelligence technology. The limitations here are perceived to be primarily economic, and to a lesser extent, there are concerns over whether adequate confidence would be developed in those functions managed by the OMS.

The OMS is an automation growth candidate with increasing reliance



Artificial intelligence, robotics, and teleoperation will amplify the role of humans in space. In the people-amplifier, flexible-capability, easy-to-change approach of advanced automation and robotics, two generic aids form the goals toward which Space Station functions are performed for more productive user applications.

on automation and migration of software from the ground to onboard. The evolutionary goal is to reduce the manual procedures in favor of automated processes and to reduce the ground dependence in favor of onboard autonomy. A strategy statement and guidelines to OMS for evolution in machine intelligence remains to be developed. A special emphasis group in advanced automation is being formed to address this issue.

Space Station Operations Task Force Study

The Space Station Operations Task Force (SSOTF) completed its study and provided recommendations to the Associate Administrator. At ATAC's request, SSOTF provided an overview of the study to the committee. SSOTF focused on optimum exploitation of the Space Station, and to a lesser extent, operations drivers on Space Station design. The principal recommendations addressed operations management structure and organizational roles and missions. Final reports of the task force studies, including A & R, are not yet completed.

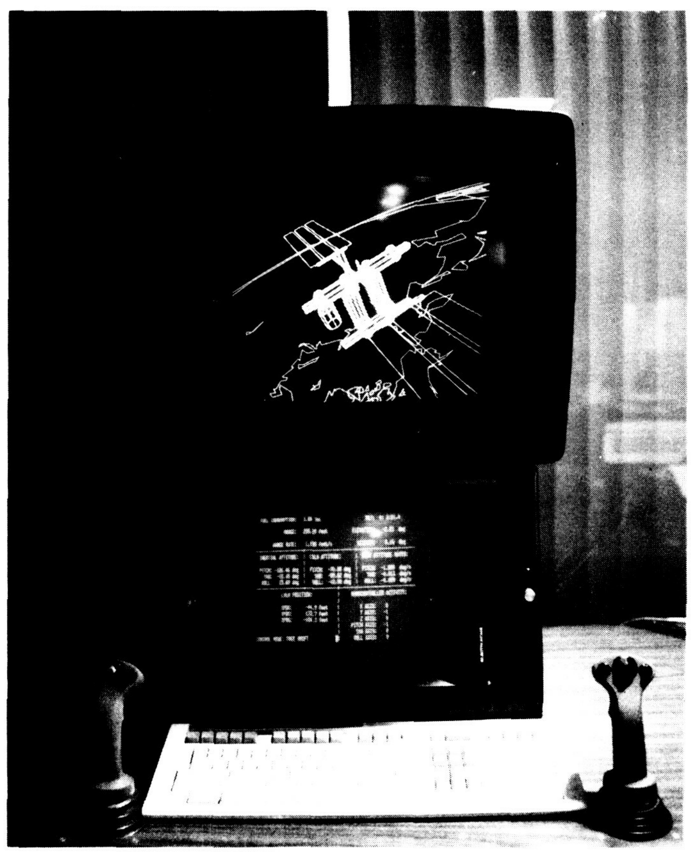
Operations characteristics involving automation and robotics included telescience, on-orbit automated systems management, the use of ground-located expert systems monitoring, the Flight Telerobotic Servicer and the Canadian Mobile Servicing Center. The SSOTF view, consistent with the OMS, is for a largely manually-operated Space Station at phase I operations. Adequate information did not exist for the task force to evaluate costs or for the task force to make cost benefit recommendations. This has been recommended for further analysis.

Automation and Robotics Panel Study

Although SSTOF's final report was not available at the time this report was written, ATAC's attention was drawn to a contract study (ref. 8) sponsored by SSOTF and prepared by the Automation and Robotics Panel (ARP) of the California Space Institute (CalSpace). The ARP draft report describes Space Station Program needs, state-of-the-technology, phase B contractor results, cost benefit arguments favoring the consideration of A & R in the Space Station Program, the pros and cons of a rapid push into A & R, and real-world examples of A & R in practical use today.

Assessment

Obviously, SSOTF has provided an important service to the Space Station Program. However, its top level recommendations, as provided to ATAC, did not make a statement on the need for automation and robotics, except for the Shuttle Remote Manipulator System (RMS) and the Space Station Mobile Servicing Center. The OMS concept can provide a mechanism for evolving advanced automation and autonomous operations if the Space Station subsystems and flight elements are properly integrated in their designs. ATAC's concern is that Space Station Program constraints, such as initial costs, time to retrain, etc. may foster a "business as usual" approach with little on-board advanced automation for an extended period.



Advancements in automation technology will allow complex simulations to be performed on the ground and in space, in real time. This photograph shows a simulation of a spacecraft interacting with a Space Station. This workstation-based, real-time, man-in-the-loop simulation system is being used to investigate a variety of integrated space operations. (Courtesy of Johnson Space Center.)

Progress on Incorporation of A & R in the Requests for Proposals for the Design and Construction of the Space Station

During this report period, the requests for proposals for the design and construction phases (phase C/D) of the Space Station Program were released by each of the four work package centers (refs. 9 - 12). Although proposals have been received from the prospective contractors, the proposals are considered sensitive and are not available to ATAC. ATAC has summarized the RFP's from an A & R perspective for the purpose of examining progress and continuity. The FTS is covered by a separate RFP and is addressed in another section of this report, even though it is a part of work package 3.

The functional specifications and requirements for the Space Station flight elements and distributed systems have been documented in Space Station Program control documents, discussed in ATAC Progress Report 4. Each work package center has prepared its separate primary requirements document to reflect its portion of the Program Definition and Requirements Document (PDRD). Other program requirements documents such as the Architectural Control Documents (ACD's), the Baseline Configuration Document (BCD), the Interface Requirements Documents (IRD's), etc. are generally cited as applicable or reference documents.

During the effort leading up to the preparation of the work package RFP's, the Space Station Program developed a "common content" package which included provisions for advanced automation and robotics, intended to be responsive to the Congressional mandate and to ATAC's recommendations. The work packages have incorporated these "common content" provisions into their RFP's in various formats and levels of detail.

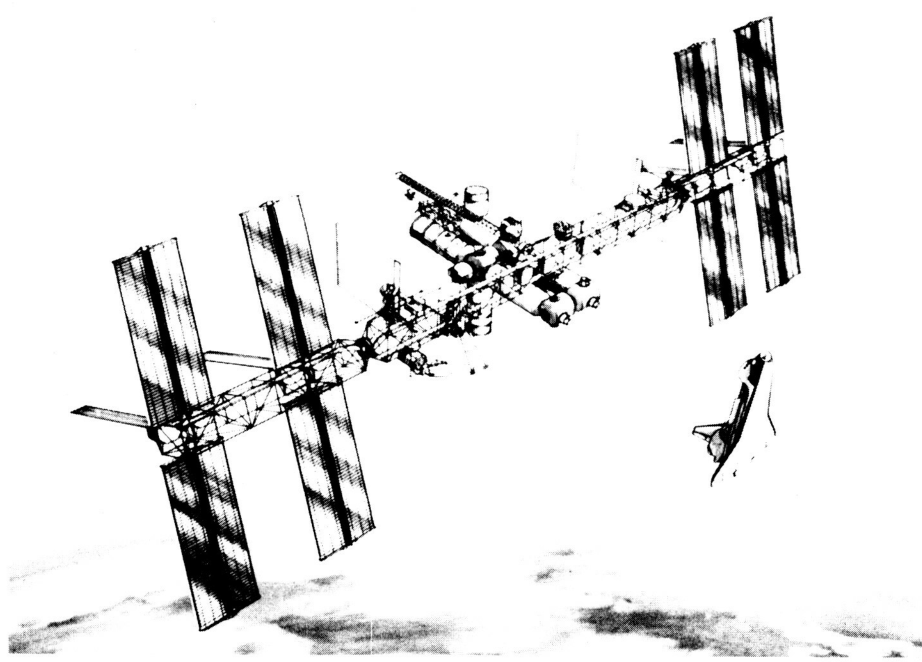
The uniqueness of each RFP makes summarization complex. However, all RFP's require the contractor to develop A & R and design knowledge capture plans and all have data-reporting requirements in these critical areas. Each of the work packages includes the requirement to provide support to the Space Station Program level A' in the development and implementation of an A & R plan.

It is not feasible here to fully duplicate the provisions in each of the RFP's relating to automation and robotics. For reference purposes, we have extracted the A & R and design knowledge capture requirements from systems engineering and integration (SE&I) specifications, from the data requirements, and from the instructions for proposal preparation.

Automation and Robotics

Both work package 1 (MSFC) and work package 3 (GSFC) include essentially identical general requirements for A & R, as follows:

> The Space Station Program is committed to an aggressive application of automation and robotics (A & R). NASA believes that innovative uses of advanced automation and robotics (A & R) in the design of the Space Station can significantly improve the design, specifically in areas which advance the state of technology and that are not in use in existing spacecraft.
>
> The contractor shall develop and implement an A & R plan that identifies how A & R technologies will be incorporated into the initial Space Station and methods for upgrading A & R capabilities for the evolutionary station.



The baseline configuration of the Space Station will provide a permanent, manned presence in space that will permit scientific research, opportunities for production and manufacturing operations, and other experimental and demonstration activities. A Flight Telerobotic Servicer is manifested for first element launch of the Space Station to support Space Station assembly, maintenance, and servicing. Design accommodations will allow the inclusion of evolutionary advancements in automation and robotics.

Furthermore, the contractor shall in its plan (both the initial plan and in updates) identify and price separately, additional A & R concepts that may benefit life cycle costs (LCC) of the program but are not considered within the baseline configuration.

The contractor's plan shall, as a minimum, evaluate and document A & R designs with an approach using typical design and operations attributes which emphasize the LCC benefits to the program. Typical attributes for consideration are: design risk, baseline applications, evolutionary applications, value to the terrestrial economy, crew and ground support time savings, increase in maintainability and reliability, hazard exposure avoidance, and effectiveness in emergencies. In particular, an estimated design, development, test and evaluation (DDT&E), deployment cost, and an LCC shall accompany each design concept.

Examples of concepts identified in phase B and considered potentially worthwhile are listed in the publications of the Advanced Technology Advisory Committee (ATAC) and specifically NASA TM-88785. The examples are neither exhaustive nor mandatory, but are offered to stimulate creativity.

The work package 2 (JSC) general requirement is as follows:

The contractor shall develop advanced integrated automation and robotics (A & R) concepts both for initial and evolutionary Space Station Program applications on the ground and on-orbit.

The contractor shall perform analysis on WP-2 systems to develop generic A & R capabilities applicable across all these systems, as well as manufacturing and test functions. Such capabilities would include, as a minimum, fault detection, isolation, and recovery (FDIR); monitoring; diagnosis; planning for automation and remote assembly; and maintenance using robotics. The product of this task shall be a defined approach for incorporating generic A & R capabilities into WP-2 systems, as well as establishing the minimum A & R levels for these systems.

The work package 4 (LeRC) general requirement is as follows:

The contractor shall provide a system level automation and robotics overview program that assures that subsystems employ automation through robotic devices, teleoperation, and advanced software to achieve cost-effective operation of the Space Station Electrical Power System.

In addition to the A & R general requirements, WP-2 includes the requirement for analysis and integration of the Space Station assembly and maintenance functions. Highlighted in this requirement are the Flight Telerobotic Servicer (FTS), the Service Facility, the Canadian MSC, and other support equipment.

Work package 3 includes a section on the requirement for integration responsibility for the FTS with the other Space Station Program elements. This includes integration for first element launch.

Design Knowledge Capture

Both WP-1 and WP-3 have essentially identical requirements, presented below. WP-2 and WP-4 requirements are a subset of the WP-1 and WP-3 statement and are italicized.

NASA's goal is to provide for a maximum of ease in the evolution of the Space Station and its adaptation to new requirements, new technologies, and advanced forms of machine intelligence. It is recognized that this goal must be pursued not only in the design of the Station, but also in the requirements for the documentation of the design, its features and its rationale. To fulfill these requirements, *the contractor shall prepare, implement, and maintain a design knowledge capture plan that will provide a comprehensive, design knowledge definition, including rationale for design chosen, specifications of the design's performance; functional breakdowns of the design showing dependencies and interrelationships; and descriptions of the design's physical appearances, relationships, and characteristics.* The contractor shall supply the particular data required for station design and operations integration and specified in other sections of the contract.

The contractor shall describe his approach to providing the design knowledge definition in machine-intelligible form, directly suitable for storage in a computerized data base and for processing by applicable software. The contractor shall also define his approach to formalize the gathering and recording of Space Station design requirements.

The contractors plan shall include the estimated development, implementation, and life cycle costs associated with his design knowledge capture concept.

Data Requirements

The data requirements of the contracts are critically important as the documentation of the contractors' considerations, findings, recommendations, and plans for A & R. Each of the work package RFP's includes similar data requirements for plans for automation, robotics, and design knowledge capture. For purposes of brevity, we have extracted here from the data requirements of work package 1, recognizing the general similarity between the work packages and also recognizing that considerable differences do exist.

The automation and robotics plans shall identify an overall approach for implementation of an effective automation and robotics program to greatly enhance the capabilities of the Space Station. The plans shall address requirements of TM 87566 (original ATAC study report) and shall include, but is not limited to, the following topics:

a. Objectives
b. Scope
c. Identification of candidate implementation
d. Appropriate mix of traditional/advanced automation concepts including artificial intelligence
e. Ranking of candidate implementations using cost/benefits attributes
f. Hooking and scarring plan for growth
g. Validation and verification plan
h. Development environment
i. Identification of reusable software with plan for its reuse within the Space Station Program
j. Back-up/redundancy requirements
k. Approach including design and analysis
l. Interfaces required
m. Estimated A & R costs in relation to IOC Space Station and relationships to operational costs of the Space Station
n. Responsibility
o. Change control
p. Automation and robotics summary/reporting

ORIGINAL PAGE IS OF POOR QUALITY

The design knowledge capture plan shall contain, as a minimum, the following information:

a. Approach to providing the design knowledge definition in machine-intelligible form, directly suitable for storage in a computerized data base, and for processing by application software.
b. Description of the knowledge to be captured, such as; specifications of a design's performance, functional breakdowns of the design showing dependencies and interrelationships, physical characteristics, CAD data, etc.

Two miniature monitors on a helmet-mounted platform provide a real-time window into a simulation scenario. The helmet positioning device allows a 360-degree field of vision. Slightly offset left and right images provide true depth of field. (Courtesy of Johnson Space Center.)

Specific Instructions for Proposal Preparation

The specific instructions are significantly varied between the RFP's. However, each generally requires that the contractor describe his approach and plan for automation and robotics, evolutionary growth, and design-to-cost. Consideration of the FTS is specifically mentioned in work packages 2 and 4. Work package 3 describes the requirements for automating the operations of the polar and co-orbiting platforms and the requirements for expert systems for platform operations support.

Assessment

ATAC cannot determine the extent to which A & R will be included in the initial Space Station, based on the RFP's. There are no specific requirements defining what or how to automate. We suspect that, to some degree, this was an intentional omission to allow the work package centers to generate "discriminators" for the evaluation process. However, a reasonable determination of the A & R content for the initial Space Station should be available soon after the contracts are awarded. The committee's assessment of the strengths and weaknesses of the work package RFP's is as follows:

Strengths

- The work package centers appear to be making a conscientious effort to ensure that the phase C/D contractors adopt useful elements of A & R. Proposers are being asked to develop quite specific plans that address the implementation process for A & R, based on selected attributes to be considered when evaluating candidate applications. Consideration and data on the life cycle cost benefits of A & R are also required.
- The RFP's make a specific point to provide for and to describe the FTS. However, they stop short of making a commitment to its use in assembly and maintenance.
- Overall, design knowledge capture requirements look good. However the RFP's require only proposed plans and costs, and they do not yet constitute a commitment to support an adequate design knowledge capture effort.
- All four RFP's recognize ATAC and use it as the basis for A&R activities. In each RFP, the proposers are also required to support the ATAC reporting activities.

Weaknesses

- There is an uneven treatment of A & R across the work package RFP's. For example, all RFP's except one are somewhat weak in the area of advanced automation. Only one RFP lists A & R as an important consideration in evaluation criteria, and only one RFP requires information on the A & R skills of the proposed contractor's staff.
- Universally, the RFP's reflect a work-package-by-work-package process for implementing A & R in the Space Station Program. The present program structure will result in a great difficulty in finding a way to ensure the identification and adoption of the most useful and cost-effective A & R candidate set. This is disadvantageous whether or not each contractor looks across work package boundaries when evaluating his A & R candidates.
- A strong commitment requiring the initial Space Station design to accommodate the evolution of A & R is not made in the RFP's. The RFP's identify the requirement to develop plans for hooks and scars to accommodate growth of A & R on the Space Station. However, reference is not made to the design guidelines manual (ref. 6) baselined as a reference document for this purpose. Special attention and effort will be required to integrate and implement these plans in a uniform, standardized approach.

Notwithstanding the recognition of A & R as an element of SE&I in the RFP's, ATAC would have preferred to see a greater emphasis on A & R by having it rank as a technical factor in the evaluation criteria equivalent to product assurance and operations.

In the immediate future, as the phase C/D contracts are awarded, the level of A & R content in the baseline Space Station will be negotiated between Space Station Program management, the work package management, and the proposers. The contract negotiations may also establish constraints on the level of A & R content for the evolutionary Space Station. After phase C/D contract award, program changes recommended by ATAC to NASA and reported to Congress may be considered above guidelines and may be more difficult to implement.

Progress on the Flight Telerobotic Servicer for the Space Station

In November 1985, Congress directed that NASA develop a flight telerobotic system (FTS), to be delivered at the time of initial Space Station operational capability for a mobile remote manipulator for Space Station assembly and maintenance and for a smart front end on the Orbital Maneuvering Vehicle for remote operations and servicing. In support of this initiative, Congress has provided an augmentation of funds for the design, development, and testing of the Flight Telerobotic Servicer.

The Goddard Space Flight Center (GSFC) was assigned responsibility for the FTS as part of work package 3. As stated in previous ATAC reports, a plan for the development and implementation of the FTS has been established. The plan includes the other work package centers and the support of the NASA Office of Aeronautics and Space Technology. During this ATAC report period, work has continued according to the plan, and proposals were received for a system definition and preliminary design study.

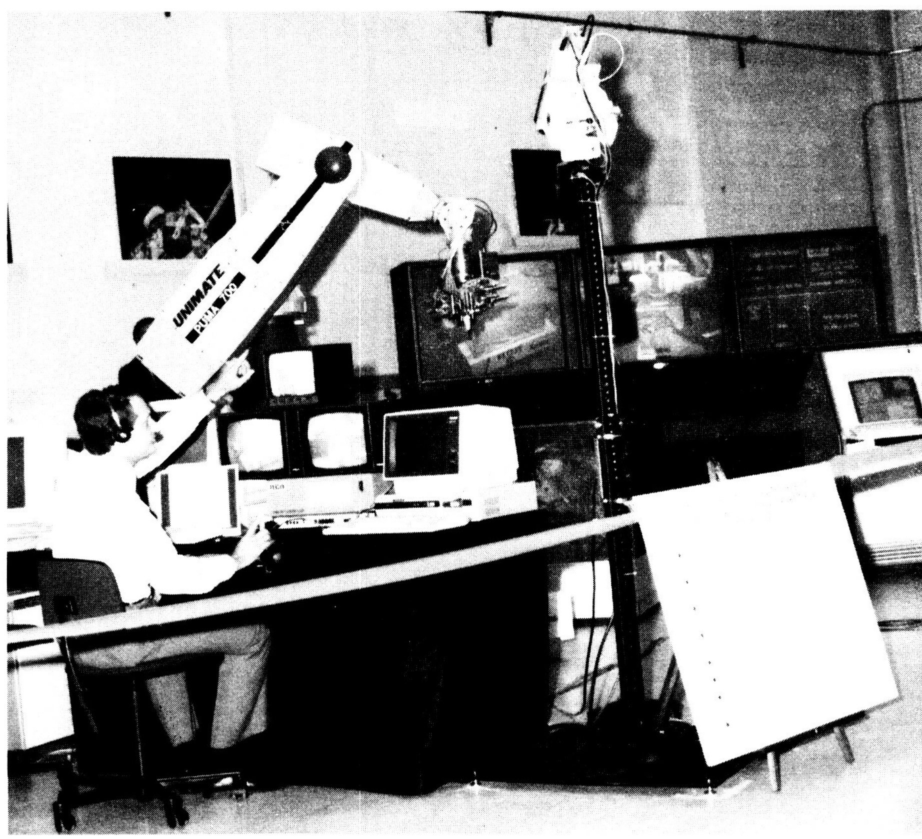
Project Technical Implementation Plan

The FTS project implementation approach developed by GSFC was presented to Space Station Program level A′ management on June 3, 1987. The schedules are tight since the FTS was the last flight element defined for the Space Station and is to be available for first element launch. In order to bring the technical risk within acceptable bounds, the FTS project emphasizes an early flight test of the contractor manipulator system prototype and the utilization of the development, integration, and test facilities to evolve the system architecture and concepts.

An early demonstration test flight is a key element in the reduction of technical risk. Many fundamental engineering questions concerning the functioning of a teleoperated manipulator system in a space environment need to be resolved in time to affect the flight system design. There is also a requirement to demonstrate and test key component designs of the FTS flight system in a zero-gravity environment prior to deployment of the system at first element launch.

The single proposed demonstration test flight captures many of the important test and demonstration objectives by combining early emphasis on definition and development of the manipulator system with the development of an in-house Shuttle mission, a workstation, and the FTS architecture and software system. Requesting a preliminary manipulator system design as part of the FTS phase C/D contract proposal allows a preliminary design review for the manipulator system immediately after the FTS phase C/D contract period begins.

Even though the schedule is tight, adoption of an implementation plan that emphasizes the early flight



A demonstration was performed for the American Institute of Aeronautics and Astronautics (AIAA) Information System Symposium attendees at the Goddard Space Flight Center on June 24, 1987. The demonstration featured orbital replaceable unit (ORU) exchanges on simulated platforms and attached payloads on the Space Station. Technologies such as shared control, world modeling and path planning, force-torque displays, compliance, automated docking using vision, robot-friendly interfaces, and graphics simulation were demonstrated. Data was transmitted over a fiber optics link, similar to the Data Management System (DMS) on the Space Station.

testing of the FTS prototype manipulator system, the utilization of advanced technology, and the availability of a calibrated development, integration, and test facility reduces the technical risk inherent in the development of a successful FTS for first element launch.

Flight Telerobotic Servicer Request for Proposals

The FTS request for proposals for a system definition and preliminary design study (phase B) was released to industry on May 1, 1987. Six responses to this RFP have been received. The phase B request for proposals, as stated in the previous ATAC report, is the first part of a two-phase procurement for the FTS. The FTS procurement approach will allow independent system concepts to be developed by two or more contractors and the resulting designs to be proposed for phase C/D. Concept security is maintained by utilizing a continuing source evaluation board (SEB) to monitor the phase B contracts. Most contractor results and reports will be treated as SEB sensitive until phase B is complete. All NASA in-house studies and their results will be openly available.

Two or more contractor teams will be chosen to accomplish a nine-month phase B definition and preliminary design study. The second phase of the procurement, currently projected to be completed in the first quarter of 1989, will select a single contractor to design, develop, integrate, and test the FTS system for the Space Station Program.

A major product of the contractors' phase B activity will be the development of the FTS "contract end-item specification". This specification will define the system that meets the FTS functional and performance requirements. It will include the details derived for all FTS subsystems, including software. A preliminary version of this specification will be due at contract start date plus 5 months. The final version of the specification will be delivered at contract completion.

A second product of the phase B study is a preliminary FTS design, supported by appropriate trade studies. Preliminary designs will be developed for the FTS telerobot, a Space Station workstation, a Space Shuttle workstation and the associated software and support equipment. Interface requirements with other Space Station Program elements and subsystems will be defined. Key trade studies identified as part of the preliminary design include

- A mix of teleoperation, preprogrammed automation, and supervised autonomy at first element launch and through the completion of Space Station assembly
- Mobility options, including the use of Space Station crew and equipment translation aids
- Telerobot sensory feedback and performance monitoring instrumentation
- OMV and Space Station platform accommodation impacts analysis
- Collision avoidance options
- Safety system options

The contractors are to design a system that will, at a minimum, be capable of the following tasks at first element launch:

- Installation and removal of truss members
- Installation of a structural interface adaptor on the truss
- Changeout of Space Station orbital replaceable units
- The mating of Space Station thermal utility connectors
- Performance of inspection tasks

At the completion of Space Station assembly, the FTS should have evolved to the extent that the above activities could be performed autonomously in addition to the following activities:

- Changeout of the Hubble Space Telescope (HST) reaction wheel ORU while the HST is secured in the Space Station customer servicing facility
- Refueling of the Gamma Ray Observatory (GRO) while it is secured in the Space Station customer servicing facility
- Servicing and maintenance of Space Station platforms and free-flyers

During the phase B study, the contractors will develop operation scenarios for the FTS which will show how their design concepts will be used in the performance of assembly, maintenance, servicing, and inspection tasks while attached to the Space Station, the Shuttle, or the Orbital Maneuvering Vehicle.

This phased approach will allow the flexibility to adjust technical performance requirements to meet the funding constraints for the phase C/D contract while providing the minimum capability required for first element launch and while maintaining the full potential, high performance design.

Assessment

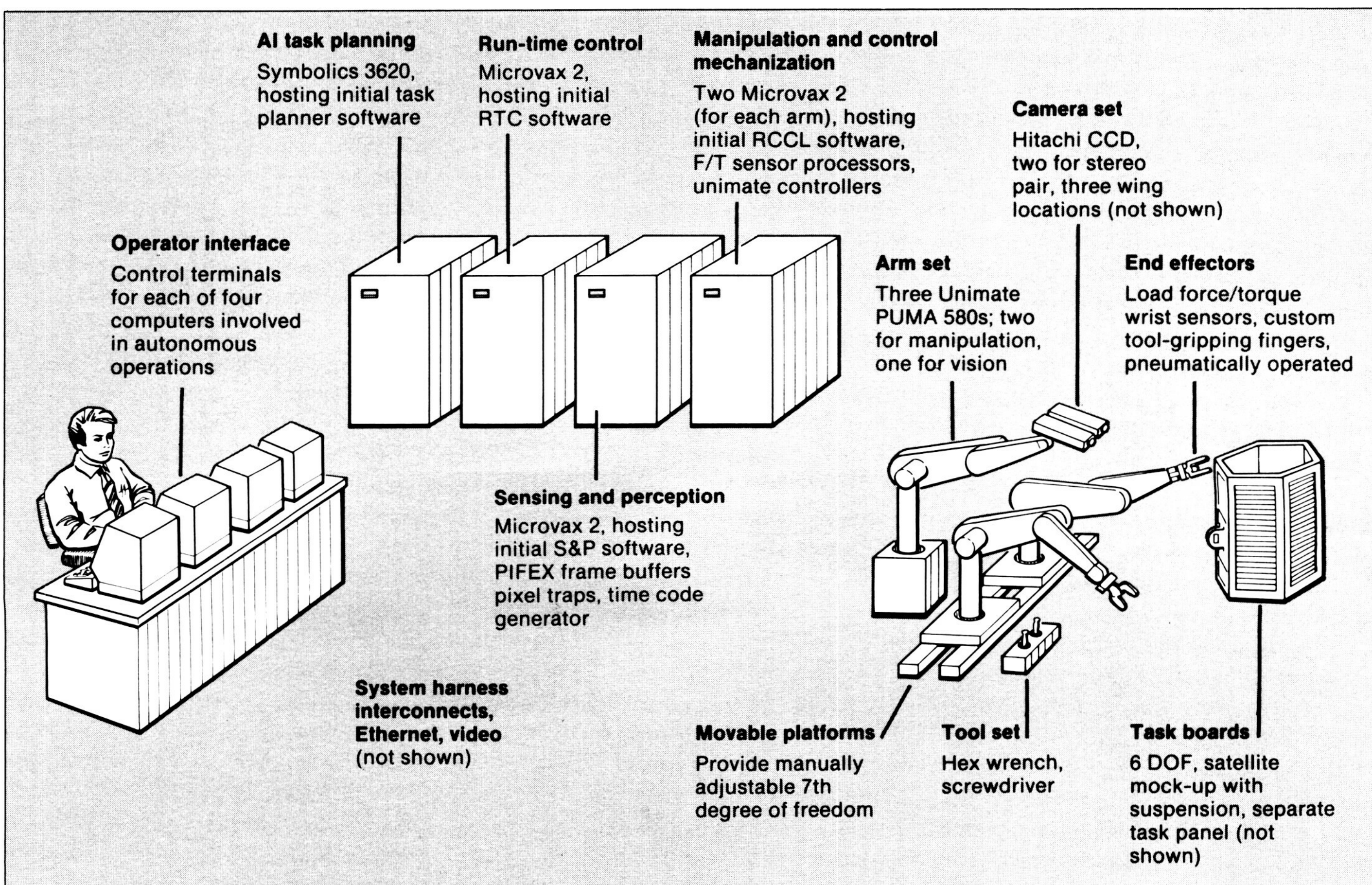
The committee is strongly supportive of the FTS program and it acknowledges the technical challenges which must be met to provide an effective FTS at first element launch. In addition, significant concerns remain over the functional integration of the FTS with the rest of the Space Station, a factor which could affect its planned utilization. Provisions need to be made to use test facilities at other work packages' facilities to encourage maximum program benefit. The committee is encouraged to see that a trade study of mobility options for the FTS is planned. The study should specifically address the potential use of the Mobile Transporter as recommended in Progress Report 4.

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

Important research and development in A & R technologies is in progress throughout NASA, as shown in Appendix F. This work is being conducted in-house, in other government agencies, and in universities and industry. NASA's research and technology development program in automation and robotics is focused in the Office of Aeronautics and Space Technology (OAST). Previous ATAC progress reports have described OAST's systems autonomy and telerobotic demonstration programs. OAST has also initiated an In-Space Technology Experiments Program, which has the potential to develop candidate experiments for A & R.

Systems Autonomy Technology Program

The OAST Systems Autonomy Technology Program has progressed in both core technology and demonstrations. In core technology, a contract was awarded to initiate development of a Spaceborne Symbolic Processor which will execute numeric and symbolic processing for large knowledge-based systems. The first milestone is the concept design and development of a flight-qualifiable breadboard unit. It is anticipated that this effort will lead to the development of a space-qualified "super-chip" family of functional modules for application in standardized modular systems. Also, joint activities in artificial intelligence (AI) research have been initiated with the Defense Advanced Research Projects Agency (DARPA) Information Sciences Office. Initially the joint activities will focus on the areas of planning, machine learning, and cooperating knowledge-based systems. In demonstration projects,



The OAST initial telerobot testbed is designed to be architecturally flexible and expandable through the use of functional modularity, distributed processing, and a hierarchical command and control structure. This allows the rapid incorporation of new core research products, including artificial intelligence sequence planning and spatial planning, and advanced teleoperation with automated control. The initial demonstration will include two manipulator arms operating from a relocatable platform, a machine vision subsystem, and a run-time task controller. Manipulator control capabilities will include cooperative dual arm handling of taskboard objects with force/torque referenced compliance. Vision capabilities will include real-time tracking and object position verification of the taskboard structures. (Courtesy of Jet Propulsion Laboratory.)

the knowledge-based system software completed checkout will provide the first level of functional capability planned for the testbed demonstration of an expert system to automate the Space Station Thermal Control System (TCS).

A memorandum of understanding between OAST and OSS has been submitted for approval. This agreement will facilitate the transfer of systems autonomy technology between the two program offices and will complement the memorandum of understanding between the two programs in the area of telerobotics, described in Progress Report 4.

Telerobotic Technology Program

The research objective of the Telerobotic Technology Program is to provide technology proof-of-concept for supervisory automation of space servicing, assembly, and repair operations. The near-term objective is to develop a telerobot testbed with an evolvable system architecture and supporting core technology products to demonstrate control automation of dual-arm task sequences, using real time machine vision and force sensing and using high fidelity dual-arm teleoperations. The long range goal is to fully automate complex, unstructured tasks.

The testbed is designed to be architecturally flexible and expandable through the use of functional modularity, distributed processing, and a hierarchical command/control structure. This allows the rapid incorporation of new core research products, including artificial intelligence sequence planning and spatial planning and including advanced teleoperation with automated control. The initial demonstration will include two manipulator arms operating from a relocatable platform, a machine vision subsystem, and a run-time task controller. Manipulator control capabilities will include cooperative dual-arm handling of taskboard objects with force/torque referenced compliance. Vision capabilities will include real time tracking and object position verification of the taskboard structures.

The run-time control (RTC) and the manipulation and control mechanization (MCM) free motion tests were completed. In these tests, the RTC performed a kinematic analysis and generated trajectory via points. It then transmitted via points to the MCM in a network transaction. The MCM read via points and called robot control C-language library (RCCL) routines for execution. The MCM then returned status to the RTC in a network transaction. These tests resulted in a calibration which improved precision from 1 cm to 2 cm over a 60 cm line. In sensing and perception development, in two separate tests, a labeled object rotating at 13.3 rpm and an unlabeled object rotating at 4.5 rpm were tracked.

The RTC/MCM free motion tests were in preparation for the achievement of the 1987 core demonstration milestones. The sensing and perception demonstration exceeded the tracking objective for the 1988 demonstration. Future activities will include actual grasping of objects on the taskboard and implementing the hybrid position and force control.

In-Space Technology Experiments Program

The Space Shuttle and, in the next decade, the Space Station will provide national facilities which can become focal points for in-space technology. In response to this opportunity, NASA's Office of Aeronautics and Space Technology has initiated an In-Space Technology Experiments Program. The program will stimulate segments of the engineering community that are interested in aerospace technology to make greater use of space facilities for in-space research, technology, and engineering experiments. It also seeks to develop and implement in-space technology experiments in a number of technical disciplines, including space structures, fluid management, space environmental effects, energy systems, thermal management, in-space operations, and automation and robotics.

The In-Space Technology Experiments Program is divided into two parts. The "Outreach Program" is for industry and university experiments, and the "Inreach Program" is for experiments from NASA centers. Both programs cover two phases of maturity; experiment definition and experiment development. OAST is especially interested in experiments which can be developed at modest cost. Situations which may allow low cost development are being investigated. Examinations are being conducted to determine whether test hardware exists from prior ground-based experiments and if a flight article can be assembled from surplus hardware for other flight programs.

The initial solicitation for the Outreach Program resulted in 231 proposals (140 from industry and 91 from universities) submitted in December 1986. The submissions included 25 proposals in the area of automation and robotics. Experiment selection is planned for September 1987. Several A & R experiments are expected to be funded.

The initial solicitation for the Inreach Program resulted in 58 proposals submitted from seven NASA centers in August 1986, including six in A & R. Experiment selection was completed in mid-July 1987. Seven proposals were combined into one space telerobotic experiment program. JSC will be the coordinating center for this activity and GSFC, JPL, LaRC, and MSFC will participate in establishing a space telerobotic research plan to implement unique telerobotics research experiments.

OAST plans to periodically conduct additional experiment solicitations for the Outreach and Inreach Programs. The goal is to build an In-Space Technology Experiments Program which transitions from the Space Shuttle into the Space Station era.

Assessment

The committee has recommended that the FTS flight experiment, described earlier in this report, should be considered as a possible source of facility hardware for the Outreach and Inreach Programs.

Expenditures for Advanced Automation and Robotics

ATAC has not attempted to obtain refinements to the estimated expenditures reported in ATAC Progress Report 4. Deviations in funding from the previous report are believed to be minimal.

The Office of Space Station is addressing concerns expressed by the committee to establish an advanced development program for A & R. The OSS Strategic Plans and Programs Division is in the process of developing a plan for advanced automation on the evolutionary Space Station. This plan, with responsive funding, is particularly critical for A & R.

TABLE 1.— 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	0.5
Systems engineering and analysis	1.1	1.0	1.2
Operations	0.1	0.8	0.4
Space Station utilization	0.4	0.8	0.2
Phase B contracts (22 months)	←	7.7	→
Total, all years			18.7
Telerobotic Servicer augmentation		10.0	20.0

TABLE 2.- NASA FUNDING FOR AUTOMATION AND ROBOTICS

[Fiscal year 1987, millions of dollars]

Office and activities	Funding
Space Station	2.3
Advanced development	
Systems engineering and analysis	
Operations	
Space Station utilization	
Phase B contracts	
Flight Telerobotic Servicer augmentation	20.0
Aeronautics and Space Technology	18.0
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	4.5
Robotics	
OMV servicing and refueling	
Automation	
Space Science and Applications	0.8
Information system and telescience	
Servicing	
Payload carriers and pointing systems	
Space Tracking and Data Systems	1.2
Improved space operations	
Total NASA funding, approximately	46.8

APPENDIX A

NASA Advanced Technology Advisory Committee

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

John H. Boeckel, Director of Engineering, Goddard Space Flight Center (GSFC)

William C. Bradford, Director of the Information and Electronic Systems Laboratory, Marshall Space Flight Center (MSFC)

Jon D. Erickson, Assistant Chief for Automation and Robotics, Lyndon B. Johnson Space Center (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

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

Walter T. Murphy, Deputy Director of Engineering Development, Kennedy Space Center (KSC)

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

Giulio Varsi, Automation and Robotics Manager, Strategic Programs and Plans Division, Office of Space Station, NASA Headquarters

APPENDIX B

References

1. NASA. 1985. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, NASA TM 87566.

2. NASA. 1985. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 1, April - September 1985, NASA TM 87772.

3. NASA. 1986. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 2, October 1985 - March 1986, NASA TM 88785.

4. NASA. 1986. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 3, April - September 1986, NASA TM 89190.

5. NASA. 1987. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 4, October 1986 - May 15, 1987, NASA TM 89811.

6. NASA. 1986. Design Guidelines Manual for Space Station Machine Intelligence, Robotics, and Automation. JSC 30424. November.

7. Technical and Administrative Services Corporation. 1985. Seminar Proceedings, Space Station Operations Seminar. NASW-4040. July 31.

8. California Space Institute. 1987. Progress Report of an Evaluation of Space Station Automation and Robotics, Draft 3. NASA NAGW-629. March 20.

9. NASA. 1987. Request for Proposal. Space Station Work Package 1 (WP01). MSFC. RFP No 1-7-KA-00052-52G. April 22/May 15.

10. NASA. 1987. Request for Proposals. Space Station Work Package 2 (WP-2). JSC. RFP 9-BF2-51-7-1P. April 25/May 15.

11. NASA. 1987. Solicitation Package for NASA Space Station Work Package 3 (WP-3). GSFC. RFP-11254/303. April 23/May 15.

12. NASA. 1987. Request for Proposal. Space Station Electrical Power System (Work Package 4). LeRC. RFP No. 3-227769. April 24/May 15.

APPENDIX C

Acronyms

A & R	automation and robotics
ACCESS	assembly concept for construction of erectable space structures
ACD	Architectural Control Document
AI	artificial intelligence
ARC	Ames Research Center
ARP	Automation and Robotics Panel
ATAC	Advanced Technology Advisory Committee
BCD	Baseline Configuration Document
C & T	communications and tracking
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacturing
DMS	Data Management System
ECLSS	Environmental Control and Life Support System
EPS	Electical Power System
EVA	extravehicular activity
FDIR	fault detection, isolation, and recovery
FTS	Flight Telerobotic Servicer
GNC	guidance, navigation, and control
GSFC	Goddard Space Flight Center
IVA	intravehicular activity
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LCC	life cycle costs
LeRC	Lewis Research Center
MSC	Mobile Servicing Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NSTS	National Space Transportation System
OAST	Office of Aeronautics and Space Technology
OMS	Operations Management System
OMV	Orbital Maneuvering Vehicle
ORNL	Oak Ridge National Laboratories
ORU	orbital replaceable unit
OSS	Office of Space Station
OSSA	Office of Space Sciences and Applications
PDRD	Program Definition and Requirements Document
PSC	program support contract
RFP	request for proposal(s)
RMS	Remote Manipulator System
SEB	source evaluation board
SE&I	Systems Engineering and Integration
SSE	Software Support Environment
SSIS	Space Station Information System
SSOTF	Space Station Operations Task Force
TCS	Thermal Control System
TMIS	Technical and Management Information System
VHSIC	very high speed integrated circuit
WP	work package

APPENDIX D

Recommended Applications for the Initial Space Station

The following are the recommended applications for the initial Space Station, derived from phase B contractor studies.

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 subjects
Experiment monitoring and scheduling
EVA task planning
Fault diagnosis for manipulators

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
Rendezvous and docking
Contingency event accommodation

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
Servicing of orbital maneuvering vehicle, orbital transfer vehicle, and EVA suits

APPENDIX E

Priorities for Implementation of A & R on the Space Station

The work package centers have recommended a preferred sequence for implementing automation and robotics on the Space Station. Different rationales have been used to establish the priorities for automation and for robotics.

A "building block" approach has been used for advanced automation. The simplest application using the most basic information is the starting point. It is enhanced in terms of its integration into individual systems and the increased level of sophistication of its expert systems to produce the next application.

The robotics rationale was to assume a certain capability from the mobile servicing center, the available end effectors and tools, and from the flight telerobotic servicer or generic space robot and then examine needs of the task complexity. The priorities for robotics represent a general ordering of the needs. Within each of the task areas, task complexity would determine the order of specific tasks added to the list.

Advanced Automation

1. Fault detection, isolation, and recovery (FDIR)

   Subsystem monitor to
   - Obtain relevant system measurements
   - Detect violation of critical parameter thresholds
   - Analyze input versus expected system behavior
   - Request additional data as required
   - Make a limited trend analysis of data

   Fault diagnostics to
   - Detect and isolate faults
   - Request additional data as required
   - Request additional system tests

   Anomaly handler and reconfigurer to
   - Evaluate the impacts of different configuration options
   - Implement the selected configuration change after crew approval
   - Monitor the configuration during and after a change, with appropriate duration and level of security

2. Short term planning and scheduling
   - Mission planner and scheduler
   - Logistics planner and scheduler
   - Crew activity scheduler

3. Resource management

4. Performance management

5. Training and instruction

6. Maintenance

Robotics

1. Servicing

2. Inspection and maintenance

3. Assembly and construction

4. Mission support
   - Docking and berthing
   - Deployment and retrieval
   - Materials handling

5. Customer accommodation
   - Installation and removal
   - Materials handling

6. Astronaut rescue

Astronaut rescue appears at the bottom of the list, not because of lack of importance, but because additional hardware —some type of propulsion system — is required and was not included in the assumed capabilities.

APPENDIX F

R & D Activities Related to Automation and Robotics

The NASA Centers have continued to support ATAC in maintaining a current synopsis of the ongoing research and development activities related to automation and robotics across the agency wide programs. The activities are grouped according to previously established categories and statused according to technology readiness levels described in previous ATAC reports.

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, computer-aided design (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
Ames Research Center	Automated design data capture	Systems engineering	3-4
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
Goddard Space Flight Center	Integrated scheduling of independent resources via a network of distributed systems	Payload data flow control Space and ground network scheduling	1
Jet Propulsion Laboratory	Knowledge-based subsystem development and integration —Configuration planning —Global schedule planning —Failure diagnosis and reasoning —Execution monitoring	System autonomy Telerobotics Ground operations Automation	2-6
Jet Propulsion Laboratory	Knowledge-based system development tools —Blackboard —Conditions model —Memory model —Process model —Reasoning engine design language —Graphics debugging —Time representation model	Expert system development	2-4
Johnson Space Center	System to capture and organize design knowledge	Station maintenance	2
Johnson Space Center	Neural network system for mission operations —Logic —Machine perception	Crew activity planning and scheduling Operations planning Mission control	3
Johnson Space Center	Knowledge representation methods	Systems engineering Systems integration	3

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

Institution	Objectives of the research	Potential Space Station use	Level
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	Development of large multidiscipline knowledge base for fault diagnosis and analysis of Space Telescope subsystems	Development of very large knowledge bases	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
Goddard Space Flight Center	Compliant force feedback and applications to use devices with such feedback	Orbital replaceable unit (ORU) replacement Assembly and maintenance Servicing of spacecraft	4
Goddard Space Flight Center	Tactile imaging skin	Telerobots Autonomous robots	3
Goddard Space Fiight Center	Six-vector force sensing using strain screws Strain moment force and tactile sensing	Telerobots Autonomous robots	2
Goddard Space Flight Center	Vision system under a real-time operating system	Telerobotics	4
Jet Propulsion Laboratory	Machine vision; construction of prototype hardware for a real-time image processing system —Development of an acquisition and tracking system —Development of a feature extractor and model matcher	Telerobotic sension	3
Jet Propulsion Laboratory	Force and torque sensing Proximity sensing Tactile sensing Sensor fusion	Telerobots	6 3 3 1
Johnson Space Center	Development of television (TV) systems for object identification and for range and range rate determination Voice command systems	Proximity operations	5
Johnson Space Center	Laser vision development Spatial position and velocity tracking	Robotic manipulator control	5
Johnson Space Center	Utilization of optical correlators to identify objects and to estimate their positions and attitudes	Robotic control systems Proximity operations	4
Kennedy Space Center	Development of adaptive control systems and software	Tracking and mating of objects having relative movement	

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

Institution	Objectives of the research	Potential Space Station use	Level
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
Lewis Research Center	Accurate position, force, and acceleration sensing, and control of flexible arms using a controlled laser system isolation, and accommodation	Robotic sensing and control	2
Marshall Space Flight Center	Utilization of high-accuracy charge injection device (CID) sensors in a hardware adaptive target-tracking system	Orbital maneuvering vehicle (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	6
Marshall Space Flight Center	Development of vision system for automatic docking using TV box scan and syntax pattern recognition	Autonomous docking and servicing	3
Category 1.3—Actuation and Manipulation			
Ames Research Center	Real-time control of limber manipulators with end-point sensing	Manipulators, robotics, and servicing	2-3
Goddard Space Flight Center	"Smart" parallel gripper with force feedback Wrist-activated automatic change system	Telerobotic technology	4
Goddard Space Flight Center	Ground telerobotic system for technology evaluation	Telerobotics and robotics	3
Goddard Space Flight Center	Lightweight extravehicular activity (EVA) tools	Spacecraft servicing	5
Jet Propulsion Laboratory	Two-arm force-reflecting hand controller "Smart" hand development Distributed control for space telerobot mechanization Hybrid (position and force/torque) control Dual-arm manipulation Multifinger hand and controller	Telerobotics technology	2 4 2 2 2 2
Johnson Space Center	Control architectures for autonomous robots	Autonomous robotics	4
Langley Research Center	Parallel-jaw end effectors with proximity detection Quick-change tool systems High-level command systems Six-degree-of-freedom (6-DOF) force and torque sensors and displays	Generic robotics and teleoperation	3 5 4 6
Langley Research Center	Laboratory prototype of dual-arm telerobotic manipulator system	Telerobotic manipulators	2-3
Langley Research Center	Coordinated multiarm control with active compliance	Servicing and construction	3

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

Institution	Objectives of the research	Potential Space Station use	Level
Lewis Research Center	Smart remote power controllers and remote bus isolators for power limiting and fault detection and isolation	Autonomous electrical power system	4
Lewis Research Center	Smooth motion servoactuator and robotic joint technology	Generic robots and teleoperation	1
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	6
Marshall Space Flight Center	Robotic servicing via task automation including —Active compliance control —Static and dynamic force limiting	Automation of robotic servicing, ORU replacement, berthing	5
Marshall Space Flight Center	Inflatable end effectors which expand inside large, irregularly shaped space structures and thereby distribute the force loads evenly	Assembly, maintenance, and repair of space structures	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 artificial intelligence (AI) technologies for autonomous systems	System and subsystem automation	3-4
Goddard Space Flight Center	Guidelines data base for development of user interfaces to expert systems	Expert systems	3
Goddard Space Flight Center	Expert assistant for designers of user interface management systems	Command and control displays	3
Jet Propulsion Laboratory	Evaluation and analysis tools to assess the merit of automating various functions and to decide where the human/machine interface should be	Optimal extent of automation and robotics utilization	4
Jet Propulsion Laboratory	Fused sensor displays Force feedback evaluation Predictive displays Analysis of human factors associated with operating a telerobot in zero gravity Operator interface to dual-arm telerobot	Teleoperation	2-4
Johnson Space Center	Anthropomorphic hand manipulator	More efficient extravehicular activity	2
Johnson Space Center	Graphic knowledge displays to aid in interface with intelligent systems	System control and maintenance	1
Johnson Space Center	Animated displays in which data and objects can be manipulated	Mission planning	6
Johnson Space Center	Continuous speech recognition in real time and in situations of high stress	Mission planning and control	5
Johnson Space Center	Interface requirements between crew members and the flight telerobotic servicer	Flight telerobotic servicer design requirements, design validation, and operations	3
Johnson Space Center	Optimized interface to advanced displays, controls, and computers	Crew workstations	2-3

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

Institution	Objectives of the research	Potential Space Station use	Level
Johnson Space Center	Laboratory test-bed for experiments in the linkage of eye, brain, and task	Control of robotics	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 —Three-dimensional (3-D) displays —Multiple dynamic windowing —High-performance graphic engines Advanced controls consolidation and workload reduction—voice, touch, keyboard, eye-slaved Information management —Concurrent processes monitoring —Intelligent automation criteria —Reconfigurable display concepts	More efficient use of crew time and workstation space	2-5
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	5
Marshall Space Flight Center	Graphical simulation for predictive display, off-line auto-sequence display, and system checkout	Teleoperations and automated servicing and assembly	3
Marshall Space Flight Center	Expert system allowing nonsimulation personnel to perform studies with complex simulation systems	Reduced-cost Space Station simulations	5
Marshall Space Flight Center	Development of tools to objectively allocate tasks between humans and automation	Improved man-machine interfaces	4
Marshall Space Flight Center	Incorporation of 6-DOF hand controller used to operate manipulator arm	Control of remote servicer, OMV, telerobotic servicer (TRS)	6
Marshall Space Flight Center	Use of force-reflecting hand controller to return force and torque information to operator	Telepresence control of servicing	5
Marshall Space Flight Center	Optimization of lighting, video camera position, and operator aptitudes for accomplishment of servicing tasks	Remotely operated servicing	5
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" multi-processor for "intelligent" processing	Advanced "intelligent" processing	3

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

Institution	Objectives of the research	Potential Space Station use	Level
Goddard Space Flight Center	Rapid prototype of "smart" telescience workstation	Remote investigator display and control	5
Goddard Space Flight Center	Robot control language on VMS operating system	Generic robot command and control	2-3
Goddard Space Flight Center	Control algorithms for system operations using inverse kinematic equations	Robot control	2
Jet Propulsion Laboratory	Self-checking computer modules Autonomous management systems for redundancy maintenance Advanced high-speed computers	More reliable and efficient computing Onboard command, control, and data processing	2-3
Johnson Space Center	A state-of-the-art tool for constructing expert systems for planning, scheduling, command, and control	Mission operations	6
Johnson Space Center	Control architecture for effective use of evolutionary automation	Mission operations	1
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
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

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

Institution	Objectives of the research	Potential Space Station use	Level
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	3
Category 2.2—System Design and Integration			
Ames Research Center/ Johnson Space Center	1988 demonstration of automated control of thermal control system (TCS) —Expert system for fault diagnosis control and reconfiguration of the TCS	Automatic control and monitoring of TCS	2-3 5
Ames Research Center/ Lewis Research Center/ Johnson Space Center	1990 demonstration of automated control of TCS and electric power system (EPS)	Automatic control and monitoring of multiple subsystems	2
Goddard Space Flight Center	Test facility for system integration and test of robotics	Servicing of platforms, attached payloads, spacecraft, and instruments	3
Goddard Space Flight Center	Flight experiment/demonstration of teleoperated and autonomous robotic manipulation —Fluid resupply —Module replacement —Structural assembly	Service bay spacecraft servicing Attached payload servicing Platform servicing Structural assembly	3
Goddard Space Flight Center	Design and development of flight telerobotic system	Assembly, maintenance, servicing, and inspection	2
Goddard Space Flight Center	Hierarchical real-time sensory interactive control	Telerobotics	4
Goddard Space Flight Center	Simulations including geometric database, kinetic simulations, and teleoperation interface	Telerobotics Training	2
Goddard Space Flight Center	Rigid and flexible body performance evaluations —Simulations —Controls —Analytical tools	Robot performance evaluation	2
Jet Propulsion Laboratory	Telerobot demonstrations —Integration of teleoperation and robotics sensing and perception —Task planning and execution —Control execution and operator interface	Telerobotics	2
Jet Propulsion Laboratory	Telerobot run-time control	Telerobotics	2
Johnson Space Center	Simulation, including visual displays, of docking and berthing activities among the Space Station, the Space Shuttle, and the orbital maneuvering vehicle	Development and training	2-4
Johnson Space Center	Expert system shells	Automation of Space Station operations	3

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

Institution	Objectives of the research	Potential Space Station use	Level
Johnson Space Center	Expert system tool development	Systems engineering	6
	—System for writing expert systems in Ada		
	—Computer-aided tool for design of centralized or distributed control systems		
	—System using simulation and qualitative modeling		3
	—Systems that use models of the domain of interest as part of their knowledge		3
	—Workstation for automated generation of programs		3
Johnson Space Center	Test-bed for testing and verifying expert systems for Space Station avionics	Systems engineering Space Station avionics	6
Johnson Space Center	Definition of a test-bed to be used on the Space Station for testing advanced automation and robotics	Evolutionary Space Station design	2
Johnson Space Center	Automated workstation to operate in real time with expert systems to present flight data to the operator	Mission operations and control	6
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	2-6
Langley Research Center	System validation techniques —System performance and reliability assessment methods —Emulation/simulation technology —Design proof techniques —Operations	Validation tools	2
Langley Research Center	Acoustic environment qualification testing	Voice control systems	3
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
Lewis Research Center	Design and development of reactionless, microgravity manipulation system —Mechanisms —Joints —Trajectory optimization	Microgravity laboratory robots	1
Lewis Research Center	Control system reconfiguration using expert systems logic	Control of systems	2

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

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Simulation, including video displays, of rendezvous and docking activities of OMV	Development of remote control systems for orbital operations	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	6
Marshall Space Flight Center	Autonomous management of large spacecraft power system	Electrical power system automation	5
Marshall Space Flight Center	Expert system for management of power loads priority lists	Common module electrical power system automation	4
Marshall Space Flight Center	Determination and evaluation of potential expert systems for mission planning on Space Station	Mission planning	1
Marshall Space Flight Center	Determining expert systems applicability and rapid prototyping for common-module electrical power system	Electrical power system automation	3
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	5
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, of free-flyers, and of the core module	OMV and OTV payload berthing Space Station maintenance and inspection	3-5
Marshall Space Flight Center	Demonstration of telerobotic servicing including —Task-primitive automation —Reflexive manipulator control —Sensor fusion —High-fidelity task simulator —Prototype hardware	Evaluation of ORU designs, servicing techniques, sensors, controllers	2-3
Marshall Space Flight Center	Neutral-bouyancy 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			
Ames Research Center	Expert system for Pioneer Venus satellite operations and scheduling	Payload data systems management	4-6
Goddard Space Flight Center	Fault diagnosis for Tracking and Data Relay Satellite system communications	Automated Space Station monitoring and safety	5
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

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

Institution	Objectives of the research	Potential Space Station use	Level
Goddard Space Flight Center	Fault diagnosis for local area networks	Automated fault detection and correction	5
Goddard Space Flight Center	Expert systems for —Platform payload scheduling —Payload command management —Data quality monitoring	Automated operations	4
Goddard Space Flight Center	Expert assistant for software project management	Software development	4
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
Jet Propulsion Laboratory	Expert system for hyperspectral data evaluation for geological exploration	Science experiments	5-6
Johnson Space Center	Software support expert systems to —Analyze simulations —Analyze code —Diagnose errors in systems for producing software —Diagnose failures in computer systems —Determine initial values for space vehicle systems —Diagnose causes of aborts and holds of launches	Flight software development Launch assistance and failure diagnoses	3
Johnson Space Center	Expert systems for proximity operations —Provide information on the position and motion of a nearby orbiting body	Crew support during the terminal phase of rendezvous	6
	—Support command and control	Proximity operations and rendezvous	3
	—Provide assistance to crew in rendezvous of Space Shuttle with the Space Station	Rendezvous operations	3
Johnson Space Center	Expert systems for monitoring and control of communications and tracking system	Communications and tracking	4
Johnson Space Center	Expert system to monitor a ground system for controlling space vehicles	Ground support to flight operations	2
Johnson Space Center	Expert system aid for allocations of crew and equipment functions	Mission operations	3
Johnson Space Center	Knowledge-based system for monitoring and controlling exercise in health maintenance facility	Crew health maintenance	6
Kennedy Space Center	Expert system for Space 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 Space Shuttle flight	Logistics management	3
Kennedy Space Center	Expert systems for diagnosing liquid oxygen system faults and for 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

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

Institution	Objectives of the research	Potential Space Station use	Level
Kennedy Space Center	Expert systems for weather forecasting for Space 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	Procurement advisor expert system to increase productivity at the center	Program management	2
Lewis Research Center	Expert system for finite-element modeling and structural analysis	Structural design	1
Lewis Research Center	Expert systems for polymer synthesis	Polymer matrix composites; construction materials	2
Marshall Space Flight Center	Fault diagnosis expert system for the test-bed for Space Telescope battery power	Fault diagnosis for various subsystems	6
Marshall Space Flight Center	Fault diagnosis and analysis expert system for Space Telescope nickel-hydrogen battery	Maintenance, diagnosis, and analysis of energy storage system	2
Marshall Space Flight Center	Fault isolation expert system for electrical power	Fault isolation for various subsystems	6
Marshall Space Flight Center	Expert systems for fault isolation, recovery, and management of power systems	Management of electrical power systems	2
Marshall Space Flight Center	Expert system for telemetry data reduction	Onboard data reduction to improve trends analysis, component failure forecasting, etc., for various subsystems	2
Marshall Space Flight Center	Knowledge-based system for automatic diagnosis and repair functions	Advisor for various onboard repair actions	2
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	4
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
Marshall Space Flight Center	Expert system for removing carbon dioxide from core Space Station module air	Improved environmental control and life support system	6
Marshall Space Flight Center	Analytical integration expert system for designing Spacelab payloads	Minimizing payload design time	3
Marshall Space Flight Center	Expert systems for dynamic scheduling of payloads	Scheduling of payloads	2

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

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Expert system for spectrometer calibration	Self-calibration of instruments and platforms	1
Category 2.4—Robotic and Telerobotic Systems			
Goddard Space Flight Center	Design of ORU's, 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	3-D computer recognition of moving targets made up of complex polyhedra	Robotic recognition of targets to be manipulated or serviced	3
Jet Propulsion Laboratory	Technology development support for flight telerobotic servicer —Force-reflecting hand controllers —7-DOF control system —Smart end effectors —Machine vision system	Flight telerobotic servicer	
Johnson Space Center	Design of robotics for assembly and maintenance —Requirements —Workstation —Simulation	Assembly and maintenance	3
Johnson Space Center	Robotics for autonomous retrieval and rescue	Retrieval and rescue of crew	3
Johnson Space Center	Intelligent robot system that can —Interpret scene images —Control motions	Assembly and maintenance Rescue and retrieval	1
Kennedy Space Center	Robotic systems to perform tile step, gap, and surface parameter measurements of orbital tiles and inspection of thermal radiator panels	Remote inspection of in-service hardware	
Kennedy Space Center	6-D tracking of moving targets	Autonomous docking and refueling	
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
Langley Research Center	Establish a data base of time and tasks for teleoperated space assembly	Assembly	4
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	6
Marshall Space Flight Center	Interchangeable tools for use by manipulator arm in servicing, assembly, and maintenance	Servicing, assembly, and maintenance	3-4
Marshall Space Flight Center	Development of module or ORU interface mechanisms	Repair and resupply	5

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TM 100777		

4. Title and Subtitle	5. Report Date
Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy - Progress Report 5	September 1987
	6. Performing Organization Code
7. Author(s) Advanced Technology Advisory Committee (ATAC) [ATAC Progress Report 5] Robert Nunamaker/Chairman	8. Performing Organization Report No. TM 100777
9. Performing Organization Name and Address Advanced Technology Advisory Committee, Chairman/Robert Nunamaker/107, NASA/LaRC, Hampton, VA 23665	10. Work Unit No. NA
	11. Contract or Grant No. NA
	13. Type of Report and Period Covered: Progress Report May 1987 - September 1987
12. Sponsoring Agency Name and Address NASA Headquarters, ATTN: Al Diaz/ST, Washington, DC 20546	14. Sponsoring Agency Code: NASA

15. Supplementary Notes

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 fifth in a series of progress updates and covers the period between May 16, 1987 and September 30, 1987.

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.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Robotics Space Station Automation Artificial Intelligence Expert Systems	Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	46	

*For sale by the National Technical Information Service, Springfield, Virginia 22161