NASA Technical Memorandum 89811

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

Progress Report 4 — October 1986 Through May 15, 1987

Advanced Technology Advisory Committee
National Aeronautics and Space Administration

Submitted to the
United States Congress
May 15, 1987

NASA
National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

Synopsis

Congress recognized, in 1984, the merit of developing a new generation of general purpose automation and robotics (A & R) technology using the Space Station as a stimulus. This technology would be efficient and flexible enough to meet the complex and varying needs of the Space Station and would be beneficial toward improving the terrestrial economy of the United States.

During the past 6 months, the focus of the Space Station Program has been on completing and incorporating the study results of the Critical Evaluation Task Force, completing the baseline design requirements and architectural configuration of the Space Station, and preparing the requests for proposals for the design and construction phase (phase C/D) of the Space Station. An Operations Task Force has been chartered, but its findings are not yet available.

In the areas of automation and robotics, the focus has been on developing and planning applications of the Flight Telerobotic Servicer (FTS), incorporating automation and robotics requirements into the design documents and requests for proposals, preparing a request for proposals for an FTS phase B definition and preliminary design study, and continuing the research and development programs. As projected, the phase B work package contractors had essentially completed their contracted studies prior to the previous Advanced Technology Advisory Committee (ATAC) report (Progress Report 3), and there are few new significant automation and robotics results in the final reports, except in specific, detailed areas.

In ATAC Progress Report 3, a variety of concerns were expressed and recommendations were made about the progress of the Space Station Program with respect to automation and robotics. These concerns addressed issues of policy, management structure, and sensitivity to the requirements of automation and robotics relating to the long term productivity of the Space Station and the benefits to the U.S. economy, which Congress has mandated and which ATAC considers necessary.

The committee is encouraged that, in his transmittal letter for ATAC Progress Report 3, the NASA Administrator renewed the agency's commitment to the importance of automation and robotics. ATAC's concerns were acknowledged, and the administrator addressed these concerns constructively by describing the actions that had been taken and those that were planned to overcome the program deficiencies.

The committee applauds the designation of a Level A Division within the Office of Space Station, chartered with direct responsibility for automation and robotics. However, we note that several of the planned actions identified by the administrator have not been implemented. Plans and goals for life cycle costing have not been established, and a level A' organizational element, reporting directly to the program director and responsible for A & R, has not been implemented. Considering the rapidly approaching critical negotiations for the design and construction phase (phase C/D) of the program, the committee is concerned that these crucial actions may not be taken in time to properly affect the design and construction of the Space Station.

Although the deficiencies are not yet fully resolved, ATAC continues to perceive significant progress in the areas of automation and robotics. A summary of the committee's assessment of progress during this report period is as follows:

1. The preliminary plan for the Flight Telerobotic Servicer (FTS) was completed and approved. The committee believes the plan is fundamentally sound and endorses the plan to compete the FTS contract as a separate procurement, starting with a phase B definition study, in order to increase the opportunity to obtain the most advanced technologies available. The FTS has now been included in the baseline Space Station configuration and in the Space Station assembly manifest on the first flight. This inclusion represents a significant commitment by the Space Station Program to the early use of the FTS as an aid to the crew during initial assembly.

   New studies have been focused on assembly and maintenance and on servicing. These studies identify, the specific assembly, maintenance, and servicing tasks, and the potential use of telerobotics, extravehicular activity (EVA), intravehicular activity (IVA), and various Space Station manipulators for performing these tasks. The program design requirements now specify that, "whenever practical and cost-effective, Station design shall baseline telerobotic manipulation with EVA as a backup." The committee believes these are important steps for the development and use of the U.S. telerobot. The potential of telerobotics to reduce EVA time by a third to a half was noted by the Critical Evaluation Task Force. However, this potential may not be realized unless there is increased awareness of the need to design the Space Station for telerobotic maintenance.

2. Significant provisions for automation and robotics have now been included in the Space Station design requirements documentation. In addition to those identified above for the Flight Telerobotic Servicer, provisions are included to support the growth and evolution of automation and robotics. Process Requirements Documents for automation and robotics and for design knowledge capture have been baselined into the program. Still, A & R (especially advanced automation) requirements are neither focused nor comprehensive and may not provide the level of guidance required for an autonomous Space Station with evolutionary growth in the high-technology A & R areas.

3. The Office of Aeronautics and Space Technology (OAST) has continued to increase its emphasis on the areas of automation and robotics. A Memorandum of Understanding and a Memorandum of Agreement have been established between the OAST and the Office of Space Station (OSS) to facilitate the transfer of telerobotic technology from OAST to the Flight Telerobotic Servicer project. These memoranda document specific products which will be delivered from OAST's telerobotic testbed program to the Space Station telerobotic test facility at the Goddard Space Flight Center (GSFC). The memoranda constitute a major step in ensuring that the FTS design and implementation will consider the most advanced technology available in space telerobotics and leverage the government's investment in advanced A & R. In addition, the OAST systems autonomy program plan has expanded core research and technology demonstrations to include all NASA centers in fiscal 1988.

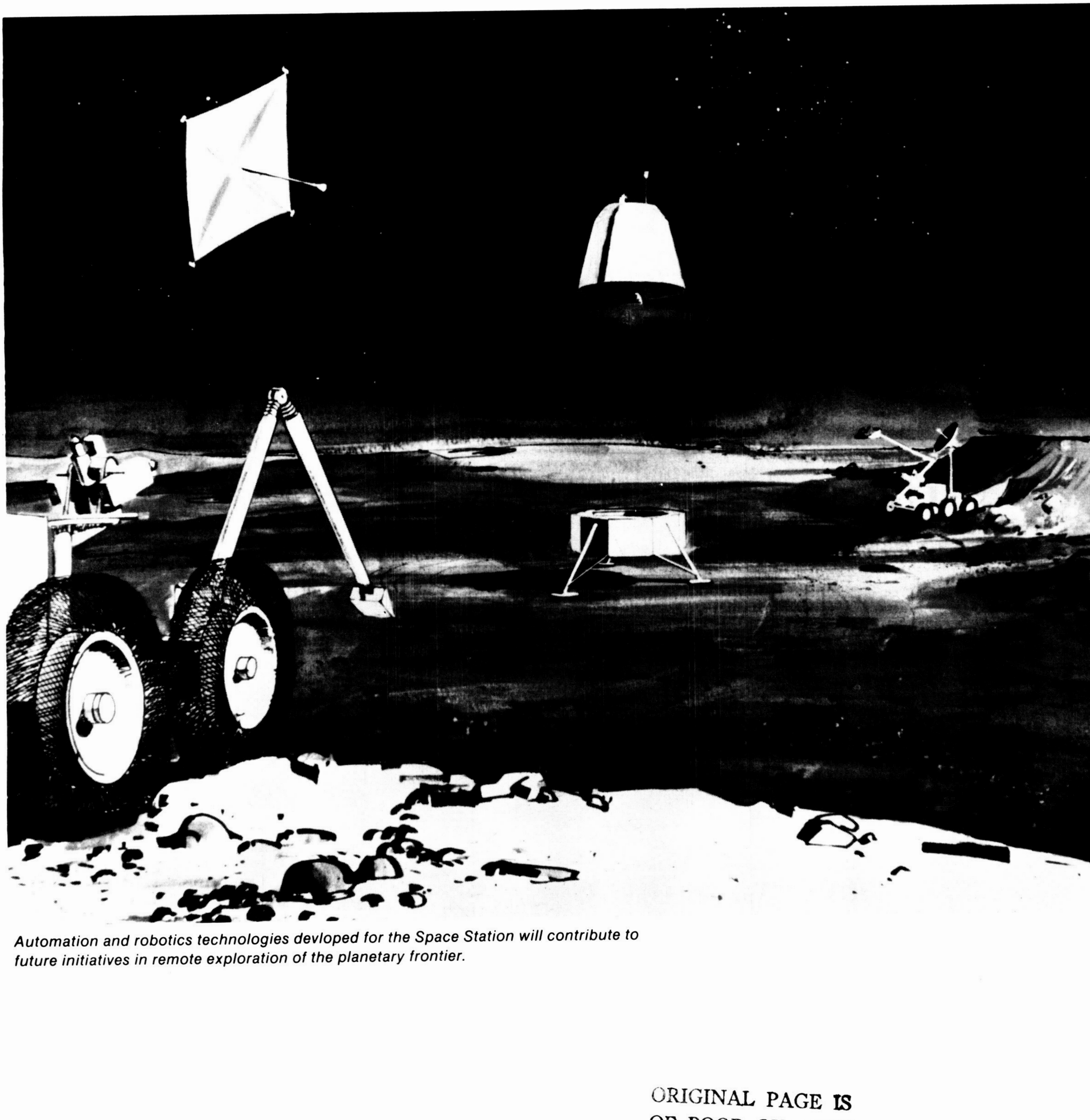
4. The NASA Office of Commercial Programs (OCP) continues to monitor A & R activities and to support the transfer of technology from NASA to the U.S. economy. NASA continues to participate in and co-sponsor symposia focusing on automation and robotics.

The principal deficiency is reflected in the lack of a Space Station wide automation and robotics plan with identified resources and design requirements baselined at a high level in the Space Station Program. Existing requirements, necessary but not sufficient, have generally been submerged to reference documents and therefore do not fully project the intent of Congress, the results of the phase B contractor studies, or the proposed goals for A & R applications which ATAC identified in its initial report to Congress.

The consequences of the lack of a Space Station-wide A & R plan are less serious for robotics applications as the result of the Congressional decision to augment the program with the Flight Telerobotic Servicer and also because of the international agreement for the Canadian mobile servicing system. However, the emphasis on these systems must not exclude the potential use of dedicated robots, as has been suggested for the laboratory module and the electric power system.

ATAC believes the steps taken will help to restore perception of the program commitment to include A & R recommendations. However, difficult decisions are yet to be made on the fiscal versus technology tradeoffs for the Space Station. This may severely impact the incorporation of advanced automation, such as knowledge based systems. The committee remains concerned that resource considerations to minimize the initial Space Station cost may inhibit the provisions for the inclusion of advanced automation without adequate consideration of the benefits in life cycle costs, productivity, and crew safety. These benefits, in total, may be several times greater than those of robotics.

It will be critically important for the phase C/D requests for proposals (RFP) to emphasize automation and robotics commitments and provisions, to emphasize the importance of minimizing life cycle costs, and to have a management structure and budget which support advanced automation and robotics. The phase C/D program support contract (PSC) request for proposals has been released and includes critical considerations for automation and robotics. However, the committee does not consider the PSC request for proposals as strongly supportive of A & R. In this report we have noted several deficiencies which we hope can be eliminated during contract negotiations and performance. ATAC has consistently recommended that selection of the contractors for phase C/D be influenced by a demonstrated awareness of A & R issues. However, the PSC request for proposals does not include A & R in the list of evaluation criteria.



Automation and robotics technologies devloped for the Space Station will contribute to future initiatives in remote exploration of the planetary frontier.

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Preface

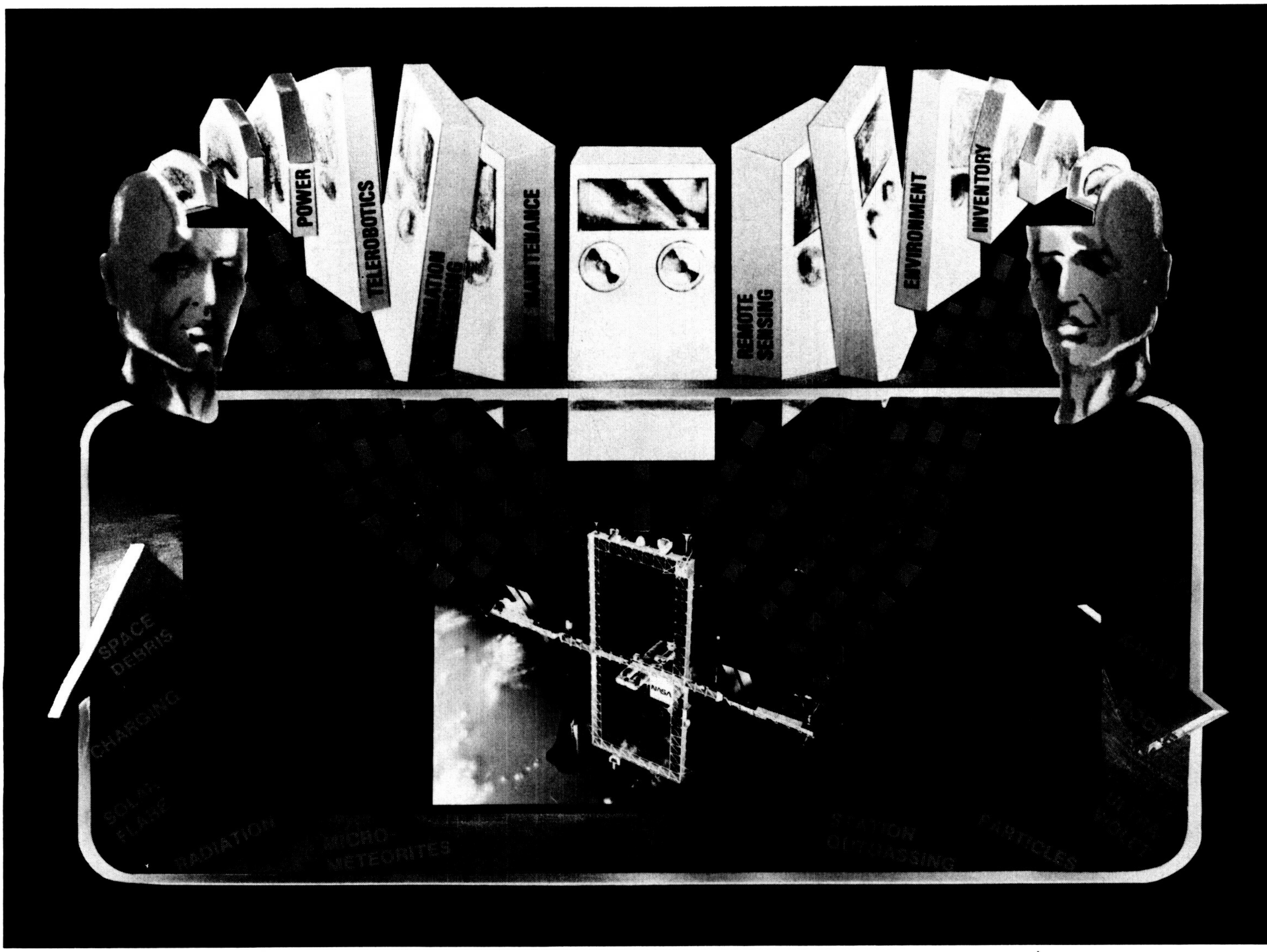
In April 1985, as required by Public Law 98-371, the NASA Advanced Technology Advisory Committee (ATAC) reported to Congress the results of its studies on automation and robotics (A & R) technology for use on the Space Station. A further requirement of the law was that ATAC follow NASA's progress in this area and report to Congress semiannually. This report is the fourth in a series of progress updates and covers the period from October 1, 1986, through May 15, 1987. (However, progress and program changes occurring after March 25, 1987, are not reflected in this document.)

During this report period

- The Critical Evaluation Task Force completed its studies and recommended changes to the configuration and assembly of the initial Space Station. These changes have been incorporated into the Space Station design.
- An Operations Task Force was chartered and has nearly completed its studies of the operations plans for the Space Station.
- The preliminary design phase of the program has been completed, and the request for proposals (RFP) for the phase C/D Space Station program support contract has been released. RFPs for the work package center flight elements design and construction will be released soon.
- The preliminary program plan for the Space Station Flight Telerobotic Servicer was completed. The RFP for the FTS phase B study contracts will be released soon.
- Additionally, the Office of Aeronautics and Space Technology has expanded its programs in telerobotics and systems autonomy in support of the Space Station.

ATAC is pleased to announce the appointment of Mr. Robert Nunamaker, a charter member of ATAC and Director for Space at the Langley Research Center, as its new chairman. Mr. Aaron Cohen has been appointed Director of the Johnson Space Center.

Drafts of this ATAC Report were prepared by the Intelligent Systems Branch at NASA's Johnson Space Center.



The evolution of computers to perform high speed knowledge based reasoning will contribute to a more autonomous, productive Space Station and will allow man to perform more critical, higher level functions.

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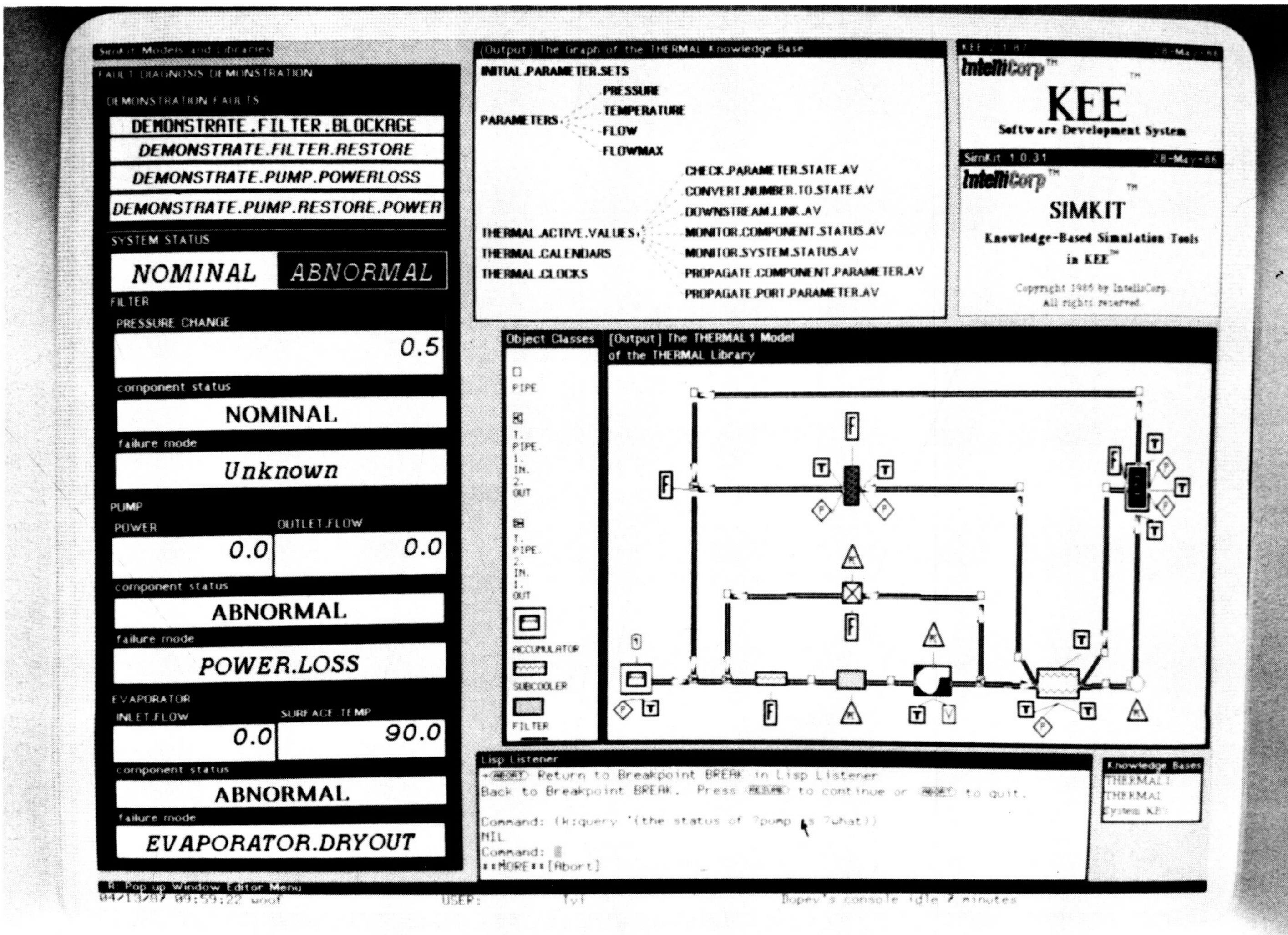
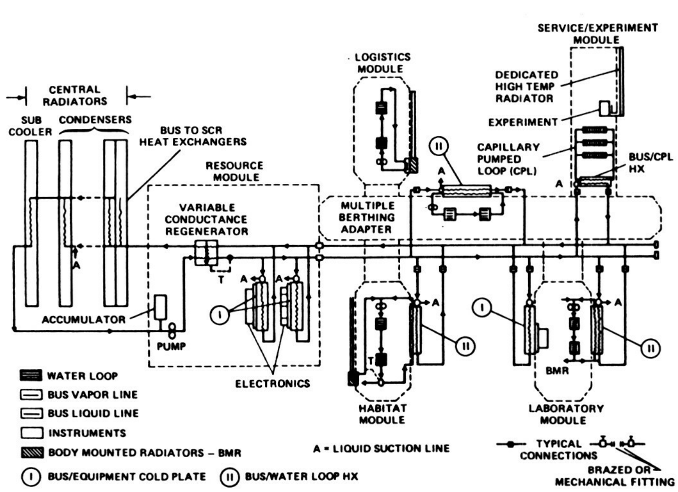




A 1988 systems autonomy demonstration will focus on automation of the Space Station thermal control system (TCS). The demonstration will be conducted within the thermal testbed at the Johnson Space Center which simulates the Space Station thermal system. A thermal expert system (TEXSYS) will be used to provide the automation capability. A display from TEXSYS (a symbolic processor prototype version) is shown in the upper portion of the illustration, and a schematic of the Space Station TCS is shown at the lower left.

The Space Station TCS consists of a central thermal bus which collects heat from distributed heat loads such as the habitat module, and transports the heat to central radiators which radiate the heat into space. TEXSYS includes models of the thermal system, stored knowledge bases, and diagnostic logic to monitor the TCS sensors and provide fault detection, isolation, and recovery.

Shown in the TEXSYS schematic is a simplified, but representative, central thermal bus including an evaporator and a condenser. TEXSYS has determined that a pump power failure has precipitated the evaporator overheating and "drying out." The systems autonomy demonstration program is described in a later section of this report. (Courtesy of Ames Research Center and Johnson Space Center.)

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, submitted April 1, 1985 (ref. 1), 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. Progress toward implementing the recommendations was assessed in ATAC Progress Report 1 (Oct. 1, 1985-ref. 2), Progress Report 2 (Apr. 1, 1986-ref. 3) and Progress Report 3 (Oct. 1, 1986-ref. 4).

In November 1985, Congress directed that NASA develop a flight telerobotic system, 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.

ATAC has been encouraged by the progress in automation and robotics. NASA adopted the ATAC recommendations for the basic program as policy. The committee's original findings have been confirmed by contractors' studies during the definition and preliminary design phase (phase B) of the program. The congressional augmentation has provided the needed impetus and focus for a U.S. telerobot for the Space Station. Increased awareness and attention to the merits of advanced automation should lead to technology implementations which will improve the productivity, reliability, and safety of the Space Station.

In Progress Report 3, ATAC expressed concerns and made specific recommendations to NASA regarding perceived deficiencies in Space Station initiatives which would inhibit automation and robotics. These concerns were openly received by program management, and ATAC is encouraged by recent actions taken in the areas of its recommendations.

This progress report occurs just as the requests for proposals (RFPs) for the design and construction phase (phase C/D) are about to be issued. The RFP for the program support contract has been released and is discussed in this report.

Minimal new design studies in automation and robotics have been identified during this report period by the phase B contractors, who essentially concluded their contracted studies during the previous report period. The major program effort involved the preparation of RFPs and the completion of design requirements and reference documents which baseline the Space Station configuration and support the phase C/D RFPs. Findings of the Critical Evaluation Task Force were incorporated into the program. A concentrated effort was conducted to accelerate the status of the Flight Telerobotic Servicer to be compatible with the level of the other Space Station elements.

The progress reported herein has been largely derived from program documentation and from materials provided by representatives in NASA Headquarters and in the various NASA centers. In addition, the committee obtained a specific presentation of FTS progress and plans.

An assessment of progress with respect to the initial ATAC recommendations is given in the following section. That section, along with the synopsis and the conclusions, provides a top level view of progress during this reporting period.

In making this assessment, ATAC has been mindful of the potential benefits of automation and robotics to the scientific user. ATAC believes that, in order to be highly productive, the Space Station must be flexible enough for adaptation to change as new knowledge is acquired. This concept was also described in the Space and Earth Science Advisory Committee (SESAC) Task Force report (ref. 5). The SESAC report supports telescience as, "essential to the success in space projects contemplated for Space Station." They noted that the role of humans in remote research activities will change as telecommunications and machine support tools for remote activities improve and experience is gained in their use. Telescience is the concept of conducting research remotely using both telecommunications and a variety of other machine based tools, thus emulating the advantages of physical presence of the science investigator at a remote laboratory.

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

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

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

The studies conducted during the definition and preliminary design phase of the Space Station Program have reaffirmed ATAC's original findings regarding the applications of A & R to the Space Station. Applications have been identified and recommended. During the definition and preliminary design phase, responsibilities for automation and robotics work were designated to personnel at program level B and project level C. The work package contractors were charged with, and accordingly developed automation and robotic plans which focused on candidate and recommended applications, assessments of technology, and preliminary design studies of selected candidates.

We noted, in Progress Report 3, that the role provided for automation and robotics in the management structure of the Space Station Program had not proved adequate for proper consideration of A & R due to the need for a top down architecture. The program management subsequently appointed a Division Director at level A with direct responsibility for A & R, and plans were announced for an organizational element at the new level A' which will perform integration studies and provide coordination of A & R across the program. Specific policies, plans, and budgets for these organizations have not been announced. ATAC believes the establishment of these organizational elements is a constructive step. We have also recommended that A & R advocates from the various NASA centers be retained within the management structure. These center representatives have been quite helpful to ATAC in assessing and reporting progress in automation and robotics.

The provision for the Flight Telerobotic Servicer (FTS) has promoted U.S. robotics to a primary element of the Space Station. The Critical Evaluation Task Force recognized the potential of robotics to reduce EVA hours but failed to define a role for the FTS in the assembly of the Space Station.The Space Station Program has now manifested the FTS at first element launch, and it has been incorporated into the Space Station baseline configuration. Specific plans are being developed for its use in assembly, maintenance, and servicing.

ATAC continues to be concerned that advanced automation will not be a significant element of the Space Station Program unless greater weight is given to life cycle costs or unless funds are set aside for this area of technology. However, the program has recently taken steps which should enhance the potential for automation to become the significant element recommended. One step has been to include automation and robotics in the design requirements. A second step has been to initiate a system synthesis study of the top down functional and physical control architectures to document and assess their abilities to support evolutionary advances in knowledge based systems. A third step was to include requirements for capture of design knowledge in phase C/D. Also, the OAST systems autonomy program has made good progress toward its 1988 demonstration of automation technology for the Space Station thermal control system.

However, there is an inadequate availability of flight qualified processors to support automation and robotics. Efforts are needed to develop processors which are not only flight qualified and targeted for Ada, the Space Station standard software language, but also are arranged in an architecture to exploit parallelism to obtain the computing speed required for autonomous control applications.

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

Progress has been made since Progress Report 3 in this top priority recommendation. The Program Definition and Requirements Document (PDRD) is the primary design requirements control document for the Space Station. Specific requirements have been incorporated into the PDRD to provide for software "hooks" and hardware "scars" design accommodations to facilitate updating A & R technology on the Space Station. The system synthesis study mentioned above will document the design accommodations of the functional and physical control architecture for evolution in automation.

In addition, requirements for the capture of design knowledge needed to support later operations of expert systems have been incorporated into the phase C/D program support contract RFP. Efforts are now under way to upgrade plans for the Technical Management and Information

System (TMIS) to provide for the relational data bases to facilitate the storage, retrieval, and transfer of this design data.

Within the program requirements documentation structure, Process Requirements Documents have been baselined for automation and robotics and for design knowledge capture. These documents provide data requirements for phase C/D of the program.

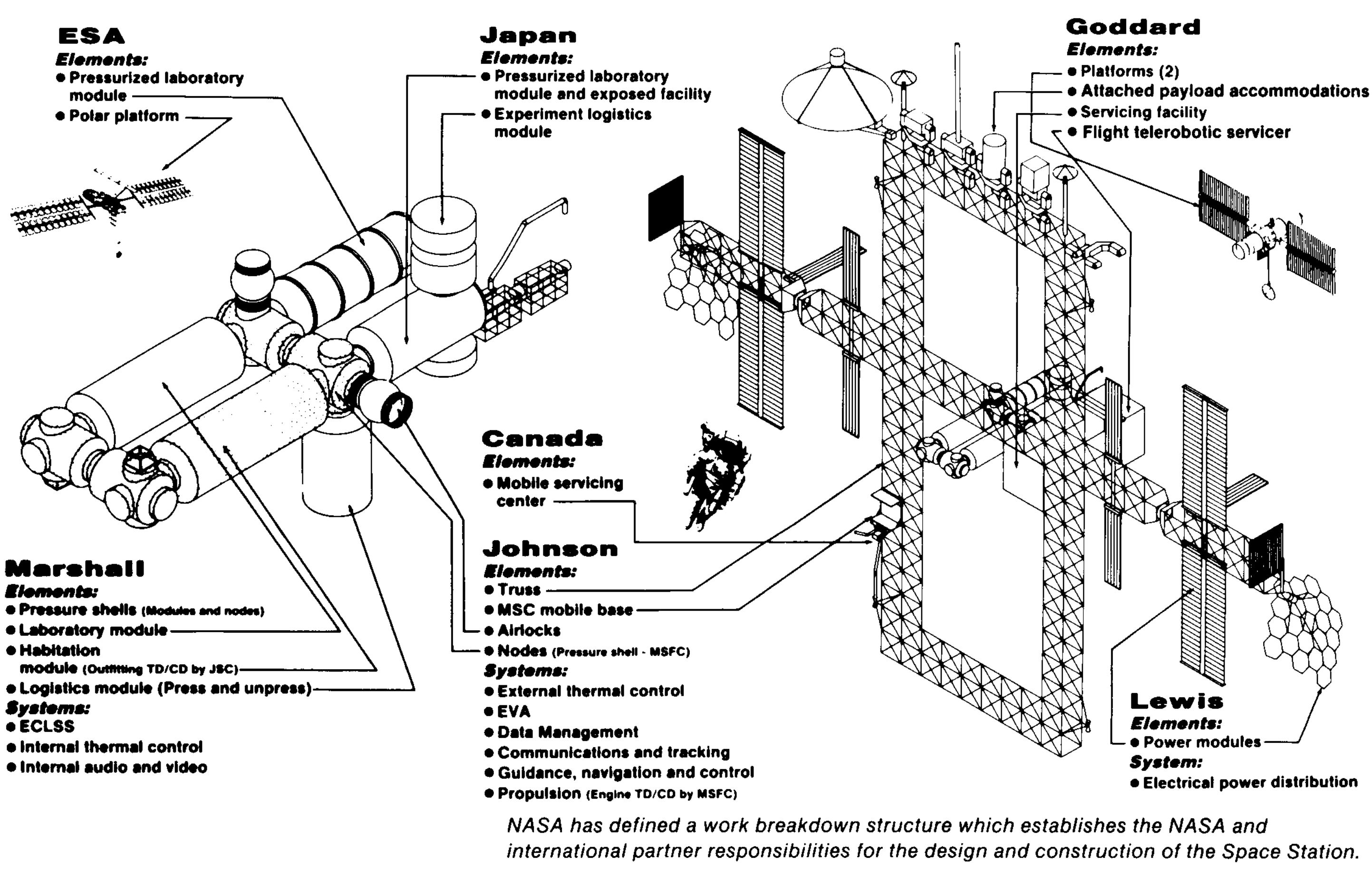
3. The initial Space Station should utilize significant elements of automation and robotics technology.

The Flight Telerobotic Servicer (FTS) and a Canadian Mobile Servicing Center (MSC) which includes a Special Purpose Dextrous Manipulator (SPDM) have been established as elements of the Space Station. Two program teams have developed architectural control documents which identify the tasks and potential uses of these robotic devices along with EVA, IVA, and various Space Station manipulators for assembly and external maintenance of the Space Station and for servicing the payloads, platforms, and free flyers. The program has also adopted the requirement to baseline telerobotic manipulation with EVA as a backup for these functions whenever practical and cost effective. An effort is under way to establish the specific roles and priorities for the different modes of assembly, maintenance, and servicing.

As noted in Progress Report 3, we can not ascertain at this time, the degree to which advanced automation will be incorporated into the initial Space Station. This will certainly depend upon the priorities, within fiscal limitations. ATAC expects that, as a minimum, expert systems will be utilized within the ground operations environment, then moved to the space environment as resources and the Space Station design permit. The degree to which advanced automation will be incorporated into the Space Station will be indicated in the submission and evaluation of the proposals for phase C/D. ***ATAC is concerned that an adequate mechanism does not exist for technologies developed by NASA to be incorporated into the contractor delivered elements.***

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

Criteria were developed during phase B of the Space Station Program. These criteria involved considerations such as safety, cost, productivity, growth and evolvability, technology risk, and benefits to the U.S. economy. However, a consistent, quantified set of criteria has not yet been applied across the program. Tasks and requirements have been established in the phase



NASA has defined a work breakdown structure which establishes the NASA and international partner responsibilities for the design and construction of the Space Station.

C/D program support contract RFP which include data requirements to support analyses of the relative tradeoffs of A & R candidates. The "building trust" and "building block" approach to incorporation of automation in Space Station systems as described in Progress Report 3 has been adopted in the Program A & R Process Requirements Document.

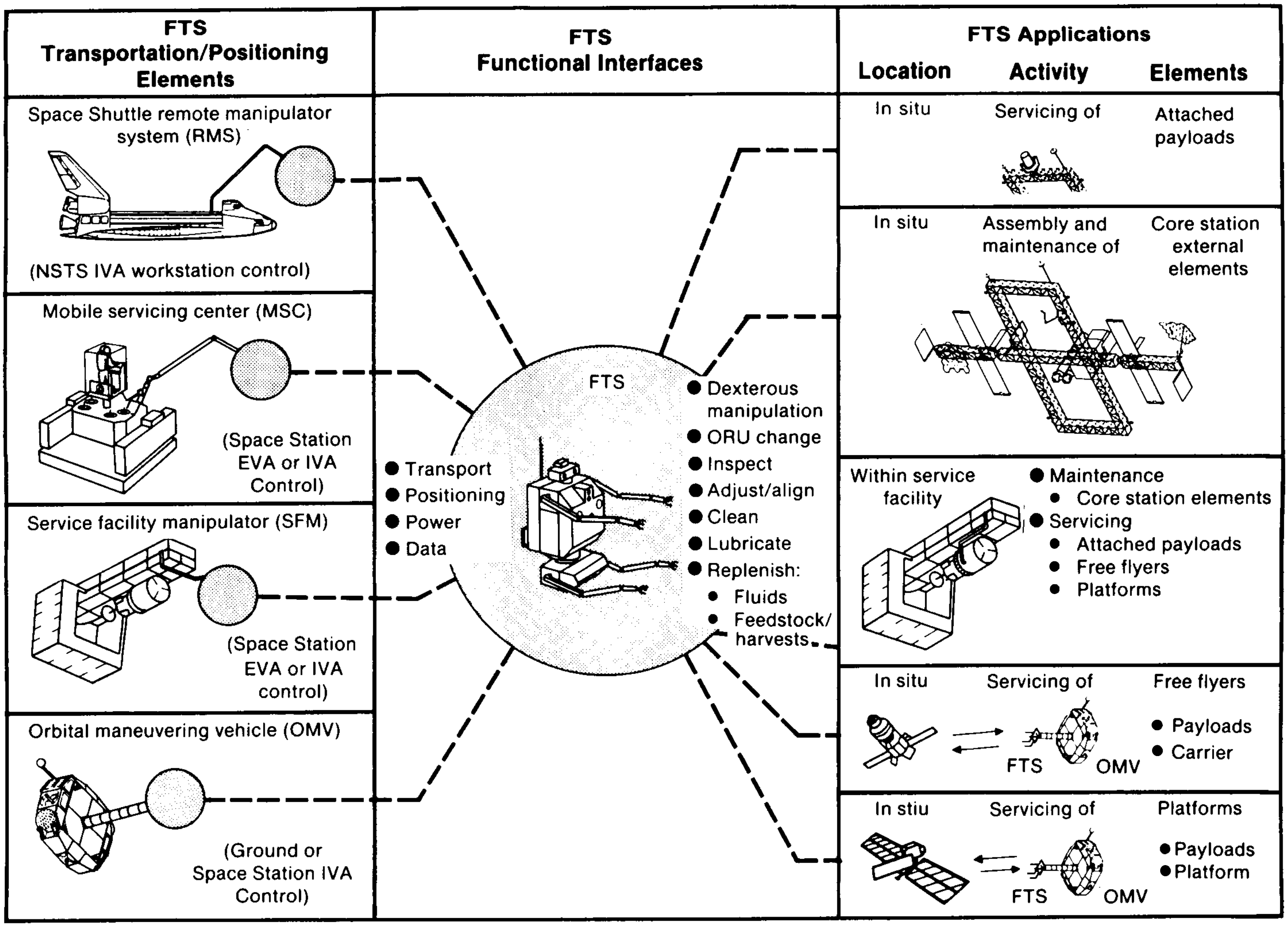
5. Verification of the performance of automated equipment should be stressed, including terrestrial and space demonstrations to validate technology for Space Station use.

The Space Station Program has requirements for testing and verifying equipment and procedures prior to launch. NASA has established testbeds which were used during phase B for testing automation and robotics components. The intent is to use the testbeds for preliminary verification studies of software and to use engineering models of the hardware to conduct validation assessments of the operational software. However, methods for verification of knowledge based systems are not receiving sufficient development attention.

Plans for the FTS include tests and demonstrations involving the testbeds and special equipment for robotic tests. The FTS development program includes plans for one or more tests of the FTS on the Space Shuttle.

The program of the Office of Aeronautics and Space Technology includes a series of robotic and systems autonomy ground demonstrations directed at the Space Station. The OAST is continuing its evaluation of automation and robotics technology flight experiments received as part of the "out-reach and in-reach" flight experiments programs. Initial experiment selections are expected during the next reporting period.

ATAC has recommended that after the phase C/D contractors are selected and the specific designs are established, the Space Station Program should proceed with a plan for the development, testing, and



The Flight Telerobotic Servicer will interface with Space Station flight elements to support the assembly, maintenance, inspection, and servicing operations of the Space Station.

demonstration of automated equipment for flight systems and elements.

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

During phase B of the Space Station Program, formal reviews, workshops, and state of the technology surveys were held. The FTS project brings together the research and program elements, and it leverages other government and industry research. The recent NASA co-sponsored Symposium on Automation, Robotics, and Advanced Computing provided a mechanism for the exchange of current technology efforts and status throughout the government, industry, and university communities. In addition, the Jet Propulsion Laboratory conducted a workshop on space robotics with over 450 attendees. The workshop has served to strengthen the collaborative space robotics research of NASA, industry, and universities. Fortunately, the Space Station contractor teams have been involved in both the commercial and the defense sectors. NASA centers have supported ATAC in maintaining the current status of its research and development efforts, as reported in appendix G.

We believe the Space Station Program enters the design and construction phase with the background understanding required for the effective use of technology developed for industry and government.

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

As previously reported, NASA is proceeding with the contractual procurement of the Technical and Management Information System (TMIS). Although this will not be available for some time, we think it will be of significant benefit to NASA and the Space Station Program. *ATAC has recommended a specific effort be established by TMIS and Space Station personnel to address provisions for design knowledge capture at the earliest possible time.*

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

As reported in Progress Report 3, no quantified plan exists to provide these measures and assessments. The specific data requirements for automation and robotics should be included in the phase C/D RFPs to allow a first assessment. The operations integration of A & R should provide the source of the effectiveness of A & R.

Recommendations for an augmented program

Recommendations 9 through 13 were made contingent upon an augmented program that would enhance the technology base and accelerate research and development. The acceleration would allow a great deal more automation and robotics technology to be incorporated into the Space Station.

Although the level of augmentation provided does not support the broad base of technology on which recommendations 9 through 13 were made, augmentation has been provided to support the development of the Flight Telerobotic Servicer, as reported elsewhere in this and revious ATAC reports. In addition, augmentation efforts are being initiated by OAST to accelerate and build up both the core research and technology program and the demonstration program through the Civilian Space Technology Initiative (CSTI) program.

Progress on Space Station Design for Automation and Robotics Utilization

ATAC has continued to monitor the progress of the Space Station design for applications of A & R during the definition and preliminary design phase (phase B). This ATAC progress report is being issued in the interim between the completion of phase B and the start of phase C/D.

In this section of the report, we will review progress which relates to

- The Critical Evaluation Task Force (CETF) study
- The A & R definition by the study contractors
- The extent to which A & R has influenced the design of the Space Station as reflected in baseline program documentation
- The definition of life cycle cost analysis methods
- The end effector strategy study

Critical Evaluation Task Force study

One of the guidelines for the CETF study (ref. 6) was to "minimize NSTS-based and Station-based EVA for assembly and operations." Program studies using the preliminary configuration of the Space Station had shown excessive hours for assembly and maintenance based on the use of EVA only. Among the options considered was the use of telerobotics, specifically the FTS and the Canadian SPDM for productivity improvements. Studies by the work package contractor, Rockwell, had indicated significant reductions in EVA hours based upon the use of robotics.

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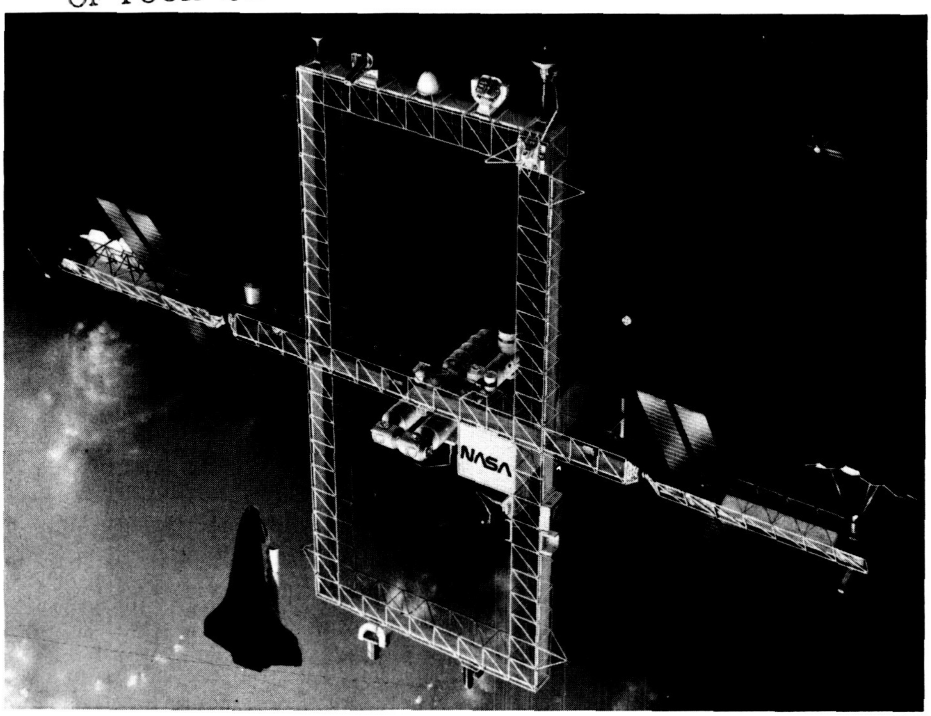


A NASA Critical Evaluation Task Force provided configuration and assembly recommendations which resulted in a Space Station design with early scientific capabilities and reduced extravehicular activity requirements during Space Station assembly.

Minimizing EVA hours was only one of several guidelines and considerations of the CETF study. The configuration and assembly approach recommended by CETF provided for deployable resource modules (nodes), with much of the external equipment moved inside the pressurized resource modules. This approach reduced the EVA hours for assembly and maintenance to supportable levels and satisfied other guidelines and considerations.

Having satisfied their guideline on EVA hours, CETF did not pursue the robotics option further, except to conclude that the "robotic capability to [further] reduce EVA is very favorable" and to note that

- Robotic assembly can start one or two days before the crew is ready for EVA on day 4
- Simple repetitive tasks could save one-third to one-half of the EVA time on early assembly flights
- Assembly robots could be upgradeable for long term dextrous manipulation
- A flight qualified teleoperated or programmed/monitored robot could be available for the first launch

However, specific manifesting of the FTS was not included in the CETF recommendations, allowing that decision to be based on further program studies and requirements definition. Subsequently, the Space Station Program manifested the FTS for first element launch.

Phase B Contractor A & R Definition Studies

The definition and preliminary design phase (phase B) of the Space Station Program is now completed. The work of the work package contractors was essentially completed prior to ATAC Progress Report 3. Final reports (refs. 7-12) confirm previous projections.

Although the contractors have continued internal research and development and some Space Station Program advanced development studies related to A & R, there are few new results reported except for specific areas of detail.

It is useful to review, for a final time, the progress and accomplishments of the contractor phase B automation and robotics studies.

Candidate applications for A & R were identified within the context of the subsystems and flight element definition of the Space Station. Assessments of the status of the technology were made (ref. 2), and based upon these two results, candidate applications for A & R on the initial Space Station were identified, as given in appendix D.

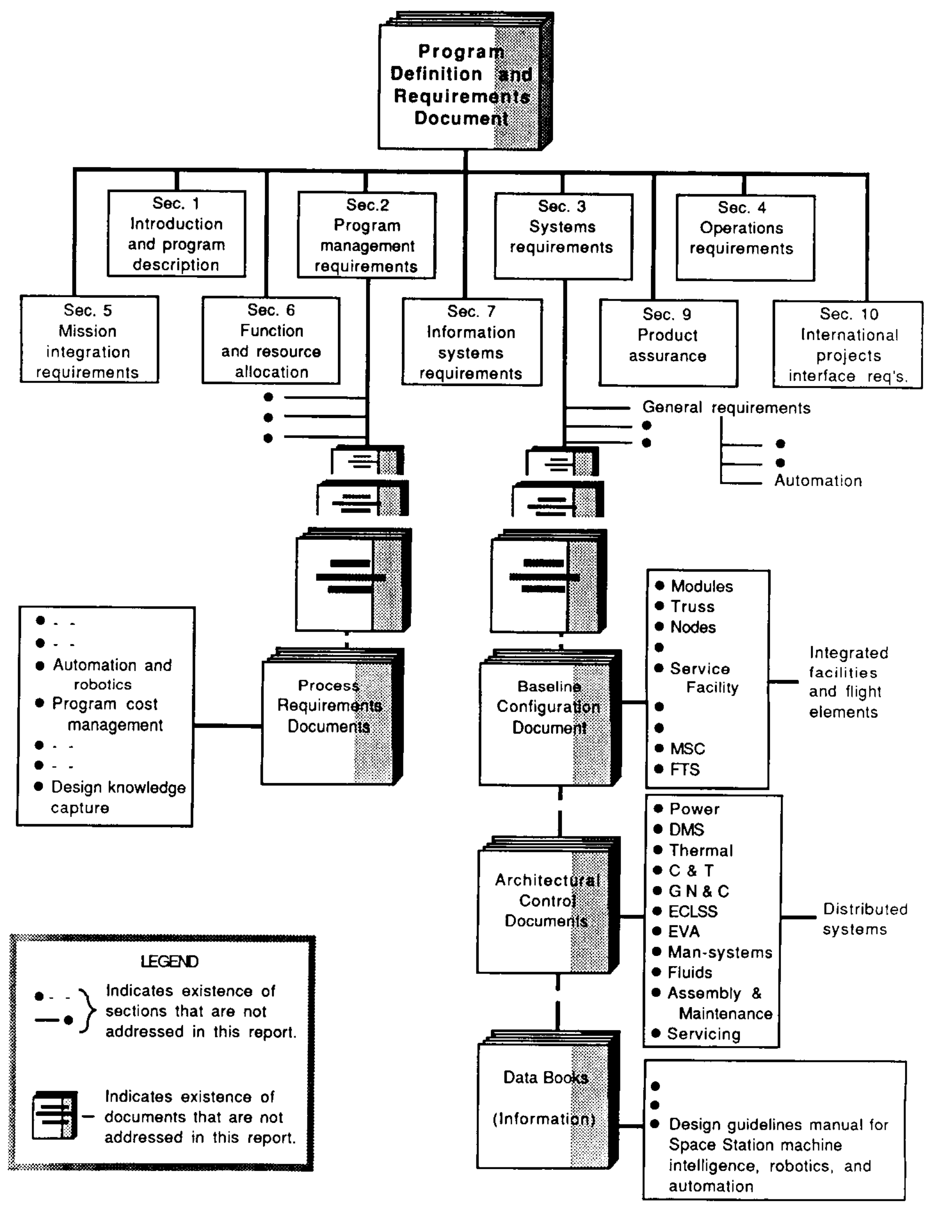
Criteria for screening and selecting the most promising candidates were developed and applied. The criteria involved safety, performance, productivity, cost, risk, and growth and evolvability. Importantly, cost studies (refs. 3 & 4) showed that the operations cost benefits of many A & R candidates exceeded the development and implementation cost in a period of only 2 to 4 years.

These studies led to a set of recommended applications for the initial Space Station as given in appendix E and to the identification of many of the provisions needed on the initial Space Station to support future A & R applications (ref. 3). These A & R studies significantly supported the requirement for a generic robot such as the Flight Telerobotic Servicer and subsequently provided input into configuration, assembly, maintenance, and servicing planning. They also provided key input in the definition of the Space Station Data Management System as a mechanism for the incorporation of advanced automation in the Space Station.

ATAC believes these studies by the work package contractors provide a sound base of data for proposal content and decisions for the design and construction phase of the Space Station.

A & R Provisions of the Program Baseline Requirements Definition

The Program Definition and Requirements Document (PDRD) and its supporting documents provide the baseline requirements, the configuration, the architecture, and the process control for the Space Station design. As such, these documents provide the technical requirements for the proposals for phase C/D. Therefore, it is useful to examine the provisions relating to A & R in these documents.



The Program Definition and Requirements Document (PDRD) provides the requirements for the Space Station. Automation and robotics requirements are embedded in the PDRD and supporting documents. This figure is intended to illustrate the location of key A & R provisions and interests and is not intended to convey a hierarchy of documents.

It is not feasible in this report to duplicate the requirements and specifications related to automation and robotics occurring throughout the documentation. It is useful to address those portions of the documentation in which automation and robotics requirements and applications are focused. For this purpose, the accompanying illustration highlights those selected portions. The following sections of this report briefly summarize A & R interests in the documentation. In addition to the specifications in these program documents, work package specifications are found in subordinate documents which we do not address.

Program Definition and Requirements Document

The Program Definition and Requirements Document (ref.13) is the top level program control document for the design of the Space Station. Higher level control documents address program policy, program directives, international agreements, and other agreements.

All other design documents are subordinate to the PDRD.

Automation and robotics requirements are distributed throughout the document. They are more specific for robotics as the direct result of the FTS and the Canadian MSC being flight elements of the Space Station. Where automation requirements are specified they are described as neither conventional nor advanced automation. Critical provisions for A & R occur as general requirements, applicable to the entire Space Station design. The general requirements (ref. 14) provide for

- Hooks and scars to support the evolution and growth of automation and robotics technology
- Sensors and actuators to allow monitoring, analysis, and control by autonomous systems
- Telerobotic manipulation as baseline, whenever practical and cost effective, with EVA as a backup
- Interfaces for robot "friendliness"
- Voice activation of computer functions where cost effective, productive, and safe
- Automation of Space Station systems management to the extent practical, cost effective, and operationally verified
- Collision avoidance by robotic systems
- Conveyance of knowledge based systems' decision reasoning to the flight crew and to the ground

Baseline Configuration Document

The Baseline Configuration Document (BCD) establishes the integrated and individual element architecture covering the Space Station functionality and general arrangement (ref. 15). This includes the Laboratory and Habitation Modules, the Mobile servicing Center, the Mobile Servicing System Maintenance Depot, the Mobile Transporter, the Service Facility, the Attached Payload Accommodation Equipment, the Logistics Carriers and Module, the Airlocks, the Flight Telerobotic Servicer, the Solar Power Module, the Truss Assembly, and the Resource Nodes.

The foremost important A & R consideration in the document is that the Flight Telerobotic Servicer is included. Although it is labeled a draft, the FTS section provides a functional description and requirements consistent with the FTS plan and at about the same level of completeness as the other elements. This includes definition of the mission functions the FTS is to perform, description of the equipment, description of the transport mechanisms, and interface definition of the FTS with the Space Station distributed systems for power, data, thermal control, communications, and control.

Other flight elements include provisions which are critical to the applications of the FTS. These include

- A provision for the Canadian MSC to provide support of dextrous end effectors. (This would encompass the FTS and the Canadian Special Purpose Dextrous Manipulator (SPDM))
- A provision for the service facility manipulator to provide an interface to the FTS which will include power and data utilities
- Compatible interfaces by Attached Payload Accommodation Equipment with the FTS and MSC
- Compatibility of the co-orbiting platform for servicing and maintenance in the Service Facility and in situ with either the FTS or the Space Shuttle remote manipulator system and with EVA as a contingency and a backup mode. Orbital Maneuvering Vehicle based in situ servicing and maintenance will use the FTS.
- Polar orbiting platform provisions which are similar to those for the co-orbiting platform

Architectural Control Documents

The Architectural Control Documents (ACDs) define the functional requirements for the distributed subsystems of the Space Station, the methods for accomplishing the functions, and the interactions. These ACDs cover EVA, Manned Systems, Thermal Control, Communications and Tracking, the Data Management

System, Environmental Control and Life Support, Electrical Power, Fluid Management, and Guidance, Navigation, and Control. In addition, there are ACDs for assembly and maintenance and for servicing which describe those activities in an integrated fashion.

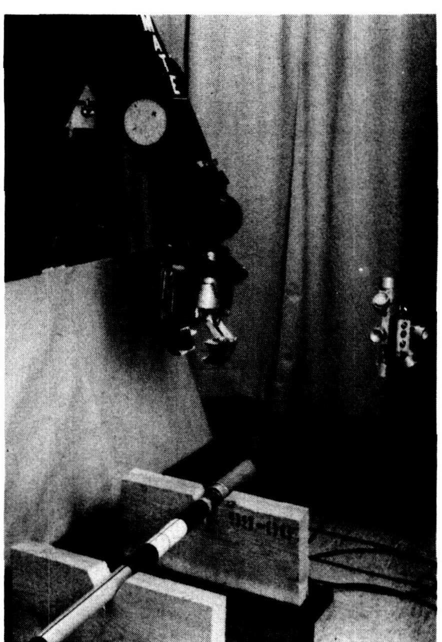
The subsystems ACDs (refs. 16-24) include significant automation requirements. The documents specify functions which the work package contractors have identified as candidates for advanced automation — planning, scheduling, display and control, fault detection, isolation and recovery, self diagnosis, etc. The ACD's neither require nor preclude the use of advanced automation to perform the functions. The automation mechanism is generally defined as a standard data processor embedded in the data management system (DMS). In turn, the data management system architecture provides for both standard and expert systems methods of automation and requires a process by which new technology can be introduced into the DMS (both ground and on-orbit) without interrupting the ongoing operations. This is an important provision for the evolution of advanced automation and robotics on the Space Station. Additionally, the DMS provides for an Operations Management System (OMS) that provides a mechanism for the implementation of autonomous control of system level functions onboard the Space Station. However, the systems design requirements cited in the PDRD to accommodate the effects of ionizing radiation (i.e. single event upset performance degradation) are not clearly reflected in the DMS architectural control document. This oversight could result in a design that will not be suitable for the support of automation and robotics.

In the area of robotics, the EVA Architectural Control Document defines interface requirements with the Flight Telerobotic Servicer and with the Canadian Mobile Servicing Center. Importantly, EVA for Space Station external inspection is to be employed only when other methods (e.g., fixed TV or robots) cannot perform the function. The Man Systems ACD defines the requirements of workstations as locations for control of telerobotics systems.

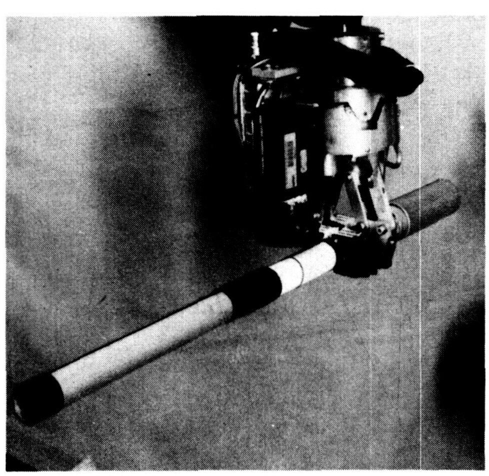
The Assembly and Maintenance ACD (ref. 25) and the Servicing System ACD (ref. 26) are qualitatively different from the distributed systems ACD's in that they define and control activities rather than hardware. The Space Station Program distinguishes servicing from maintenance as follows:

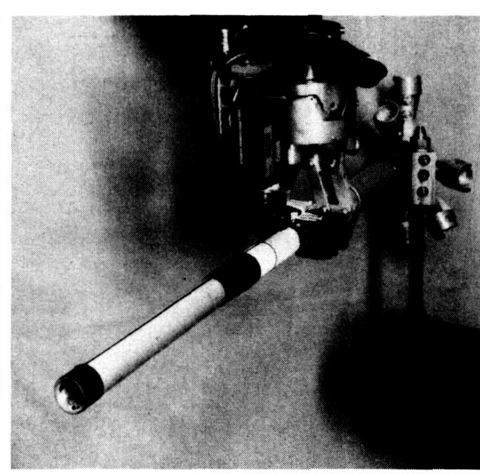
- Servicing comprises tasks performed on user or customer hardware such as external platforms, attached payloads, and free flyers normally operated externally
- Maintenance comprises tasks performed on the Space Station hardware

These two ACD's are significant to robotics on the Space Station because of the vital role that robotics is projected to play in the areas of assembly, maintenance, and servicing. The two ACD's associate the capabilities of the robots, manipulators, and EVA with assembly, maintenance, and servicing tasks.



Indications of the feasibility of truss assembly using a telerobot was demonstrated by the assembly of a column and node using a PUMA manipulator under teleoperator control. The column and node are from the Space Shuttle ACCESS (assembly concept for construction of erectable space structures) experiment. (Courtesy of Langley Research Center.)





The Assembly and Maintenance ACD establishes the assembly and maintenance architecture by associating assembly and maintenance requirements with the Space Station systems and elements that provide the capability to meet these requirements. Assembly is characterized as consisting of

- Construction of the truss and related structural elements
- Installation of systems and modules
- Verification

Maintenance includes both preventative and corrective maintenance and the functions of

- Inspection, checkout, and testing
- Repair and restoration

The Servicing System ACD establishes the overall user servicing system architecture. The system architecture is defined in terms of the capabilities of the various support elements involved in user servicing and the specific functional requirements for servicing.

For many, if not most, of the required assembly, maintenance, and servicing tasks, there is more than one option for performing the task. An additional study effort is underway to establish the priority of the options for performing each task. ***However, these two ACD's serve to reduce much of the concern expressed by ATAC in Progress Report 3 regarding deficiencies in the Baseline Configuration Document and in the Architectural Control Documents.***

Process Requirements Documents

The Process Requirements Documents are a part of section 2 of the PDRD and serve to define task, management, and data requirements for ensuring success of the program in specified areas. There are 18 Process Requirements Documents in the areas of system engineering, verification, and operations.

Automation and Robotics Process Requirements

The purpose of the Automation and Robotics Process Requirements Document (ref. 27) is to define the NASA and contractor actions that will implement flexible capability A & R in the Space Station and transfer A & R technology to the U.S. terrestrial economy according to the intent of Public Law 98-371 and the NASA policies adopted from the NASA Advanced Technology Advisory Committee recommendations. A further purpose is to relate these actions to the Space Station Program systems engineering and integration process which provides their program context. However, ATAC does not consider this document adequate to guide the contractors for phase C/D of the program.

The A & R Process Requirements Document describes the A & R roles in support of program goals, the key attributes of A & R, and the life cycle costing of A & R designs. The document adopts the preferred sequence for implementing automation and robotics as reported in ATAC Progress Report 3 and in appendix F of this report. A management approach and flow is identified with a top down architecture starting at level A of the Space Station Program. Program data requirements for A & R are

- A design, development, testing, and evaluation plan for A & R
- An automation integration plan
- A robotics integration plan
- An evolutionary Space Station A & R plan
- An automation and robotics design document

Process Requirements for Design Knowledge Capture

The purpose of this process requirements document (ref. 28) is to define design knowledge capture requirements placed on the Space Station designers. It describes the objectives and benefits of design knowledge capture, the steps in the process of design knowledge capture, and a process flow involving the program designers and relational data bases within the Technical and Management Information System.

Advances in technology now make possible the electronic collection and retention of both the preferred design and the information which led to the design definition. Design knowledge which is machine interpretable can be utilized directly by software application programs. This potential cannot be established retroactively, as source design knowledge will no longer be available. Early paybacks derived from design knowledge capture will be major benefits for operations, maintenance, design reviews, system integration, sustaining engineering, growth, and machine intelligence. Possible applications include, but are not limited to, training, system monitoring, malfunction detection and diagnosis, planning, execution of maintenance and repair procedures, and automatic guidance of robots. Design knowledge which is provided only in man-readable, non-electronic form is not considered to be captured.

The document defines a capture strategy based on the use of current technology, such as CAD/CAE systems, specification language systems, and relational data bases. The program data requirements for design knowledge capture are

- Project management plans for design knowledge capture development
- Conversion plans of Space Station Program design documents
- A definition document of the initially installed design knowledge capture system
- An acceptance package for the design knowledge capture system
- Review and audit reports of design knowledge capture
- Deliverable Space Station Program design knowledge

Space Station Cost Management Process Requirements

The Space Station Cost Management Process Requirements document (ref. 29) establishes the process to be used within the Space Station Program for the definition, allocation, and control of both developmental and operational costs. The document provides for

- A process for the management and control of both development and life cycle costs
- A strategy for integrating the engineering and cost decision processes
- A set of standard tools for cost assessments and trade studies
- A process to establish management cost commitments and accountability for program implemention

Data Books

Design Guidelines Manual for Space Station Machine Intelligence, Robotics, and Automation

The design guidelines manual (ref. 30) is a reference-only document providing guidelines for the accommodation of automation and robotics in the design of the Space Station. It gives guidelines intended to provide the hooks and scars necessary to integrate improved automation, robotics, and machine intelligence into the Space Station design as these improved technologies become available.

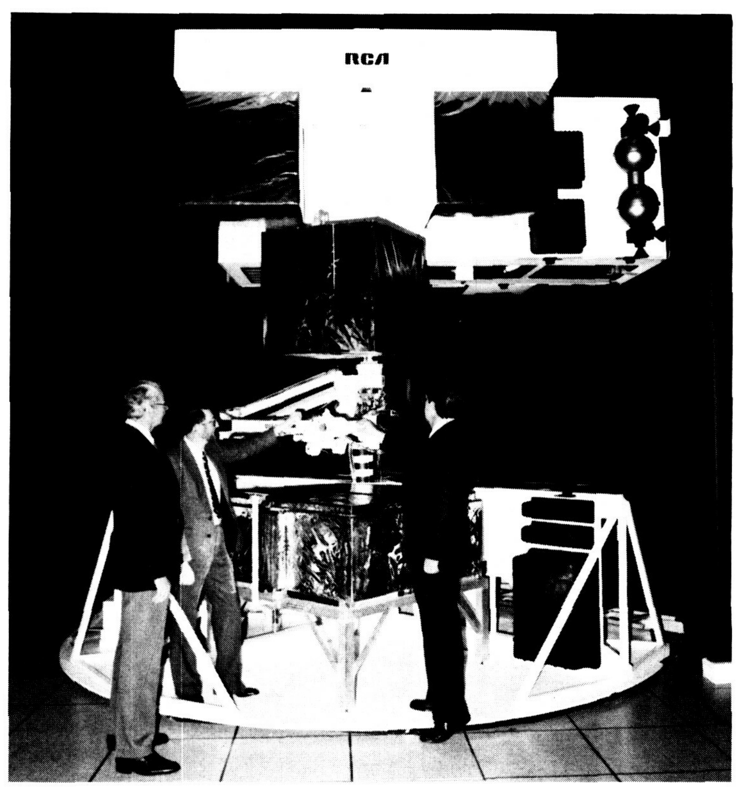
Definition of Life Cycle Cost Analysis Methods

The use of A & R in the design of the Space Station may significantly decrease Space Station life cycle cost while increasing the safety and productivity of the crew. To quantitatively understand these potential benefits from A & R, it will be necessary to perform a number of trade-off studies in phase C. Two documents that discuss analysis tools can be used for these studies. These documents are the Cost Management Process Requirements document and the Automation and Robotics Process Requirements document. Both documents present a similar concept for relating the systems engineering and costing of design options.

The cost management document discusses a program cost management process that makes use of two major types of analysis tools. One is the Model for Estimating Space Station Operations Cost (MESSOC). This model has the capability to compute operations costs in approximately 20 categories which cover items such as crew time, maintenance, and repair. Automation and robotics benefits can be largely related to these three items. Therefore, MESSOC should have the capability to quantitatively study A & R trade-off options.

The other model discussed in the program cost management document that can be used to understand A & R benefits is the System Accounting Model (SAM).

An interface mechanism for transferring large replacement modules from one spacecraft to another is evaluated by engineers from the Marshall Space Flight Center and the Goddard Space Flight Center.



This model is an input/output accounting model that treats each major work breakdown category of the Space Station as a "small business" which supplies services or goods and also demands services or goods. This supply and demand feature of the model allows a designer to study the cost impact of a design alternative on each work breakdown element of the Space Station. Costs related to the operational elements as well as to the other elements of the Space Station are handled by SAM. In fact, SAM uses MESSOC to compute operational costs.

The Automation and Robotics Process Requirements document discusses life cycle costing from a more general point of view than does the program cost management document, but it is consistent with the analysis approaches presented in the program cost management document. Therefore, if prospective contractors follow these documents in their phase C/D activities, A & R cost trade-offs can be accomplished.

End Effector Strategy Study

In order to avoid duplication of effort for end effector studies and development, to avoid unnecessary logistics, and to avoid complex interfaces and cost impact, the Space Station Program commissioned a study which was completed in December, 1986. This study provided definitions of end effector terms, and it collected and identified program functional requirements and tasks for end effectors. It assessed current state of the art end effector technology, and it provided guidance to the program in developing a strategy for end effectors and their development.

The study was conducted by an ad hoc working group with participants from the program office, the work package centers, the Jet Propulsion Laboratory (JPL), the Langley Research Center (LaRC), and the international partners. Langley Research Center (LaRC) provided the lead and the background work to integrate inputs from the participants.

The approach taken for the study was to survey all program documents and identify requirements for end effectors, to survey all end effectors reasonably related to potential use in space, and then to form a comparative assessment of the available technologies and the program requirements. From the comparative assessment, a set of program options was developed for a program wide end effector strategy. As part of the study, a definition of terms was developed that will form part of a process to implement the strategy.

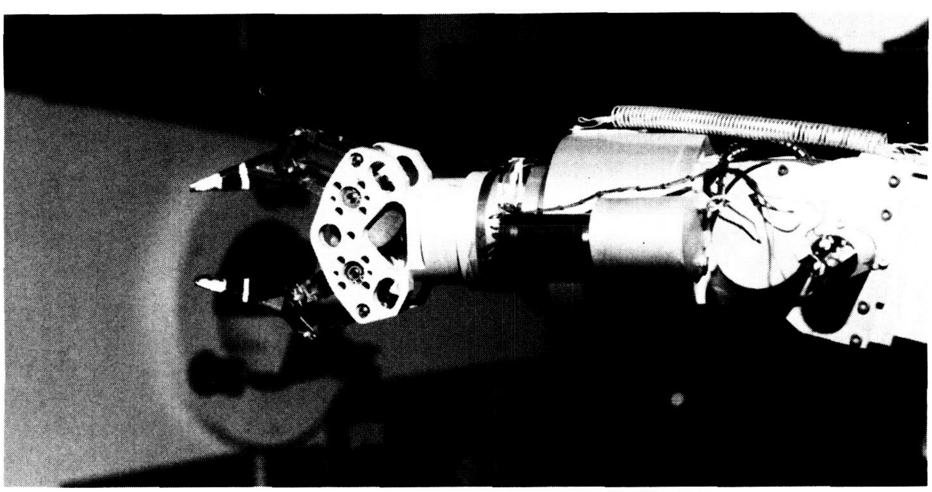
The study identified several areas that merit further consideration for a continuing study activity to

- Further identify requirements that specifically call for or imply the use of end effectors
- Develop quantitative methodologies for selecting the best program policies in commonality, interchangeability, etc.
- Identify and address technology issues
- Establish a consistent program policy with respect to end effectors

From the study, the need was identified for a major activity to address the issue of upgrading or redesigning the current National Space Transportation System (NSTS) Standard End Effector and to define the degree to which a common Space Station end effector/assembly can be used by all Space Station participants, including international partners.

In addition, the need for work on certain end effector/assemblies was clearly identified. Work is needed in extending umbilicals to handle the transfer of cryogenics, heating and cooling, hazardous fluids, and power. Minimally, a study activity to develop a new EVA-compatible, small, standard grapple for orbital replaceable units (ORUs), as suggested by the European Space Agency, is in order. Definition and advanced development of sensor end effectors/assemblies was mandated by the existence of strong Space Station Program requirements and the lack of any activity in this area, within or outside the program.

End effectors are a key part of remote manipulator systems. End effectors will be required for Space Station activities such as docking, satellite retrieval, inspection, parts changeout, fluids replenishment, etc. (courtesy of Marshall Space Flight Center.)



Progress on the Flight Telerobotic Servicer for the Space Station

As reported in ATAC Progress Report 3, a plan for the development and implementation of the Flight Telerobotic Servicer (FTS) has been established (ref. 31). This plan furnishes organizational, management and schedule details. Cost and funding information is noticeably absent. Technical details are consistent with those reported in ATAC Progress Report 3.

During this ATAC report period, the planned activities of the FTS have been defined, a "skunkworks" activity was conducted to identify and address issues critical to FTS development, and the development of FTS requirements has been initiated. These items are described in the following sections. In addition, critical requirements related to the FTS have been incorporated in the overall Space Station design, as described in the previous section of this ATAC report.

Flight Telerobotic Servicer

The FTS is to perform on-orbit tasks that will enhance crew activities and other operations required of the Space Station Program, of the National Space Transportation System (NSTS), and of the Orbital Maneuvering Vehicle (OMV). The planned activities of the FTS are characterized as follows:

- Installation, removal, and reconfiguration of Space Station components, attached payloads and components, platform payloads and components, and other equipment. At the time of the Space Station first element launch, the FTS shall have the capability to perform, as a minimum, the support of truss assembly activities, changeout of orbital replaceable units (ORU), and the mating and demating of thermal utility connections.
- Manipulation of items such as ORUs, tools, parts, and consumables at the worksite.
- Servicing, maintenance, and housekeeping operations at the Space Station and in situ on free flyers and platforms.
- Inspection and monitoring of systems at the Space Station and in situ on free flyers and platforms. This inspection and monitoring will include the use of visual extension aids such as vision systems, video links, targets, and optical codes.
- Attaching itself to the worksite to provide alignment, stability, retention, release, and accessibility to the workpiece, with knowledge of the location and orientation of itself and of the workpiece.
- Interfacing with, attaching to, and operating from the Space Shuttle Remote Manipulator System (RMS), the Canadian Mobile Servicing Center (MSC), the OMV, the Service Facility Manipulator (SFM), the Space Station fixed manipulator system, and other host systems. The FTS requires that the host system supply the appropriate power, data, video links, and location support. In addition, the FTS requires utility port capability when the telerobot is secured to the worksite (detached from the host) and Space Station communications and tracking (C&T) coverage is not possible because of interference. With adequate radio frequency links, the FTS can operate without connection to any host or utility source.
- Supporting astronaut extravehicular activity (EVA).

In order to develop the concept for the FTS, certain ground rules (absolute requirements) and certain constraints (highly desirable but subject to trade studies) were established. The following ground rules were established:

- Safety (particularly crew and critical hardware safety) is a major design consideration. Safety analyses must consider the worst case for all operating environments.
- The FTS must meet the Space Station criteria for critical systems in that it must be both fail safe and fail recoverable.

In addition, recognizing that these criteria may be modified, and depending on the result of trade studies and budget considerations, it is desirable that

- The capability shall exist for the FTS to be brought into the Space Station pressurized modules and be secured, powered, maintained, and tested there.
- The FTS will be stored in a protected facility outside the pressurized modules. Protection is primarily against contamination and extreme temperatures. The facility will accommodate limited servicing of the FTS, such as battery charging, testing, calibration, and checkout of FTS systems.
- The FTS shall be transported to and from the various worksites by the MSC, the SFM, the system supporting the crew and equipment mobility function, the Space Station fixed manipulator system, the NSTS, and the OMV.
- Any task identified for the FTS must be designed so that it can be accomplished by EVA astronauts equipped with appropriate tools.

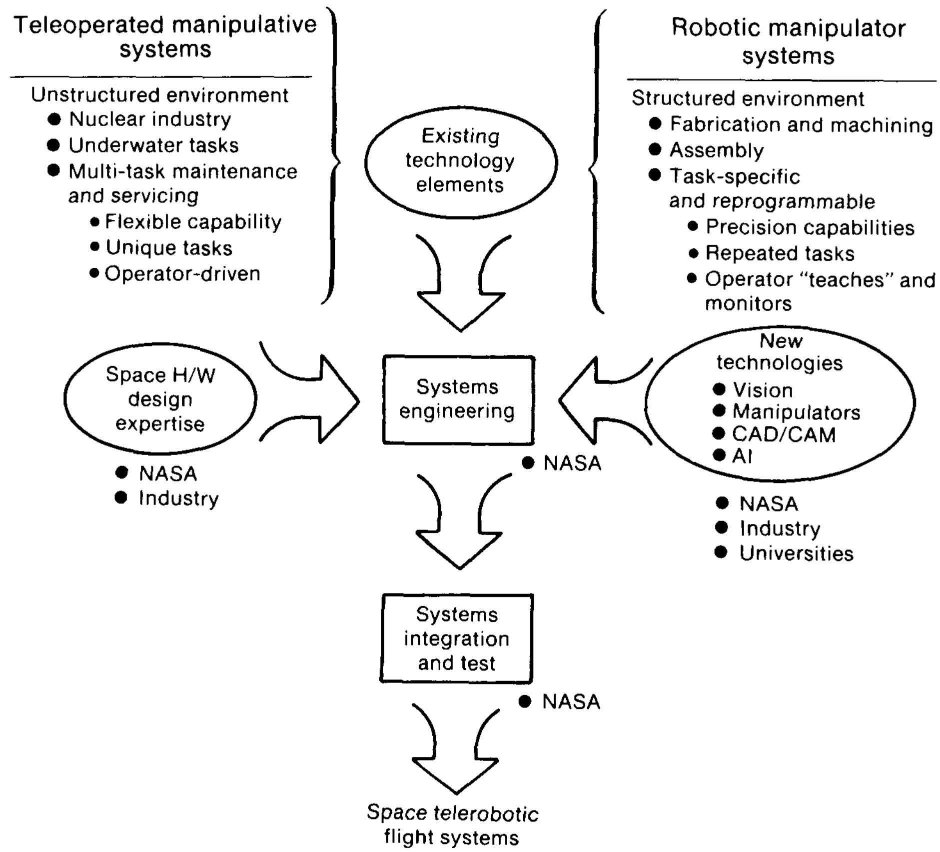
- All FTS subsystems that are essential for maintaining crew safety and for the operation of critical hardware shall be two fault tolerant, fail safe, and on-orbit restorable.
- The Space Station will provide a data link between the FTS workstation and the FTS. In addition, the FTS will require simultaneous transmission of up to four channels of broadband color video for the monitoring system. These transmissions must be available in both hardwired and radio frequency links.

Between Space Station first element launch and its initial operational capability, the FTS will gain the capability of performing tasks of increasing difficulty and complexity, including supervised, highly autonomous operations.

FTS Project Management

The FTS project is one of the Goddard Space Flight Center (GSFC) projects that form work package 3. The FTS was defined as a Space Station flight element near the end of the Space Station phase B study effort. It was decided that more industry competition would occur if the FTS were not part of the work package 3 prime contract and therefore, the FTS will be procured separately and provided to the work package 3 prime contractor as government furnished equipment for integration with the Space Station. In addition, the development of the FTS will draw upon the existing technology development efforts within NASA as well as drawing upon industry developed telerobotic technology. These factors required that the FTS project office at GSFC have both programmatic and project responsibilities.

The major responsibility of the FTS project office is to develop a Space Station flight element, available at



The development of a telerobotic system for space flight requires a systems engineering approach to integrate existing manipulator systems technology with space design expertise and with new technologies under development. A major challenge in developing the flight telerobotic servicer is to unite the technologies in existing teleoperated manipulator systems (which were designed to meet many different needs) with the technologies in existing robotic manipulator systems (which were designed to be task specific).

first element launch, that is a multipurpose tool with capabilities that can help reduce EVA requirements. Furthermore, the FTS must be designed so that its capabilities can grow and improve between first-element launch and the completion of Space Station assembly and that the FTS can accommodate technology enhancements thereafter. To accomplish these goals, the FTS project office has the responsibility to manage the design, development, and delivery of the flight element, to conduct both the simulation and the flight testing of telerobotic concepts for potential inclusion in the flight element, to evaluate telerobotic technologies for potential system improvement, and to facilitate telerobotic transfer to industry.

The FTS project office is supported by research and development laboratories in NASA. An agreement has been reached between NASA's Office of Aeronautics and Space Technology (OAST) and the Office of Space Station (OSS) that enabling and enhancing telerobotic technologies being developed in OAST will be provided to the Office of Space Station robotic laboratories for evaluation. FTS contractors will evaluate OAST technology for applicability and appropriateness when new technology is being used in the FTS conceptual design.

This approach will leverage the government's ongoing research and development in space telerobotics to provide the most advanced technology available to the FTS at minimum cost.

Skunkworks Activity Summary

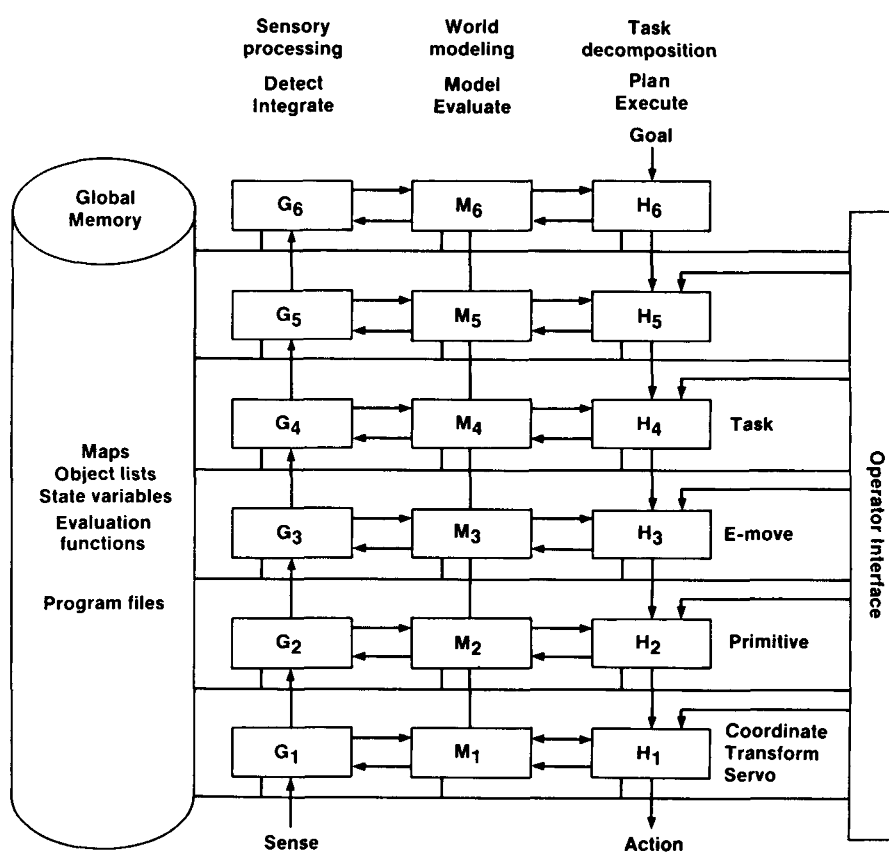
The FTS project conducted a "skunkworks" activity to develop the requirements definition, specifications, and feasibility analyses for the FTS project. Representatives from Goddard Space Flight Center (GSFC), Marshall Space Flight Center (MSFC), Johnson Space Center (JSC), Langley Research Center (LaRC), Ames Research Center (ARC), the National Bureau of Standards (NBS), and the Oak Ridge National Laboratories (ORNL) participated in this activity. The major conclusions and recomendations of the "skunkworks" activity were

- The worksite environment, and the interface between the telerobot and the worksite environment should be considered to be one system and, as such, they must be developed in unison.
- The initial FTS mobility requirements can be satisfied by existing and planned transport devices associated with the Space Station.
- FTS operation without an umbilical is necessary, and telerobot management of its own umbilical is not practical.
- Full robotic autonomy requires technology development.
- Efficient remote operation of the FTS requires a high level of supervised autonomy because of speed of light delays, restricted data links, human factors, and safety considerations.
- Computational requirements are drivers in the overall system design.
- The technical risk in developing a minimally useful system for first element launch is low, since the feasibility of the required teleoperation capabilities has been demonstrated.
- The technical risk in the project is related to the degree of operational flexibility and autonomy chosen for implementation in the initial FTS system.
- A unifying system architecture is required to facilitate system understanding so that growth and enhancement can be developed and implemented without system redesign.

FTS Requirements Development

The FTS is to be designed as a multipurpose tool. However, the Space Station design has not been finalized, the initial platform design has not been completed, and Space Station attached payloads have not been chosen. It is, therefore, impossible to completely define all the activities that the FTS will be called upon to perform or support or to adequately define the workspaces in which the FTS must function. For these reasons, the FTS project defined a robotic assessment test set (RATS) to provide a representative sample of activities that could be used for both determining the "tall pole" design requirements and for assessment of competing design approaches. Activities included in the RATS are

- Assembly
  - — Truss assembly
  - — Utility line connection
  - — Structure interface adaptor (SIA) to truss connection
  - — Solar dynamic array assembly
  - — Payload interface adaptor (PIA) to SIA connection



The Flight Telerobotic Servicer architecture is a hierarchical structure for which a different fundamental mathematical transformation is performed in each layer. This system architecture was adopted to ensure that enhancements could be introduced into the system at later dates and to facilitate system comparisons.

- Maintenance and servicing
  - — Solar power converter ORU changeout
  - — High Resolution Solar Observatory (HRSO) film cannister changeout
  - — Solar Maximum Mission main electronics box replacement
  - — Hubble Space Telescope (HST) axial instrument changeout
  - — HST reaction wheel assembly changeout
  - — Gamma Ray Observatory (GRO) refueling
  - — Electrical connector inspection
  - — In situ platform and free flyer ORU changeout

Each of the RATS tasks has the following characteristics:

- Concepts are sufficiently advanced that drawings and dimensions are available.
- Activities and tasks are representative of many of the real tasks that will be performed on the Space Station.

GSFC worked with the other work package centers to ensure that representative activity scenarios were developed. RATS descriptions were developed in three levels, as follows:

- RATS level 1 is the mission description
- RATS level 2 contains the detailed scenario
- RATS level 3 contains specific engineering numbers

The system architecture that is being used to unify the FTS project is defined in the NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM) (ref. 32). The RATS completely fits into this unifying architecture. The inputs to NASREM at the task level are mission descriptions (e.g. utility line connection/RATS level 1). All RATS tasks were decomposed into the basic building blocks (move, attach/release, locate, manipulate) which correspond to inputs to the elemental move level (level 3/E-move) of the NASREM model. The RATS activity essentially accomplished the NASREM level 4 (task level) activity which is to decompose the missions in terms of the desired actions that are performed on specific objects. These commands are functionally above the manipulator (EVA astronaut or specific robotic device) dependent levels in the NASREM hierarchy.

ATAC is reinforced in its support of the fundamental soundness of the FTS plan and observes that actions have already been taken to implement it. The plan incorporates the agency wide efforts required for a successful FTS program. ATAC strongly endorses two new elements of the plan not identified prior to our previous report.

The first element is the organization of a steering group for the FTS. Dr. Robert Cannon of Stanford University has accepted the chairmanship. The steering group will provide high level technical guidance for the FTS by reviewing and evaluating the FTS baseline technology to ensure that it is realistic in the Space Station era.

The second element is the decision to openly compete the phase B contract for the FTS instead of incorporating it in the work package 3 phase C/D request for proposals. The FTS phase B study is the first phase of a two-phase procurement for the design and development of a FTS that will be capable of performing assembly, maintenance, servicing, and inspection on the Space Station. The work package 3 contractor will retain the responsibility for integrating the FTS into the Space Station. The competitive phase B study contracts will provide an opportunity to refine requirements and technology options before the FTS design is final, thereby obtaining the best possible FTS conceptual design.

There is a major design integration issue for Space Station Program management in the current approach. This approach attempts to adapt the FTS, within its performance envelope, to any environment through special purpose end effectors and user guidelines as opposed to the approach of establishing requirements on the Space Station design to enable many more tasks to be performed.

ATAC has recommended that additional consideration be given to the mobility of the FTS. Program requirements (ref. 33) provide for the flexibility of a Mobile Transporter to transport crew and equipment independently of the MSC. This Mobile Transporter could provide more mobility on the Space Station for the FTS. The FTS has a small mass compared to that of the Canadian Mobile Servicing Center, to which it would attach in the current Space Station configuration. This approach would only supplement, not replace, the requirement that the FTS attach to the MSC, which has extended reach and positioning capabilities.

Also, due to the modified A109 procurement, with two or more contractors for the FTS phase B study contracts, no reports of contractor progress will be available to ATAC for assessment of progress or for reporting to Congress for 9 months after the contract award. Other FTS activities, including the NASA in house phase B studies, will be reportable.

Progress in Incorporation of A & R in the Request for Proposals for the Program Support Contract

The request for proposals (RFP) for the hardware elements of the Space Station are not yet available for the design and construction phase (phase C/D) of the Space Station Program. The RFP for the program support contract (PSC) is available. ATAC has provided the following comments on the PSC RFP (1) as an element of its review of progress in A & R and (2) for the purpose of providing an opportunity for deficiencies to be overcome in contract negotiations and performance.

The program support contract (PSC) request for proposals (ref. 34) is perceived by ATAC to contain a serious attempt to emphasize A & R. However, it appears that the PSC request for proposal does not place the emphasis and value on A & R intended by Congress. Automation and robotics is treated as one of the many aspects for systems engineering rather than as a program initiative. ***The RFP also includes deficiencies which ATAC believes can be corrected during negotiations.*** If not corrected, deficiencies already identified for phase B of the program will be further promulgated. The following sections discuss these issues.

General Provisions for A & R

The PSC request for proposals included several supportable provisions which convey recognition and attention in support of A & R. These include

- A stated commitment to an aggressive application of A & R
- A call for "appropriate" use of automation to relieve the flight crew of routine tasks
- A special note of the FTS and of its inclusion in the first element launch
- A requirement for an executive summary statement of proposed efforts to incorporate A & R into the program (but only as a subset within systems engineering)
- A requirement for a description and discussion of methods and criteria to be used in preparing and implementing the Space Station A & R plan, including integrating the work package inputs and optimizing the incorporation of cost effective features in the Space Station Program
- A requirement for an A & R assessment plan and for the integration and support of A & R implementation and coordination at NASA centers, including robotic and EVA trade studies and automation analyses.

The committee also identified the following deficiencies and has recommended that corrective actions be taken during the assignment phase for the PSC.

- A & R should be identified as an item for the program design reviews, as is done for other factors.
- The sections in the Program Definition and Requirements Document (ref. 14) in which the principal automation and robotics requirements reside should be adopted and referenced. This approach has been used in other sections of the RFP.
- A separate A & R cost breakout and accounting should be required. There are forms for cost breakouts for areas including systems engineering and integration, and for safety, reliability and quality assurance, but not for A & R.

A & R Assessment Plan and Integration

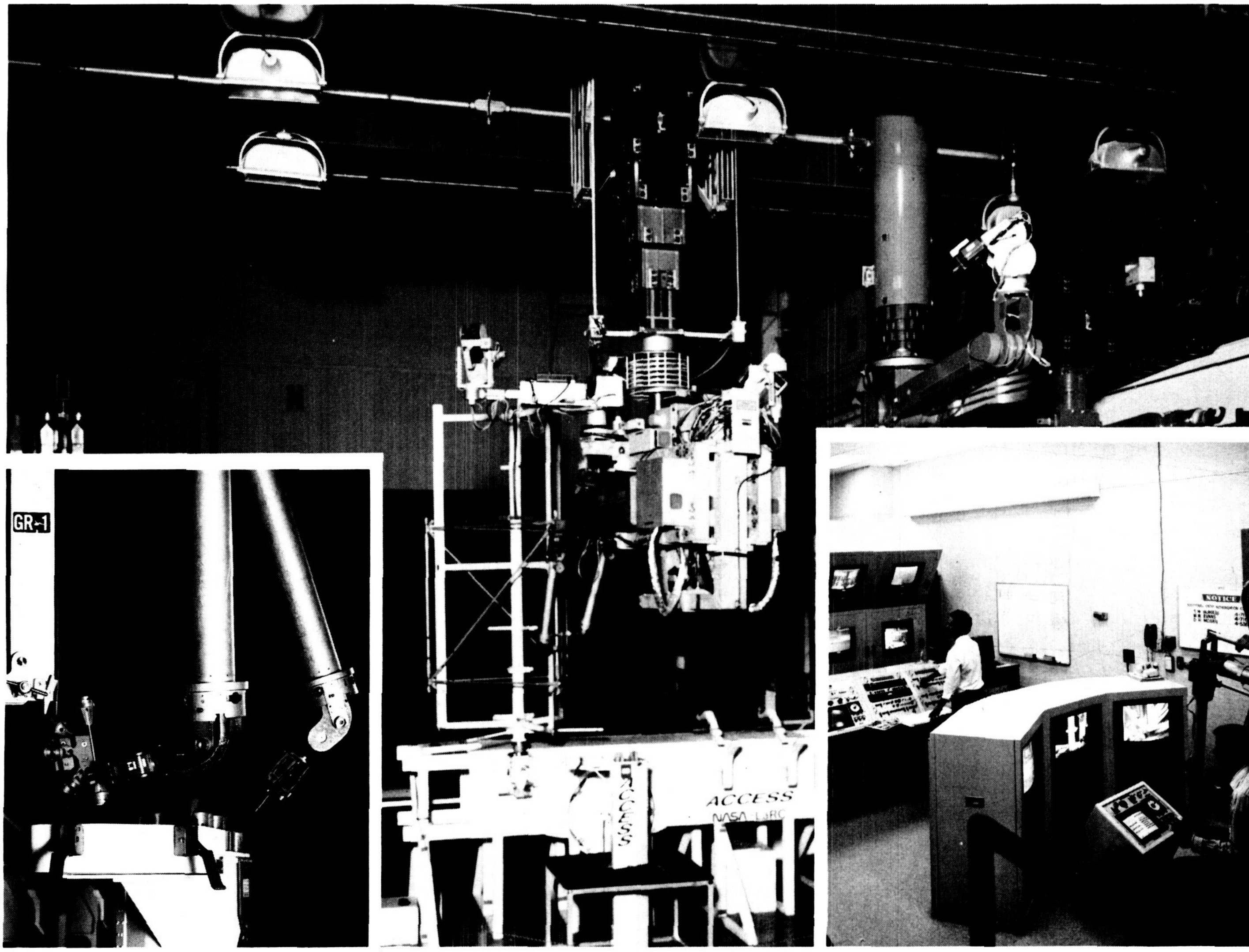
The statement of work requires the maintenance of an A & R plan with suggested applications to be pursued, and it identifies support of A & R implementations through trade studies and automation analysis. However, there needs to be a full set of A & R plans minimally including those listed in the Automation and Robotics Process Requirements (ref. 27).

A & R Data Requirements

There are 38 listed data requirements. A & R is not on the list. Instead, there are three A & R data requirements listed as part of Data Requirement 26 — Systems engineering and analysis requirements, plans, assessments, and status reports. The 3 listed A & R requirements are

- Assessment plan studies, reports, and status
- Robotics/EVA trades and recommendations
- Analyses of automation to improve productivity status

An important set of data requirements identified in the A & R Process Requirements Document as listed previously in this ATAC report is omitted in the RFP.



An overall view of the Oak Ridge National Laboratories test setup for construction of ACCESS experiment hardware shows one bay assembled and being raised by the manipulator to prepare for the assembly of another bay. Insets show the dual-arm manipulator and the control station for the master slave manipulator. (Courtesy of Langley Research Center.)

Design Knowledge Capture

The Program Support Contract RFP includes a reasonably good treatment of this critical issue. The statement of work incorporates the requirements called out in Process Requirements for Design Knowledge Capture (ref. 28) and refers to the document. All of the critical elements appear to be in place. In particular, the RFP requires that data be in machine intelligible form, that a common NASA format be established for CAD data, and that a specification language system be selected. The items in Data Requirement 25 of the RFP that refer to design knowledge capture are essentially complete and will be critical to the success of the effort. It is not clear, even in view of the requirements in the statement of work, that adequate priority is given to design knowledge capture.

Life Cycle Costing

In general, the set of statements concerning life cycle cost in the RFP admits a life cycle costing approach that would be adequate to make informed tradeoffs of design issues. In particular, various sections apprise the prospective contractors of the importance of designing to minimize life cycle costs. In the statement of work, the contractor is required to develop and integrate a program design to a life cycle cost process. The contractor is also required to perform life cycle cost assessments and to suggest life cycle cost allocations. In other sections, the goals are stated only in terms of "acceptable" life cycle and crew productivity costs.

The different sections are inconsistent in describing how NASA wants the contractor to implement costing. In one section there is an emphasis on modeling, and in another section there is an emphasis on a management approach. Ideally, all these sections should refer to one or a few reference documents when they emphasize a certain aspect of costing. There are no such references. The Space Station Cost Management Process Requirements document (ref. 29) is not cited in these sections and is included in the list of documents for reference only.

Award Fee Areas of Emphasis

This area represents a major deficiency in the PSC request for proposal. Through the first two years of the program contract, there is no mention of automation and robotics as a consideration in fee award. Similarly, there is no mention of design knowledge capture or life cycle costing. There is undoubtedly some weight for these areas, but apparently they are submerged to the point of insignificance.

Selection of Contractor

ATAC can not ascertain if significant weight will given to the selection of a contractor based on a sensitivity of the issues of automation and robotics, as consistently recommended by the committee. A & R is not included in the list of criteria on which prospective contractors will be evaluated. There is no mention of A & R in the personnel qualifications requirements and no indication that the personnel required will have expertise in the area of A & R.

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

The NASA Centers have continued to support ATAC in maintaining a current synopsis of the ongoing A & R work within NASA. This synopsis is reported as appendix G. There are several changes since ATAC Progress Report 3, especially in robotics, reflecting research support to the Flight Telerobotic Servicer.

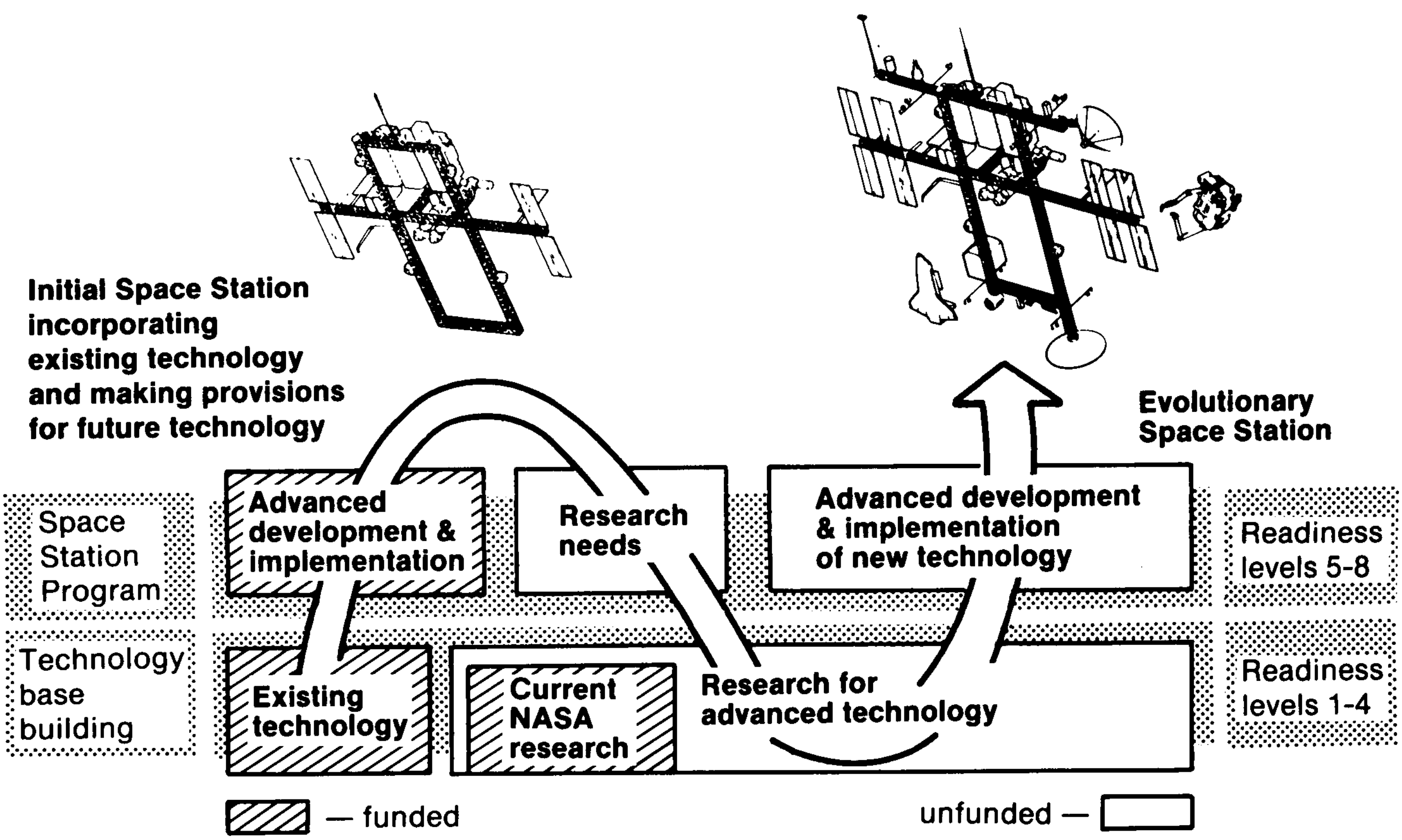
The Office of Aeronautics and Space Technology conducts the major A & R research program. The OAST program has two major thrusts — telerobotics and system autonomy. It includes ground demonstration projects in these two areas.

Telerobotic Demonstration and Technology Transfer

The OAST is funding the development of component technologies for telerobotic systems in five areas of "core" technology. These areas are

- Sensing and perception: machine vision hardware and software; "feel" sensing by force, torque, grasp, and tactile sensing; and the fusion of these sensing types for robotic control
- Task planning and reasoning: the application of artificial intelligence to robotic tasks, including sequence planning, fault detection, diagnosis and recovery, spatial trajectory planning, and real time control
- Operator interface: design and analysis of controls and displays for efficient human control of telerobots
- Control execution: research and development of hardware and control software to execute manipulation with robotic arms and end effectors
- System architecture and integration: hardware and software technologies for integrating telerobotic systems, including the design and implementation of hierarchical and distributed control, traded control from teleoperated to autonomous modes, and data systems

The Telerobotic Demonstration Program utilizes a testbed located at the Jet Propulsion Laboratory to progressively integrate and demonstrate the ability of these integrated "core" telerobotic technologies to perform space assembly and servicing tasks. A



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

series of demonstrations is scheduled on this testbed through the year 2000. Several "core" technologies will be integrated in 1987 to perform autonomous, machine vision, and force sensing directed satellite tasks using six-degree-of-freedom, dual arm manipulation. In 1988, teleoperator control technology will be integrated with this autonomous system to create a telerobotic system capable of trading control between teleoperated and autonomous modes for demonstrating a variety of space assembly and servicing tasks.

In 1989, seven-degree-of-freedom, flight qualifiable manipulator arms with end effectors capable of sensing grasp force will be added to the demonstration, as will the software and control hardware adaptations to control them. OAST and the Office of Space Station have signed memorandums of understanding and agreement to transfer these technologies (through 1989) to Goddard Space Flight Center's telerobotic test facility for the Space Station for evaluation, ensuring that the Flight Telerobotic Servicer design can make use of the most advanced space telerobotic technology available.

In 1990, the OAST demonstrations are planned to incorporate mobility, laser sensing, CAD and artificial intelligence based planning, error detection and recovery, and an advanced "virtual" work station for operator control. Later demonstrations are planned to include the ability to recognize and acquire unlabelled objects from a cluttered background, autonomous navigation, real-time artificial intelligence based planning and control, and the use of multiple, cooperating robots.

The early telerobotic demonstrations are focused on technologies applicable to the Space Station. OAST and OSS plan a long term technology transfer program to continue the flow of advanced telerobotic technology to the evolving Space Station. The OAST program will also support other telerobotic mission needs such as planetary rovers.

Systems Autonomy Demonstration Project

The Systems Autonomy Demonstration Project provides for four increasingly complex ground demonstrations. The first demonstration, in 1988, will be a joint effort of the Ames Research Center and the Johnson Space Center for an expert system to control the thermal control system testbed at the Johnson Space Center. This testbed is representative of the eventual Space Station thermal control system (TCS) and is used to develop and evaluate emerging thermal control technologies for potential use on the Space Station.

Additional demonstrations are scheduled for 1990, 1993, and 1996. The 1990 demonstration will involve coordinated control of two Space Station subsystems through cooperating expert systems. The two target Space Station subsystems will be the thermal control system integrated with the electrical power system. The 1993 demonstration will involve hierarchical automation of multiple subsystems, and the 1996 demonstration will involve distributed automation of multiple subsystems.

TCS automation involves the implementation of current expert systems technologies into the real time dynamic environment of a complex electrical mechanical Space Station system. It includes

TABLE 1.- EVOLUTIONARY DEVELOPMENT OF CORE TECHNOLOGY CAPABILITIES IN SUPPORT OF INCREASING SYSTEMS AUTONOMY TECHNOLOGY DEMONSTRATION LEVELS

Demo year	1988	1990	1993	1996
Technology demonstration level indicator	*"Intelligent aide"* Control of mission operations single subsystem	*"Intelligent apprentice"* Control of multiple subsystems	*"Intelligent assistant"* Hierarchical control of multiple subsystems	*"Intelligent associate"* Distributed control of multiple subsystems
Technology areas				
Task planning and reasoning	• Rule-based simulation • Fault recognition/ warning/limited diagnosis • Scheduling/rescheduling • Reasoning based on standard procedures • Knowledge representation-generic "shells"	• Model-based simulation • Fault diagnosis for anticipated failures • Planning/replanning • Reasoning about non-standard procedures • Knowledge acquisition-semiautomatic	• Integration of CAD/CAM knowledge base • Fault recovery from unanticipated failures • Planning under uncertainty • Reasoning about emergency procedures • Knowledge acquisition-automatic	• Integration of multiple CAD/CAM knowledge bases • Fault prediction and trend analysis • Real-time planning/ replanning • Reasoning/learning • Automatic knowledge acquisition from CAD/CAM data
Operator interface	• Goal and casual explanation displays	• Operator aids for unanticipated failures	• Task oriented dialogue, human error tolerance	• Goal driven natural language interface
Sensors and perception	• Real-time simple-object recognition • Integrated point sensor data	• Multiple class 3-D object recognition • Multisensor data integration	• Extract 3-D description of unknown objects • Tactile verification and fused augmentation of 3-D vision	• Extract and maintain 3-D scene model • Real-time system state estimation
Control execution	• Real-time control of flexible structures	• Coordinated control of flexible structures	• Cooperative control of flexible structures	• Cooperative autonomous intelligent systems (robots)
System architecture and integration	• Monitor/simulated control of single subsystem • Ground-based VLSI prototype processors • Standards for programs environment • Interface standards	• Coordinated/simulated autonomous control of multiple subsystems • Ground-based VHSIC prototype multiprocessor • Standardized validation techniques • Network protocols	• Simulated/autonomous ground and space hierarchical control • Space-borne VHSIC symbolic processor • Advanced validation techniques based on new theory • Network protocols for hierarchical systems	• Simulated/autonomous cooperative control of simulated systems • Several VHSIC symbolic processors • Expanded validation techniques • Network protocols for distributed systems

real-time nominal control, fault diagnosis and correction of real time problems, design and reconfiguration advice on the thermal control system testbed, and an intelligent interface to both novice and expert users. The TCS demonstration will accelerate the transfer of systems autonomy research technologies to user applications in a real-time operational environment and will increase user confidence in the new technologies.

During the past 6 months, a prototype development stage was completed with the implementation and demonstration of a small, but significant expert system prototype integrated with a static thermal control system software simulation. The follow-on requirements definition stage is well underway and will culminate with a formal system requirements specification and a formal system requirements review.

The electrical power autonomy demonstration system, which will comprise the second target system of the 1990 demonstration, will consist of a space power system typical of that used on the Space Station. The demonstration system will consist of the energy conversion system, a power management and distribution system, a battery-electrochemical energy storage system, and a number of simulated loads. The electrical power system (EPS) controller, which requires a relatively fast response to system anomalies, will incorporate expert systems technologies into real time control, to include fault detection, classification, isolation, and system restoration. The EPS will also include an "advisor" for planning and replanning the distribution of the power/energy resource in the event of an anomaly. The "advisor" will also serve as an intelligent interface on system reconfiguration to both expert and novice users.

In 1988, the demonstration of a preprototype autonomous power system is planned. This demonstration will be used to transfer the systems autonomy research technologies to the electrical power system design domain. The 1988 demonstration will also be the preparatory stage for the 1990 combined systems autonomy demonstration of the autonomous power system with the thermal control system. The electrical power system autonomy demonstrations will be conducted on the testbeds at the Lewis Research Center.

The major technology thrusts for the TCS and EPS demonstrations are

- Integration of knowledge based systems into a real time environment
- Causal modeling of complex components and elements
- Combining model based and experiential knowledge for diagnosis
- Trend analysis heuristic rules
- Expert system validation methodologies

The combined systems tests, starting with the 1990 demonstration, will consist of separate, but cooperating and interacting systems connected by high speed data links. Because of the nature of these systems, especially fast reacting systems such as the power system, they will be operated in the testbeds of the responsible center. Ready access to the resident domain experts and the support of the resident technical discipline personnel will be a key element contributing to the success of these demonstrations. This will also expose the maximum number of technology and domain experts to these advanced automation technologies and will be an important aid in transferring the technologies to the users in the most expeditious manner.

Upon the completion of the 1990 combined systems demonstration, preparations will begin for participation in the more comprehensive demonstrations in 1993 and 1996.

OAST plans to implement an augmented program in fiscal 1988 to accelerate and build up both the core research and technology program and the demonstration program.

Progress in Transfer of Technology to the U.S. Economy

Efforts continue to be made by the NASA Office of Commercial Programs (OCP) to effect technology transfer to and from NASA. The OCP sponsored a Commercial Users Panel which met at the Jet Propulsion Laboratory's Space Telerobotics Workshop on January 21, 1987. This panel reviewed NASA automation and robotics planning and progress before the workshop began and listened to presentations by NASA and other A & R researchers at the workshop. The panel then met in closed session to discuss and recommend opportunities for NASA telerobotics and related technologies in the commercial sector.

The panel represented commercial areas such as agriculture, automotive, chemical processing and pharmaceuticals, construction and excavation, hazardous waste and munitions, health and medical services, mining, ocean engineering, semiconductors and nuclear utilities. Organizations providing panel participants included the Ford Motor Company, the U.S. Army Aberdeen Proving Ground, Fluor Technology, Inc., the DuPont Savannah River Laboratories, Telerobotics, Inc., Perry Offshore, the Electric Power Research Institute, the U.S. Bureau of Mines, Caterpillar, Inc., International Business Machines, and the Veterans Administration — Rehabilitation.

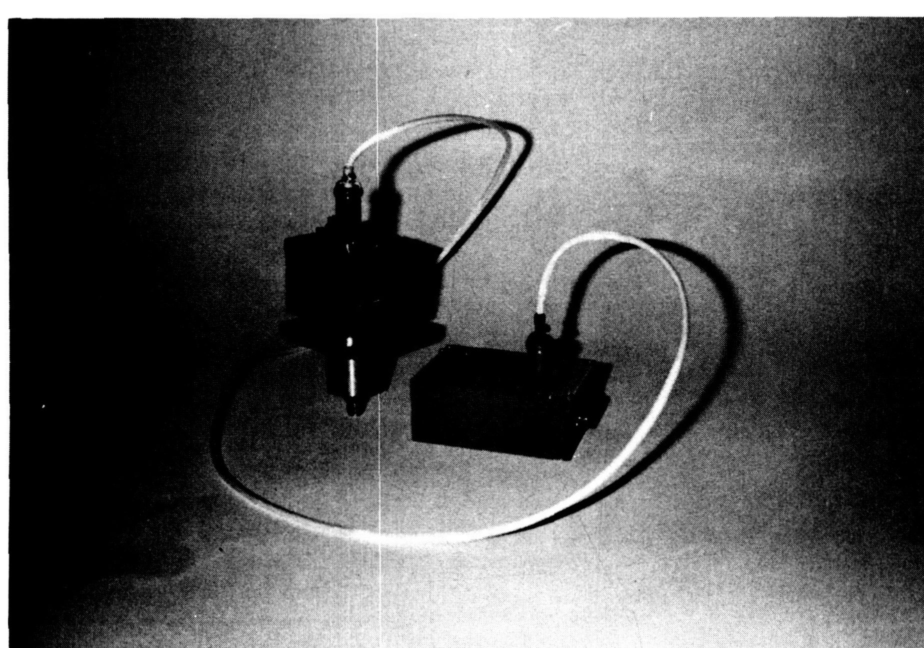
Results of the panel discussions will be presented in the proceedings of the workshop.

Furthermore, the Office of Commercial Programs is sponsoring, through the Kennedy Space Center, a 3 year cooperative effort with the Electric Power Research Institute (EPRI) to transfer systems autonomy expert systems software to the electric power industry.

The National Bureau of Standards office, which is responsible for encouraging the use of robotics in U.S. industry, has also been enlisted as a full member of the Flight Telerobotic Servicer team. This involvement will facilitate a two way transfer of technology and experience between industry and the FTS project.

The Second AIAA/NASA/USAF Symposium on "Automation, Robotics, and Advanced Computing for the National Space Program" was held March 9-11, 1986, in Arlington, Virginia. This symposium provided a forum for government, university, and industry executives and researchers to discuss recent progress in automation, robotics, and advanced computing in a variety of applications for space and terrestrial programs. The symposium was organized as a partial response to the congressional mandate for NASA to develop a strong program in advanced automation and robotics for the Space Station and for the benefit of the national economy. Session III of the symposium focused on "Robotics for the Space Station and Beyond." Topics in this session included

- The Space Station Telerobotic System
- The Evolution of NASA's Robotics Technology Program
- An Integrated Approach to Spacecraft Design for Robotic Servicing
- NASA's Systems Autonomy Demonstration Project
- Space Assembly and Maintenance Systems



Smart, integrated sensors will play a significant role in achieving advanced automation by incorporating data processing, local control, built-in-test, and redundancy management at the sensor level. (Breadboard photograph courtesy of Honeywell, Inc. and Martin Marietta Denver Aerospace.)

Expenditures for Advanced Automation and Robotics

NASA has continued to provide ATAC with estimates of expenditures for automation and robotics. These estimates are updated for the fiscal year, 1987, in the same format as in previous reports. A particular concern of the committee is the area of advanced development for A & R within the Space Station Program. The program has not established an advanced development program for A & R. The funding identified is that within other advanced development initiatives which can be directly related to A & R. A defined advanced development program in A & R is required to satisfy the needs for automation as the Space Station evolves.

TABLE 2.— 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

*Revised from progress report 3

TABLE 3.- 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

Conclusions

Compliance with ATAC Guidelines

ATAC believes that the Space Station Program is showing increased awareness of automation and robotics issues, as indicated by several recent actions described in this report. ***The committee is pleased with the actions taken in the areas of concern expressed in its October 1986 report.***

However, ATAC also noted that many of the actions taken have had the quality of ad hoc remedies to highlighted deficiencies and are not yet part of a well integrated plan with adequate funding and clearly defined policies and objectives. For example, the Automation and Robotics Process Requirements document delegates much of the A & R responsibility (especially for life cycle cost tradeoffs) to the program support contractor without establishing clear, overall value scales and conceptual guidelines for tradeoffs. Our specific concern is that the constructive actions taken recently (for example, the inclusion of A & R provisions in control documents) are weakened by this lack of careful overall planning and may later become ineffective when exposed to program pressures. **We have recommended that early attention be given by the new program level A′ to develop an integrated, comprehensive A & R plan for the Space Station.**

Space Station Design

As expected, there are few significant new results to report from the work package contractors who completed their studies and focused on preparations for their phase C/D proposals. ***Major progress has been made in the definition of the FTS and its integration into the overall Space Station design.*** A majority of the concerns expressed in the committee's last report about the provisions for A & R in the Space Station design documents are being addressed, as reflected by

- Provisions for growth
- Requirements for design knowledge capture
- The emphasis on the need for A & R
- The preferred use of robotics whenever practical and cost effective
- The incorporation of A & R process requirements
- More consideration of operations costs
- Recognition of the need for robot "friendliness" in Space Station design

However, the committee notes that the proposed goals it originally established for A & R applications (ref. 1) do not appear and are not referred to at any significant level in the design documentation, nor have they been replaced with an improved set of goals. Furthermore, A & R requirements are generally disparate and submerged to reference documents of reduced consequence.

Robotics

Major progress has been made toward bringing the status of the FTS up to a level comparable to the other Space Station elements. This is very important if other Space Station flight elements are expected to be designed for telerobotic applications. Although the Critical Evaluation Task Force did not make a specific recommendation on the use of the FTS, the program has included the FTS in its first assembly flight manifest. This is an important step in reflecting the agency's commitment to robotics. The establishment of the assembly and maintenance ACD and the servicing ACD is a significant step toward making important decisions on the applications of the FTS, the Canadian MSC, and EVA.

The committee has noted an important decision by the program to retain flexibility by providing for the Mobile Transporter to be used as an autonomous device for crew and equipment transportation. ***ATAC has recommended that the Space Station Program examine the merits of attaching the FTS directly to the Mobile Transporter for more rapid transport on the Space Station.***

Advanced Automation

The significant progress which has been made about prospects for advanced automation lessens, but does not eliminate, the committee's concern. Critical provisions have now been incorporated into the design documentation for hooks and scars and for design knowledge capture. The absence of these provisions were key concerns of ATAC, as expressed in our previous report. ATAC also perceives increased sensitivity to operations and life cycle costs. ***But the committee remains concerned that fiscal priorities may inhibit the inclusion of advanced automation, especially since the recent announcements regarding overall Space Station costs.***

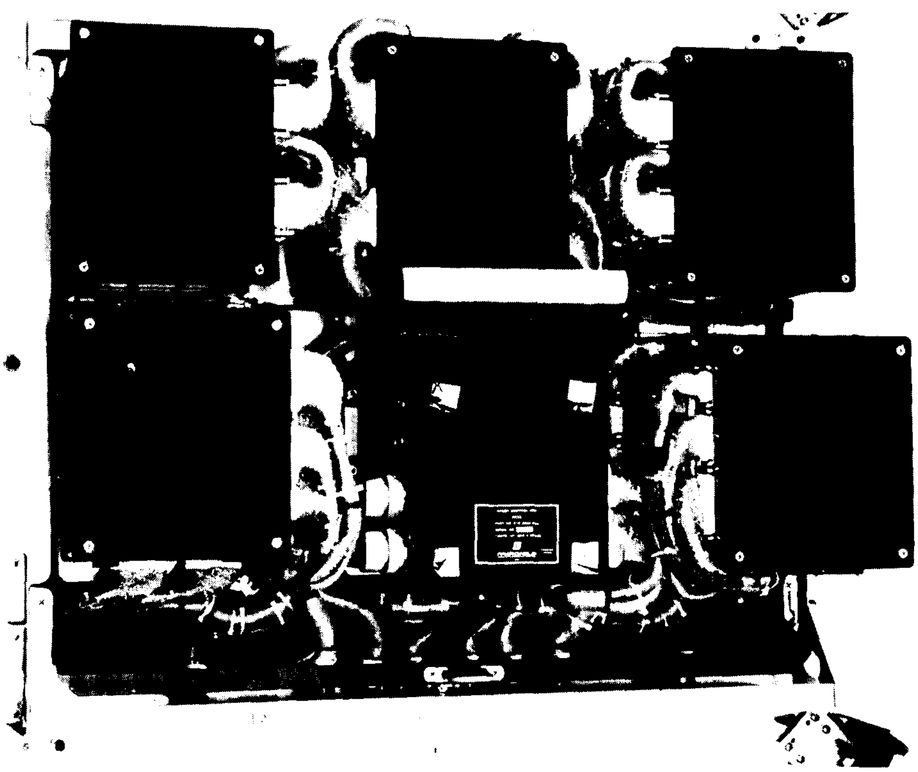
There is little evidence that the advanced automation goals originally proposed by ATAC have been recognized in the Space Station design. Similarly, a neutral approach appears to have been taken regarding the study results of the phase B contractors in the area of advanced automation.

The committee is concerned about the lack of flight qualified processors, with architectures to exploit parallelism, to obtain the computing speed required for autonomous control applications. The committee has recommended increased emphasis on advanced development in this area.

Design Knowledge Capture

The previous concerns of the committee have been addressed by provisions in the design document, but we caution that these provisions must remain intact in any examinations of fiscal priorities. The committee has also noted that changes need to be made in the Technical and Management Information System (TMIS) to provide for the required relational data bases.

A mockup of the Hubble Space Telescope scientific instrument command and data handling module will be used to develop guidelines for robot serviceable hardware. The mockup will be used to demonstrate different approaches to robotic servicing. (Courtesy of Goddard Space Flight Center.)



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APPENDIX A

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

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APPENDIX B

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APPENDIX C
Acronyms

A & R	automation and robotics
AI	artificial intelligence
ACCESS	assembly concept for construction of erectable space structures
ACD	architectural control document
AIAA	American Institute of Aeronautics and Astronautics
ARC	Ames Research Center
ATAC	Advanced Technology Advisory Committee
BCD	baseline configuration document
C & T	communications and tracking
CAD	computer-aided design
CAE	computer-aided engineering
CETF	Critical Evaluation Task Force
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
LeRC	Lewis Research Center
MSC	mobile servicing center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NSTS	National Space Transportation System
OAST	Office of Aeronautics and Space Technology
OCP	Office of Commercial Programs
OMS	operations management system
OMV	orbital maneuvering vehicle
ORNL	Oak Ridge National Laboratories
ORU	orbital replaceable unit
OSS	Office of Space Station
PDRD	program definition and requirements document
PSC	program support contract
RATS	robotic assessment test set
RFP	request for proposal(s)
RMS	remote manipulator system
SFM	service facility manipulator
SPDM	special purpose dextrous manipulator
TCS	thermal control system
TMIS	Technical and Management Information System
VHSIC	very high speed integrated circuit
VLSI	very large scale integrated
WP	work package

APPENDIX D

Candidate A & R Applications for the Initial Space Station

Part 1—Program Elements Addressed by ATAC

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

Part 1—Program Elements Addressed by ATAC (concluded)

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

Part 2—Program Elements Not Specifically Addressed by ATAC

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

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

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

APPENDIX E

Recommended Applications for the Initial Space Station

Knowledge-Based (Expert) Systems

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

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 and 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 G

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 Flight 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	3
Marshall Space Flight Center	Development of vision system for automatic docking using TV box scan and syntax pattern recognition	Autonomous docking and servicing	2
Category 1.3—Actuation and Manipulation			
Ames Research Center	Real-time control of limber manipulators with end-point sensing	Manipulators, robotics, and servicing	2-3
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	5
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	2-4
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

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	2-4
Marshall Space Flight Center	Graphical simulation for predictive display, off-line auto-sequence display, and system checkout	Teleoperations and automated servicing and assembly	2-3
Marshall Space Flight Center	Expert system allowing nonsimulation personnel to perform studies with complex simulation systems	Reduced-cost Space Station simulations	4
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	6
Marshall Space Flight Center	Optimization of lighting, video camera position, and operator aptitudes for accomplishment of servicing tasks	Remotely operated servicing	4
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 —System for writing expert systems in Ada —Computer-aided tool for design of centralized or distributed control systems —System using simulation and qualitative modeling —Systems that use models of the domain of interest as part of their knowledge —Workstation for automated generation of programs	Systems engineering	6 3 3 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

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	3-5
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	4
Marshall Space Flight Center	Hardware system for autonomous docking utilizing high-accuracy solid-state sensors	OMV and Space Station docking and berthing	3-4
Marshall Space Flight Center	Expanded simulation capability to support studies of the OMV, 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
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 —Support command and control —Provide assistance to crew in rendezvous of Space Shuttle with the Space Station	Crew support during the terminal phase of rendezvous Proximity operations and rendezvous Rendezvous operations	6 3 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	3-5
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	5
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	4

APPENDIX H

Transmittal Letter of the NASA Administrator

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NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Office of the Administrator

DEC 10 1986

Honorable Edward P. Boland
Chairman
Subcommittee on HUD-
Independent Agencies
Committee on Appropriations
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

As you know, the Congress directed, in Public Law 98-371, that NASA establish an Advanced Technology Advisory Committee (ATAC), in conjunction with the Space Station program, to identify specific Space Station systems which advance automation and robotics (A&R) technologies. The initial recommendations of the ATAC were transmitted to the Congress in March 1985. A further requirement of P.L. 98-371 is that the ATAC follow NASA's progress in automation and robotics for the Space Station, and report to Congress semiannually. Transmitted herewith is the third progress report of the ATAC.

This report acknowledges that "major progress has been made in the definition and preliminary design of applications and technologies for automation and robotics on the Space Station," and that "substantial progress has been made in the development of a U.S. telerobotic capability for the initial Space Station." However, at the same time, the report outlines a series of shortcomings in NASA's current efforts. I intend to have these matters addressed, and the Associate Administrator for Space Station, Mr. Andrew J. Stofan, has already undertaken significant steps toward this end. A synopsis of the current ATAC progress report is presented below, followed by descriptions of the corrective measures taken by the Space Station program.

- Major progress in definition and preliminary design of applications and technology for Space Station A&R is sufficient to merit extensive inclusion of A&R in the initial operating capability and growth Stations. NASA agrees that significant work has been accomplished, and intends to capitalize on it through Phase C/D and beyond. The potential enhancement resulting from the use of A&R has also been stated by the Critical Evaluation Task Force in its redefinition of the Program. No firm conclusions have been reached, however, on the appropriate level or timing of A&R capabilities.

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- Planning for operations and system autonomy is not progressing quickly enough to influence design, and the benefit in life cycle costs offered by advanced automation is not being appreciated or balanced against initial cost. NASA acknowledges that, to date, the emphasis on an architectural approach to satisfy a diverse set of users has been far greater than on operations. However, program planning is now entering a phase in which the deficiencies cited by ATAC should be overcome.

  In mid September, the Operations Task Force (OTF) was organized and chartered to study Space Station operations and to provide timely recommendations for the Phase C/D RFP. We scheduled intensive briefings for the OTF on A&R applications and opportunities and expect them to formulate an operations concept that includes consideration of A&R and initial costs in evaluating design tradeoffs.

- A&R considerations must be given high priority in the Phase C/D procurement process. NASA fully concurs with this finding, and the Program is developing the Phase C/D RFP documents in a manner which explains the position which NASA wishes to take with regard to A&R (including design knowledge capture). A requirement is imposed that all RFPs contain equally explicit language on the value of A&R to the program and importance of the various benefits expected from A&R applications. We will also include in the evaluation criteria section of the RFP precise guidance regarding the importance of the quality and quantity of A&R applications.

- NASA is perceived as not committed to the inclusion of A&R recommendations in the Program. NASA believes that such a perception is a consequence of the predominant focus to date upon the Space Station architecture. However, a series of steps have been undertaken by the Program to correct this perception:

-- the appointment of a Division Director at Level A with direct responsibility for A&R, and a planned organizational element at Level A', reporting directly to the Program Director, responsible for A&R coordination across work packages and for program-wide tradeoffs;

-- enhanced programmatic capability in system analysis, engineering and integration through the establishment of the Level A' organization and pending selection of a strong supporting contractor; such a capability will enable performance of trade-offs and examination of options which will result in an optimal plan for A&R applications;

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-- appointment of an A&R advocate to the procurement working group supporting the coordination of the Phase C/D RFPs; and,

-- the establishment of the Operations Task Force;

o <u>Use of the Space Station Flight Telerobotic System (FTS) has not been planned</u>. As of the date of the printing of the ATAC progress report, only a preliminary plan for the FTS was in place. However, since receiving the responsibility for development of the FTS in May 1986, the Goddard Space Flight Center has been assembling a strong team and developing a detailed program plan. A preliminary set of requirements has been formulated, and final requirements, suitable for inclusion in an RFP, are expected in January 1987. The FTS RFP will be a separate procurement from the balance of Work Package 3, in an effort to incorporate the widest range of the most advanced technologies. Furthermore, recognizing the principal uses of the FTS, NASA has formulated two teams focusing upon assembly/maintenance and servicing, at the Johnson Space Center and Goddard Space Flight Center, respectively. These teams are examining the systems aspects of those functions, and formulating "architectures" for their performance using the capabilities available through both the FTS and extra-vehicular activity.

I believe the foregoing demonstrates that the Program is taking heed of the constructive advice offered by the ATAC, and is thereby increasing the Program strength in the important field of automation and robotics.

In closing, I would like to take this opportunity to note that with my recent appointment of Mr. Aaron Cohen as Director of the Johnson Space Center, the ATAC has lost a most effective Chairman and enthusiastic A&R advocate. I have appointed Mr. Robert A. Nunamaker, Director for Space at the Langley Research Center, and a charter member of the ATAC, to succeed Mr. Cohen as ATAC Chairman, to insure a continuity of outstanding leadership.

Sincerely,

James C. Fletcher
Administrator

Enclosure

cc: Honorable S. William Green

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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 fourth in a series of progress updates and covers the period between October 1, 1986, and May 15, 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.

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