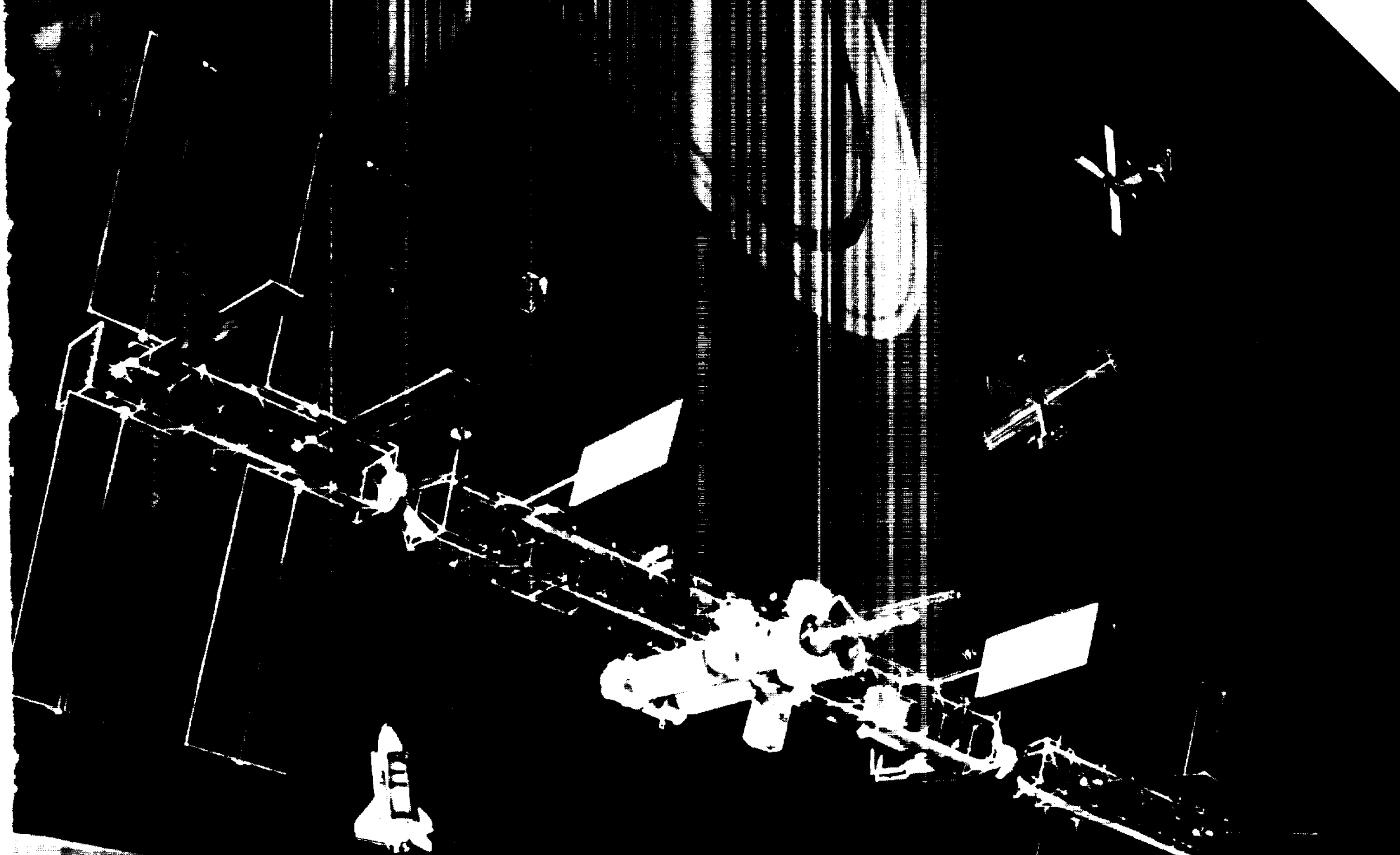
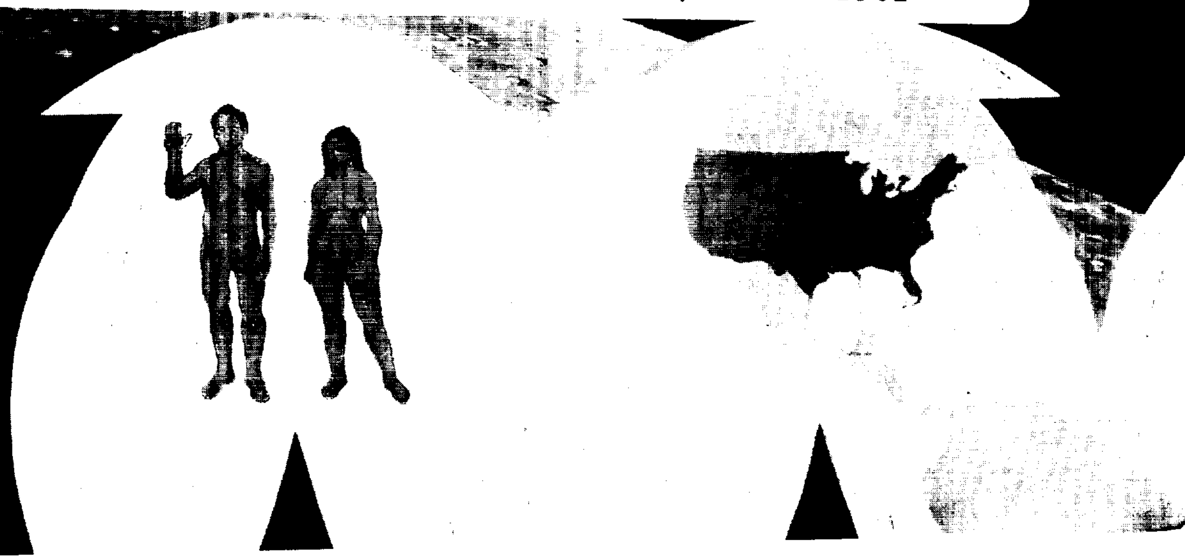
NASA Technical Me[illegible]89

Progress Report **6**

March 1988

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





NASA

Advanced Technology Advisory Committee

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

NASA Technical Memorandum 100989

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

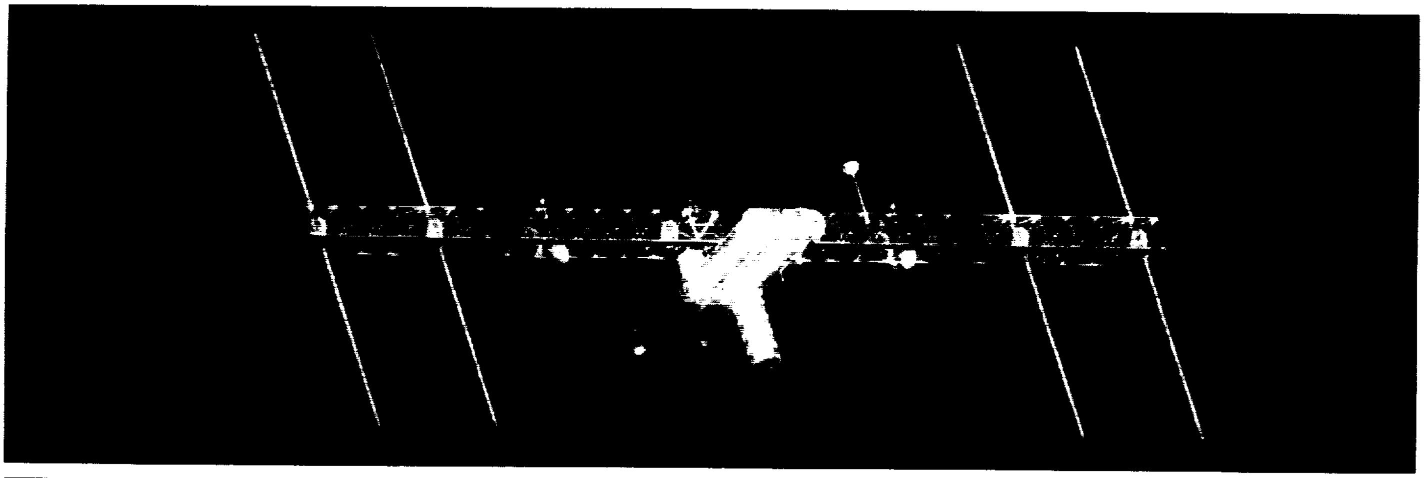
Progress Report 6 — October 1987 Through March 1988

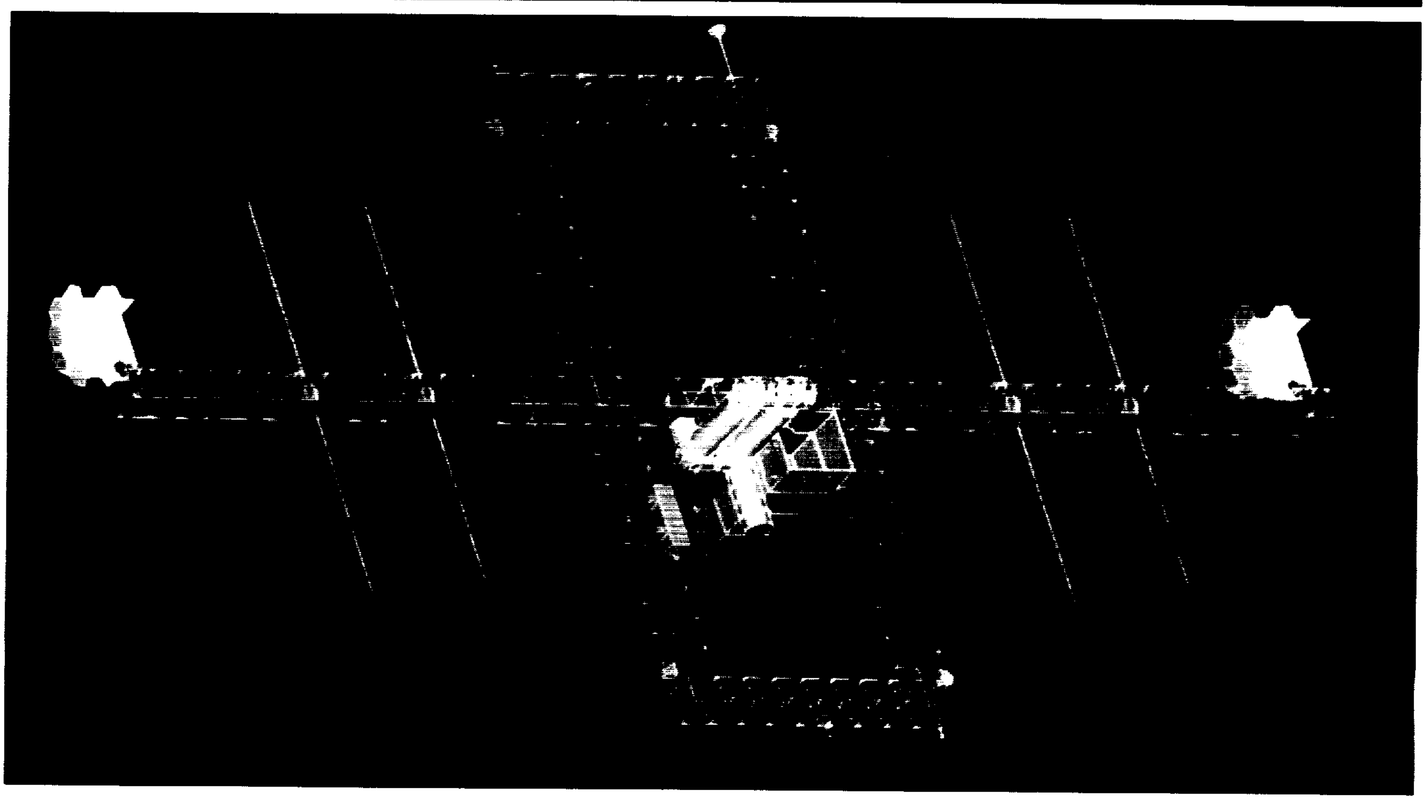
Advanced Technology Advisory Committee
National Aeronautics and Space Administration

Submitted to the
United States Congress
June 15, 1988

National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas





The Space Station is to be built on a phased basis, starting with a baseline configuration and evolving into an enhanced capability configuration. Intended to operate for several decades, the Space Station will be capable of further growth, in both size and capability. The drawing at the top shows a representative view of what the baseline Space Station manned base may look like. Two unmanned, polar-orbiting, scientific platforms are also included in the baseline Space Station Program. The ultimate design of the enhanced capability version of the Space Station has not been determined. However, the enhanced capability design will build upon the baseline configuration. One way in which the baseline configuration might be expanded, based on studies completed this past year, is shown in the lower drawing. (Computer generated drawings — courtesy of Langley Research Center.)

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Executive Summary

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

During this report period, activities related to Space Station (SS) advanced automation and robotics were focused in the following five areas:

1. The possible impacts on advanced A & R due to budgetary considerations
2. Space Station Program (SSP) plans for A & R
3. Space Station work package contractors
4. Flight Telerobotic Servicer (FTS)
5. The progress of the Office of Aeronautics and Space Technology (OAST) technology base research and development (R&D) and of related Space Station Advanced Development

1. Impacts on A & R due to budgetary considerations

The new National Space Policy emphasizes the Space Station as the key to the United States' future in space. It additionally emphasizes the importance of intensive research and technology development in the fields of automation and robotics. A & R will increase Space Station productivity, and in return, the Space Station is needed to develop and test A & R technology for space exploration and exploitation. The considerations of national budget priorities have resulted in a phased approach to the Space Station. Currently, the Space Station Program (SSP) is reexamining the program plan, based on the latest cost and budget information. **The basic issue hampering progress in advanced A & R for the Space Station has been a fluctuating budget for the SSP.** Since A & R requires up-front investment to obtain operations benefits, this environment makes it difficult for NASA to maintain its emphasis on A & R. Nevertheless, the A & R budget for the current year shows substantial increases. Congress initially intended an affirmative action program for A & R. It is ATAC's view that NASA should continue to maintain the early investments in A & R and extend the program schedule in the face of early years' budget reductions rather than defer A & R. Deferral of A & R will have a long-term negative impact. Incentives for consideration of A & R must be provided continuously, in spite of budgetary pressures.

2. Space Station Program Plans for A & R

The Space Station Program has described, for discussion purposes, its approach to developing a Space Station design and development phase (phase C/D) plan for automation and robotics. An A & R plan for phase C/D has been recommended by ATAC as a priority need. A document is being written by SS level I and is currently in outline form. This document will serve as a top-level A & R plan to be used by management as a guideline and as an assessment tool to evaluate the Space Station A & R activities in terms of A & R policy, goals, products, schedules, etc. The A & R implementation plan, to be written by level II and which will contain more specific information and plans, is being drafted. An approach was described by the SSP to manage the process of considering A & R. Emphasis will be placed on designing the baseline Space Station so that A & R can be included as (and when) appropriate. The committee concurs with this emphasis but cautions that significant elements of A & R on the baseline Space Station are not only desirable, but are necessary to ensure that later A & R can be accommodated.

3. SS work package contractors

The contractors have been selected for the four Space Station work packages (WP's). Each is currently working under a six-month letter contract until program requirements and contract negotiations are final. Although the contractors' plans include extensive "classical" automation, the work package procurement process did not result in a strong set of proposals for the use of "advanced" A & R. Only work packages 1 and 2, where there was competition for the contracts, produced interesting and valuable proposed applications. The WP-2 proposal, which included expert-system-augmented fault detection, isolation, and recovery (FDIR), onboard knowledge-based systems for the Operations Management System (OMS), use of the FTS for selected assembly and maintenance functions, and a tele-operated Crew and Equipment Retrieval System (CERS), is viewed as the only proposal containing strong A & R elements. The WP-1 proposal provides for an intravehicular (IVA) laboratory robot which leverages the FTS technology. The FTS is a part of the responsibility of work package 3, but has separate contractors and is treated in this report separately from the WP-3 prime proposal. The WP-4 proposal proposes an Electrical Power System (EPS) design which would employ the FTS for telerobotic exchange of Orbital Replaceable Units (ORU's). **But, based on the continuing budget considerations, the committee is concerned over the potential impact on "hooks and scars" for A & R, and on the proposed baseline candidates.**

4. Flight Telerobotic Servicer

Based on current information, the Flight Telerobotic Servicer is progressing according to plan. The committee is encouraged by the proposed leveraging by the WP-1 contractor of the FTS technology for a laboratory intravehicular robot, by the proposed utilization of the FTS by the WP-2 contractor for Space Station assembly and maintenance tasks, and by the WP-4 contractor for ORU change-out. Polar platform designs, being studied in WP-3, incorporate robot-friendly features for ORU changeout, and a concept for a resident robot that will work with an automated expendable launch vehicle (ELV) payload.

Level II plans to obtain the services of a leading telerobotic contractor in order to provide advice and guidance for robot-friendly design.

5. OAST technology base R&D and related Space Station Advanced Development

The OAST is now in the fifth year of its Automation and Robotics research program, which has grown from $4M in FY1984 to over $25M in FY1988. Memoranda of Agreement have been signed between the OAST and the OSS on both of the foci of this program: System Autonomy (Artificial Intelligence) and Telerobotics which tie these R&D activities as closely as possible to the needs and opportunities of A & R in Space Station. A number of significant accomplishments have been made by this program including the following. Prototype expert system software has been developed for demonstrating the capability of knowledge-based systems to perform real time control of the Space Station thermal system testbed. A new technique has emerged from the research in machine learning which may revolutionize available methods for studying large data bases. Its name is AUTOCLASS, and it may well have a first order effect on the science that can be performed on Station. A concept definition of a space-qualifiable symbolic very high speed integrated circuit (VHSIC) multiprocessor has been developed, which is designed to lead to a greatly expanded capability to use artificial intelligence programs in space. An expert system for aiding the Shuttle Integration Communications Officer in mission control has been developed and will be evaluated (off-line but real-time) on the next Space Shuttle flight. In Telerobotics, a pair of force reflecting hand controllers and "smart hand" end-effectors have been fabricated for evaluation by the Flight Telerobotic System office at GSFC. The OAST Telerobot evolutionary testbed has completed its first demonstration, which showed the capability to autonomously track, grapple and despin a spinning satellite, and to perform tasks representative of servicing under the control of an artificial intelligence planner. The OAST R&D program is being complemented with increased advanced development funding of A & R in the Space Station Program. A significant portion of current SSP advanced development funds is primarily targeted to an evolutionary capability. Commitment of advanced development funds to increase the productivity of both the initial-capability Space Station and the evolutionary Space Station should continue to be emphasized, particularly to ensure incorporation of key hooks and scars.

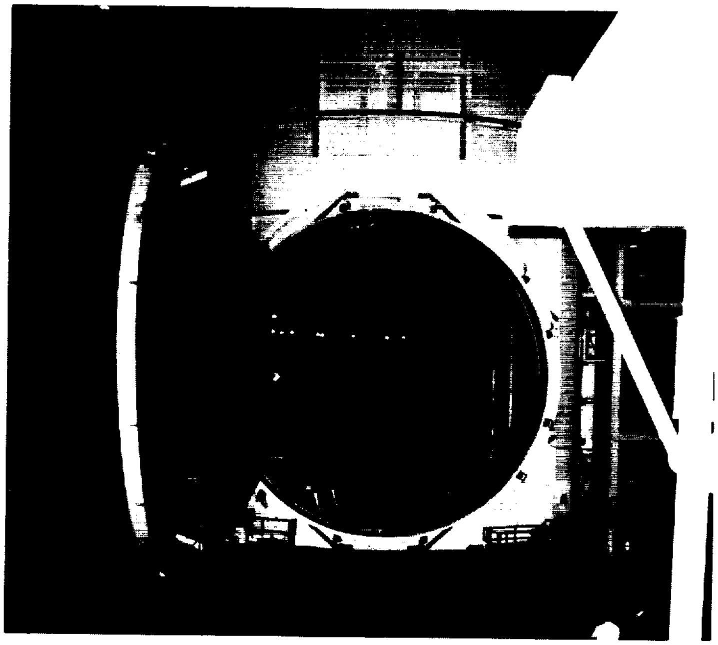
Areas of Progress

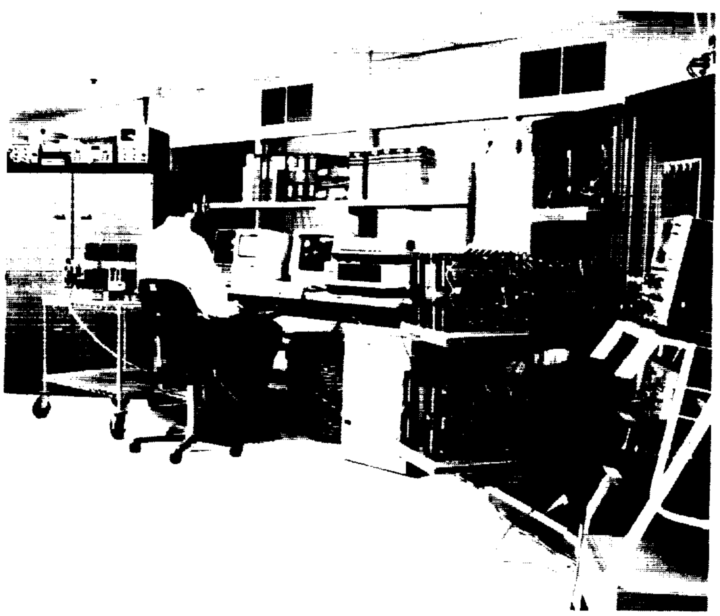
- Contractors have been selected for the work packages for phase C/D of the Space Station Program. Negotiations are expected to be completed in the June 1988 timeframe.
- The SSP, at levels I and II, has further defined its approach for developing a Space Station A & R plan and for integration of A & R.
- Contractors, Martin Marietta and Grumman, were selected for the phase B definition and preliminary design of the FTS, and work is proceeding. A parallel in-house effort has continued with definition and trade studies.
- The SSP has significantly increased the fiscal year 1988 budget for advanced A & R development in addition to the continuation of the FTS budget.
- Technical agreement has been reached between NASA and the National Research Council of Canada for Canada's participation in the SSP. Canada will provide the Mobile Servicing System (MSS). In one of its operational modes, the FTS will attach to the manipulator arms of the MSS for mobility and positioning.
- A Memorandum of Understanding (MOU) between the OAST and the OSS has been approved. The MOU will facilitate the transfer of technology in Systems Autonomy between the two program offices. This will complement the previously approved MOU, which addressed Telerobotics.
- The OAST Systems Autonomy Technology Program plan was developed to cover a timeframe of approximately ten years. The plan includes development of appropriate "core" technology and selected demonstration projects. The first demonstration project is that of an autonomous thermal control system. In 1990, a combined systems demonstration is planned for autonomous operation of cooperating thermal control and electrical power systems.
- The first scheduled OAST ground telerobotics demonstration was conducted. In this demonstration, an integrated telerobotic system, consisting of vision, manipulation, and control subsystems, tracked and grasped a spinning satellite model and stopped it with a smooth motion. This demonstrated several advances, most notably in automated vision and force/torque feedback. Also, it was demonstrated that the same physical structure and control architecture was suitable for both teleoperation and supervised autonomy modes.

- Over 100 proposals were received for the new program, University Space Engineering Research Centers. A number of the proposals are in the A & R fields.
- The Office of Space Sciences and Applications (OSSA), as part of its Telescience Testbed Pilot Program (TTPP), is developing initial recommendations for requirements and design approaches for information systems of the Space Station era. Fourteen universities are working with seven NASA Centers to conduct the testbed experiments, which were started under the SS advanced development program.
- The Office of Commercial Programs (OCP), in conjunction with the Technology Utilization Office at each NASA Center and with the Research Triangle Institute's Technology Applications Team, has underway or planned, a number of A & R-related applications engineering projects with industry. OCP is also supporting a Center to provide a mechanism to assist U.S. industrial firms in acquiring appropriate (especially NASA) A & R technology for application in computer integrated manufacturing systems.

Areas Requiring Future Attention

- Although there is significant management attention to the need to minimize operations as well as minimizing design costs, criteria are not yet available for development of life-cycle costs.
- Mechanisms should be established for encouraging program and project managers in timely adoption of A & R into the SSP.
- During phase B, the work package contractors recommended a wide range of A & R candidates for the initial Space Station. The recommended candidates are not being considered in phase C/D activities. The committee recommends level II revisit this issue.
- Priority has been given to the development of the A & R plan for the Space Station Program. This work has been started at level I and within at least three level II working groups. One group has already had change requests (CR's) to the program baseline accepted which promote the increased use of automation in the Space Station Information System (SSIS).
- A top-down policy statement supporting the requirements for early design knowledge capture is needed. There are interfaces that need to be specified with the Technical and Management Information Systems (TMIS) and the Software Support Environment (SSE). The Committee recommends that workshops and industry contracts be conducted to address this issue.





A sequence of increasingly complex ground demonstrations is being conducted to accelerate the transfer of research technologies in autonomous systems to Space Station applications. Major payoffs of systems autonomy to the Space Station will be reduced operations costs, increased productivity, and increased probability of mission success.

The first demonstration, in 1988, will be a joint effort by ARC and JSC for an expert system to control the Thermal Control System (TCS) testbed at JSC. This testbed is representative of the eventual Space Station TCS and is used to evaluate emerging thermal control technologies for potential use on the Space Station. The thermal vacuum chamber, shown in the first photograph, is a part of the TCS testbed. The 1988 demonstration is significant in that it will be one of the first knowledge-based systems to control a large complex system in real-time with real operational hardware.

The second demonstration, in 1990, will involve coordinated control of two Space Station subsystems testbeds through cooperating expert systems. The two subsystems will be the TCS and the LeRC 20 kHz Space Station electrical power system (EPS). The controller for the EPS autonomy demonstration will incorporate expert systems technologies into real-time control and will include fault detection, classification, isolation, and system restoration. The EPS autonomy demonstration will also include an expert "advisor" for scheduling and replanning the distribution of the power resources in the event of an EPS anomaly. The EPS autonomy demonstration will be conducted on the 20 kHz testbed at LeRC with the Space Station Core Module testbed at MSFC and the TCS testbed at JSC providing "smart" load sources. The second photograph shows the 20 kHz testbed at LeRC. The third photograph shows the Core Module testbed at MSFC.

Preface

In April, 1985, as required by Public Law 98-371, the NASA Advanced Technology Advisory Committee (ATAC) reported to Congress the results of its studies on automation and robotics (A & R) technology for use on the Space Station. A further requirement of the law was that ATAC follow NASA's progress in this area and report to Congress semiannually. In this context, ATAC's mission is considered to be the following:

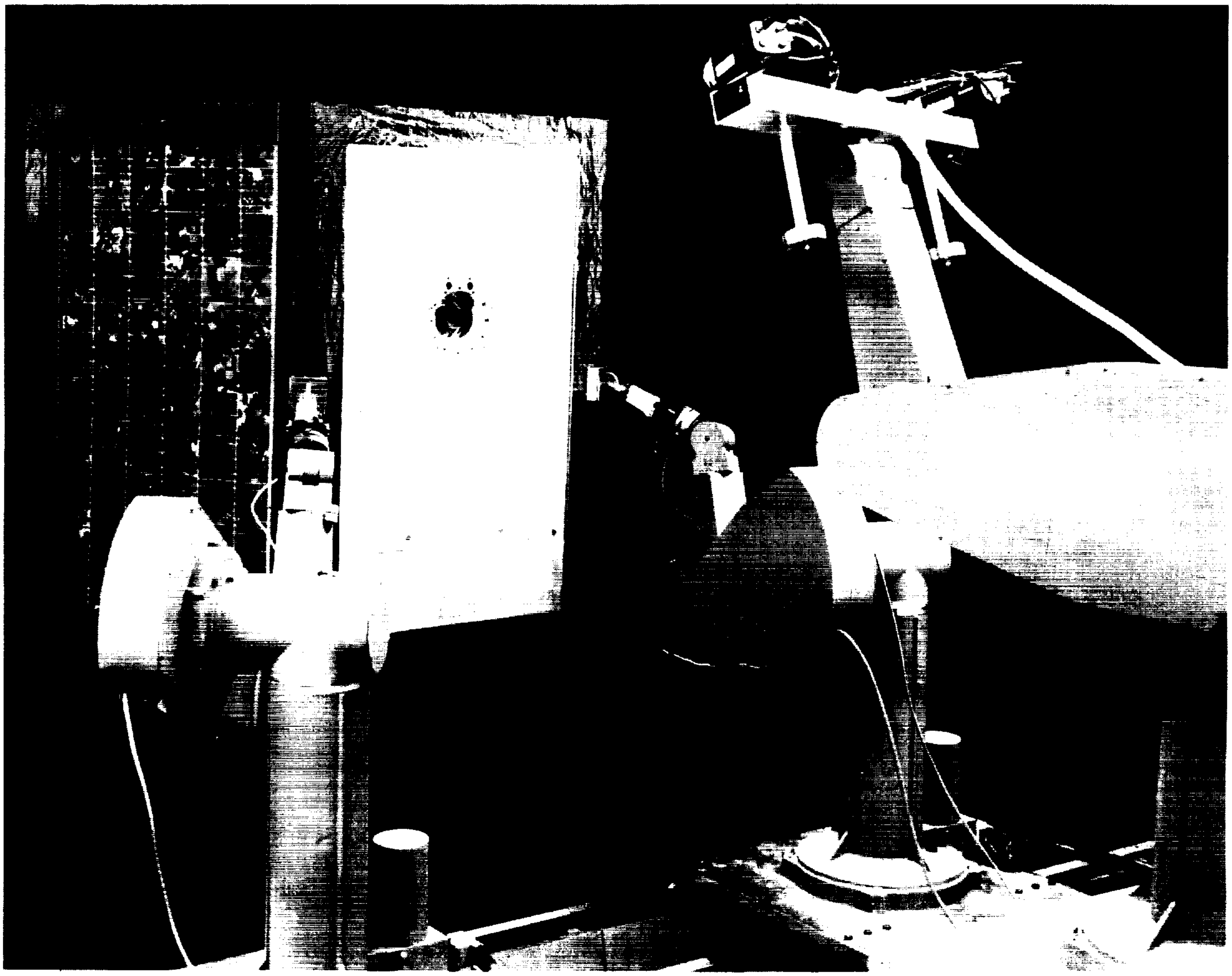
> ***Independently review the conduct of the Space Station Program and assess the integration of A & R technology. Based on assessments, develop recommendations, review the recommendations with NASA management, and discuss their implementation with consideration for safety, reliability, and cost effectiveness.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

This report is the sixth in a series of progress updates and covers the period of October 1, 1987, through March 31, 1988. ***However, progress and program changes occurring after February 15, 1988, are not reflected in this document.***

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

ATAC wishes to acknowledge its appreciation of two charter members who are no longer with the committee. John H. Boeckel, formerly with the Goddard Space Flight Center (GSFC), has recently retired from NASA. Donna L. Pivirotto, of the Jet Propulsion Laboratory (JPL), has been assigned to manage the Rover element of the MARS Rover Sample Return Study.

New ATAC members are Carl Solloway, NASA Headquarters, and Henry Plotkin, GSFC. In addition, Dr. Saul Amarel, of the Department of Computer Science of Rutgers University, and Dr. Takeo Kanade, Acting Director of the Robotics Institute of Carnegie-Mellon University, have consented to serve as consultants to the committee.



A major milestone in automation and robotics research and development, performed under NASA's Civil Space Technology Initiative, was achieved when robotic tracking and grappling of a spinning satellite model was demonstrated on the telerobotic testbed at the Jet Propulsion Laboratory. Under supervised autonomy, an advanced machine-vision system recognized the satellite, derived the parameters of the satellite's motion, and transmitted the parameters to a manipulation control system, which brought the two manipulator arms in contact with the spinning satellite. At the instant of contact, feedback was transferred to force sensors so that the satellite was brought smoothly to a halt at the desired position. The same robotic architecture also demonstrated teleoperation with dual arms, performing a variety of tasks representative of servicing operations.

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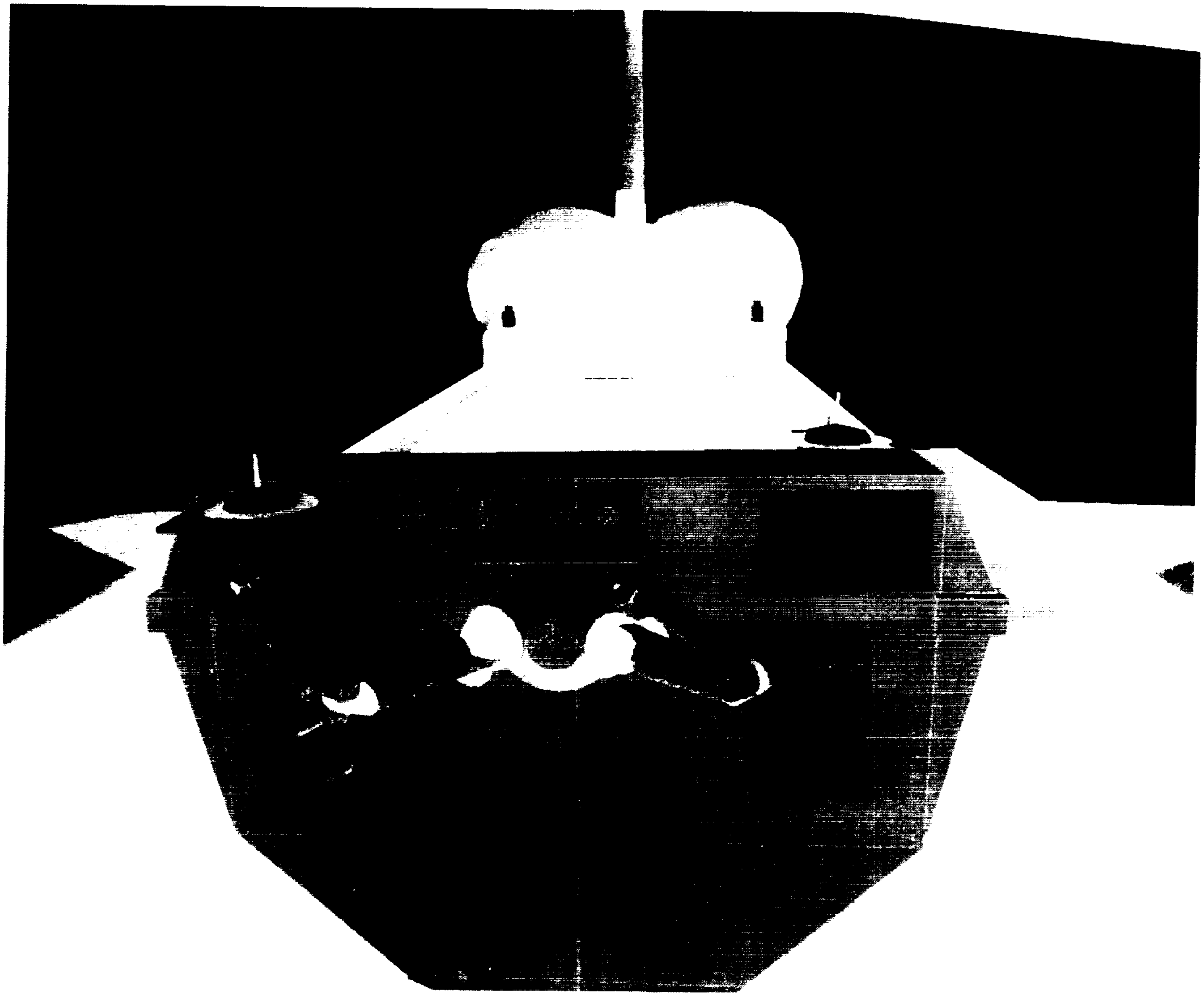


This concept for the Demonstration Test Flight (DTF) of the Flight Telerobotic Servicer (FTS) consists of a pair of robot arms on a rotating base attached to a Space Shuttle across-the-bay structure. A variety of test tasks are on the across-the-bay structure, certain of which involve using the Space Shuttle Remote Manipulator System (RMS) to move objects. This scene was generated from a dynamic display done on an I.'IS (Silicon Graphics) terminal. The dynamic display helps define the tasks and establish time lines. The software also checks for object interference and rotation limits at manipulator joints. (Courtesy of Goddard Space Flight 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 was submitted April 1, 1985 (ref. 1) and proposed **goals** for automation and robotics applications for the **initial** and **evolutionary** space stations. Additionally, ATAC provided **recommendations** to facilitate the implementation of automation and robotics in the Space Station Program. These recommendations were accepted as **policy** by NASA.

ATAC has continued to monitor and to report semiannually NASA's progress in automation and robotics for the Space Station, as further mandated by Congress. The reports are documented in ATAC Progress Reports 1 through 5 (refs. 2 - 6). These previous reports covered the definition and preliminary design phase (phase B) of the Space Station Program. In these semiannual progress reports, ATAC has documented progress, identified areas of concern, and provided further recommendations to NASA management. This is the sixth semiannual progress report.

The Space Station Program currently plans a "phased" approach to the total program. The first phase would provide a "baseline" Space Station with a future option which, if exercised, would provide an enhanced Space Station beyond the baseline Space Station. This current report period covers a timeframe during the startup of the design and development phase (phase C/D) of the Space Station Program. Phase C/D leads to a permanently inhabited Space Station, to be operational in the mid-1990's. During this report period, the work package contractors for phase C/D were selected, and fact-finding and trade studies are being conducted to support further program definition and contract negotiations. These activities have been conducted in concert with Congressional and conference committee considerations of national budget priorities.

In support of ATAC's charter, the Space Station Program provided a review of the program's activities related to A & R at an ATAC review, held January 13-15, 1988. Topics presented to ATAC included the following:

- The level I Space Station Program advanced development efforts and the objectives and approach for development of a program plan in the areas of advanced automation and robotics
- The level II Space Station Program plans and approach for integration of advanced automation and robotics, including systems engineering and integration, utilization and operations, information systems, and international partners' contributions
- The A & R content of the phase C/D work package contractors' proposals
- Progress on the Flight Telerobotic Servicer

The committee review also included the following selected topics by other NASA programs related to A & R for the Space Station:

- The Office of Aeronautics and Space Technology (OAST) progress and plans in systems autonomy and telerobotics
- The Office of Space Sciences and Applications (OSSA) Telescience Testbed Pilot Program
- The Office of Commercial Programs recommendations pertaining to transfer of technology

The review of the above topics, along with materials solicited from the NASA organizational elements, are the primary sources of information for this report.

In addition to the above review topics, the committee was fortunate to be provided presentations describing:

- Activities at the Environmental Research Institute of Michigan (ERIM) Center for Autonomous and Man-Controlled Robotic and Sensing Systems
- Activities at the University of Wisconsin Center for Space Automation and Robotics
- Research and development in automation and robotics at the Martin Marietta Aerospace, Denver Corporation

An assessment of progress with respect to the initial ATAC recommendations is given in the following section. This assessment, along with the executive summary, provides a top-level view of progress for the reporting period.

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

As in the previous reports, this section provides a summary assessment of NASA's progress toward fulfilling the committee's original recommendations adopted as Space Station Program policy. In this report, for the first time, the committee will assess progress against all 13 original recommendations. Recommendations 9 through 13 were based on an augmented program, with funding levels recommended initially by the California Space Institute (CALSPACE) Automation and Robotics Panel (ARP) (ref.7). Although the higher funding level has not occurred, NASA has exhibited progress which merits inclusion. For convenience, each recommendation is stated before the assessment of progress. The committee is also taking under consideration whether its recommendations should be revised for phase C/D of the Space Station Program.

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

Early in phase B of the Space Station Program, ATAC submitted its initial report. NASA adopted the ATAC recommendations as policy. In response to this policy, the Space Station Program (SSP) developed an A & R plan for phase B, established A & R events on the engineering master schedule, added tasks to address A & R in the contractor studies, and established an ad-hoc organization to address A & R requirements and issues. Significant progress was made, including the following:

- Identification, study, and recommendations of A & R candidates and applications for the Space Station (refs. 2 - 5)
- Recommendation of priorities for the implementation of A & R on the Space Station (appendix E)
- Initiation of the Flight Telerobotic Servicer project, and identification of the merits of a generic robot (ref. 3)
- Support of the onboard Data Management System and Operations Management System as supportive to A & R (ref. 4)
- Analyses showing the life-cycle cost benefits of several A & R candidates (refs. 3, 4)
- Identification of a preliminary set of hooks and scars required on the initial station to support evolution of A & R (table 1)
- Cooperative efforts by the OAST and the OSS in the areas of telerobotics and systems autonomy demonstration projects (refs. 3 - 5)
- Preparation of a design guidelines manual for A & R on the Space Station (ref. 8)
- Preparation of Process Requirements Documents for A & R and design knowledge capture for the Space Station (refs. 9, 10)

ATAC also provided recommendations for making A & R the significant element originally intended. These included the following:

- Establishing a top-down organizational structure for A & R (ref. 4)
- Developing an integrated plan for A & R, with goals and budget for A & R (ref. 5)
- Providing proper weight for life-cycle costs in decisions on A & R candidates (ref. 3)
- Establishing an advanced development program for A & R in the SSP to bring technology candidates to the stage of readiness for use in space (ref. 5)
- Adopting and implementing actions for design knowledge capture, design for robot friendliness, and hooks and scars in the baseline station for the incorporation of A & R in an evolutionary Space Station (ref. 4)

A top-down organizational structure for A & R in the SSP was established during our previous report period (ref. 6). During the current report period, the SSP has developed an approach for an A & R plan which addresses the above recommendations and, importantly, states the Space Station goals and policy in A & R. The committee has recommended to NASA that this plan be highly visible, both inside and outside the Space Station Program. The committee notes that many program participants will benefit from a clear communication of the role of A & R through a statement of policy in phase C/D and a list of expected products.

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

ATAC considers this the top-priority recommendation. ATAC is encouraged that the Office of Space Station level I Strategic Plans and Programs Division, responsible for A & R, has placed upon itself, a high priority to establish the specific requirements for hooks and scars on the baseline Space Station to accommodate evolution and growth in automation and robotics. Level II working groups in advanced automation and robotics are also addressing this objective. However, essentially no prime contractor support is available until after the Program Requirements Review (PRR) and contract negotiations are

TABLE 1.— PROVISIONS NEEDED FOR FUTURE A & R APPLICATIONS (HOOKS AND SCARS)

- **General**

  A design for structures, modules, and fittings adapted to assembly by anticipated manipulators

  Definition of "robot-friendly" interface standards for
  —Connectors
  —Fasteners
  —Replacement unit designs
  —Pathways
  —Data interchange

  Umbilical connections and attachment fittings that will accommodate power, communications, and fluids supply and provide stability for robots

  Incorporation of markings and lights to simplify computer vision implementation

  Growth toward autonomous robots

- **Sensors**

  At least the reservation of locations, connectors, and processing capacity for sensors to permit the monitoring and analysis of important trends

  Accommodation of evolutionary sensor systems (computer vision, for example) to support the operation of vehicles in proximity to the station

- **Information and Data Management**

  Provision for prognostication routines that will track the performance of station components and permit replacement on the basis of need rather than on a maintenance schedule

  Provisions for the incorporation of built-in test equipment on all data systems

  Provision for understanding and responding to fault indications (including access to CAD/CAM/CAE data bases)

  Growth capacity (memory and processing speed) without major rework

- **Guidance, Navigation, and Control**

  Provision for computer control of all Space Station traffic, including support for the control of multiple free-flyers

  Evolution of automated docking of free-flyers

  Provision for an expert system to perform trend identification and attitude control and to serve as an interface with the mass management control systems to keep the Space Station's center of gravity within design limits

- **Communication and Tracking**

  Accommodation of miniature television cameras and laser radars to support more automated docking and berthing

- **Habitability**

  Support for computer vision hardware and sophisticated analysis tools in the health maintenance facility

- **Extravehicular Activity**

  Provision for specialized computer vision and monitoring software for operation of the airlock as an emergency hyperbaric chamber

complete. This will require a concerted effort, since the work package contractors apparently did not address this in any depth in their proposals, and no conceptual designs or preliminary designs have been analyzed from the systems engineering view across the entire station for these A & R accommodations. There is some focus on early A & R applications, even though they may not be funded. This focus has shifted much-needed emphasis and effort away from commitment and follow-through in the area of accommodation for future growth.

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

ATAC, in its initial report to Congress (ref. 1), proposed a set of goals for A & R on the initial and the evolutionary Space Station (tables 2 and 3). Negotiations have not yet been conducted with work package contractors on the content of their phase C/D effort, including A & R. However, for the first time, we can begin to identify elements of A & R that may be on the initial Space Station. There are relatively few, but nevertheless significant, A & R candidates and applications in the proposals for the baseline Space Station, as shown in the following sections of this report.

Definition of the A & R requirements for the initial Space Station is being given high priority by the Space Station Program. The definition efforts include convening a panel of recognized experts in advanced automation (ref. 11) and forming SSP working groups for advanced automation and for robotics. However, in the current period of letter contracts and preparations for the Program Requirements Review, A & R and design knowledge capture efforts have been deferred. Deferral means the loss of A & R and design knowledge capture or more difficult inclusion of them later for the lack of critical initial design considerations. Concerns of the committee are the following:

- The initial station must have the design accommodations (hooks and scars) for later inclusion of A & R
- The A & R candidates which have been proposed for the baseline and enhanced stations must be funded
- The Software Support Environment must be extended to support the development of knowledge-based systems for in-space or on-ground use
- Program priority to include items which require added initial cost is needed so that A & R requirements will not be deleted

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

Criteria were developed during phase B which were used by several of the phase B work package contractors to rank and select their A & R candidates. However, no criteria are established by the SSP on which program managers base a decision to implement an A & R approach when there is an alternative. Since most A & R candidates require additional funds for implementation, the tendency has been to reject the candidate. Safety, reliability, maintainability, productivity, etc. are also considered. ATAC has recommended that greater weight be given to the life-cycle cost benefits of A & R and to the reductions in crew time for operations and maintenance.

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

- **Electrical Power**

  Controllers enhanced by expert systems for
  —Load distribution and switching
  —Solar array orientation
  —Trend analysis
  —Fault diagnosis

- **Guidance, Navigation and Control**

  Expert systems for
  —Station attitude control
  —Experiment pointing
  —Orbital maintenance and reboost
  —Rendezvous navigation
  —Fault diagnosis

- **Communication and Tracking**

  An executive enhanced by expert systems for
  —Communication scheduling
  —Rendezvous tracking
  —Data rate selection
  —Antenna pointing

- **Information and Data Management**

  An executive enhanced by expert systems for control of
  —Subsystem statusing
  —Trend analysis
  —Fault diagnosis
  —Redundancy and configuration management
  —Data base management

- **Environmental Control and Life Support**

  Controllers enhanced by expert systems for
  —Trend analysis
  —Fault diagnosis
  —Crew alarm
  —Station atmosphere monitoring and control
  —Hyperbaric chamber

- **General**

  Teleoperation of mobile remote manipulator with collision avoidance

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

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

  Primary station control in space with appropriate backup

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

It is too early to assess the Space Station Program for the testing and verification of specific Space Station equipment. The A & R plans should include provisions for the verification, validation, and demonstration of new A & R technologies. Plans for the FTS include both ground-based and Space Shuttle flight-based demonstrations prior to Space Station first element launch. The SSP is evaluating concepts for the Demonstration Test Flight (DTF) of FTS technology. Ongoing demonstration projects in telerobotics and in thermal control and electrical power systems autonomy are being conducted or planned in jointly sponsored OAST and OSS organizations.

The OAST Systems Autonomy Technology Program has designated verification and validation methodologies of knowledge-based systems as one of its major technical challenges. Program research and development (R & D) is being conducted in both core technology and demonstration projects to address this important issue.

In the Systems Autonomy Demonstration Project for automation of the Space Station Thermal Control System, verification and validation of the expert system performance are objectives of the demonstration in the thermal vacuum chamber at the Johnson Space Center (JSC), in the latter part of 1988. Verification and validation techniques will rely strongly on current state-of-the-art experience in the performance verification of other large complex software systems through extensive simulation and testing. These techniques will include path analysis on critical states, code review and walk-through, hardware and software simulation and laboratory testing, and review by a panel of verification and validation experts.

Verification and validation techniques will also be tested in the 1988 demonstration for automation of Space Shuttle ground mission communications control. The testing approach will be to use the expert system in parallel with the current conventional operational system during extensive Space Shuttle simulations and during the next Space Shuttle flight (STS-26). As confidence builds in the reliability of the expert system, the expert system will eventually replace the current conventional system. Additionally, in 1988, the flight demonstration of AI-based aeronautics control software will be conducted onboard the NASA Advanced Transport Operations Support (ATOPS) aircraft, a Boeing 737.

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

- **Propulsion**

  An intelligent controller for
  —Fuel distribution and management
  —Leak detection and evaluation

- **Electrical Power**

  An autonomous intelligent controller for
  —Power management
  —Fault detection and isolation
  —Maintenance scheduling

- **Guidance, Navigation, and Control**

  An intelligent controller for
  —Fully automatic rendezvous and docking
  —Space traffic control
  —Remotely piloted vehicles
  —Collision avoidance

- **Communication and Tracking**

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

- **Information and Data Management**

  An intelligent system for
  —Fault detection, isolation, and repair
  —Natural language interface with crew

  A data base manager for
  —CAD/CAE bulk data storage facility
  —Retrieval and routing to requestors

- **Environmental Control and Life Support**

  An intelligent controller for
  —Ensuring fail-safe/fail-operational modes
  —Fault detection and isolation
  —Chemical analysis of air and water
  —Toxic gas analysis

- **Habitability**

  An intelligent system for
  —Health maintenance
  —Speech interpretation and synthesis
  —Physiological monitoring
  —Automated medical decisions
  —Trend analysis

- **Structures and Mechanisms**

  Advanced work station
  Intelligent actuators
  Teleoperators

- **Orbiting Platforms**

  An intelligent system for
  —Process control
  —Maintenance control
  —Planning and trend analysis

- **General**

  Robots for
  —Inspection, maintenance, refurbishment, and repair
  —Fuel and materials transfer
  —Detecting hazardous leaks
  —Satellite retrieval and servicing

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

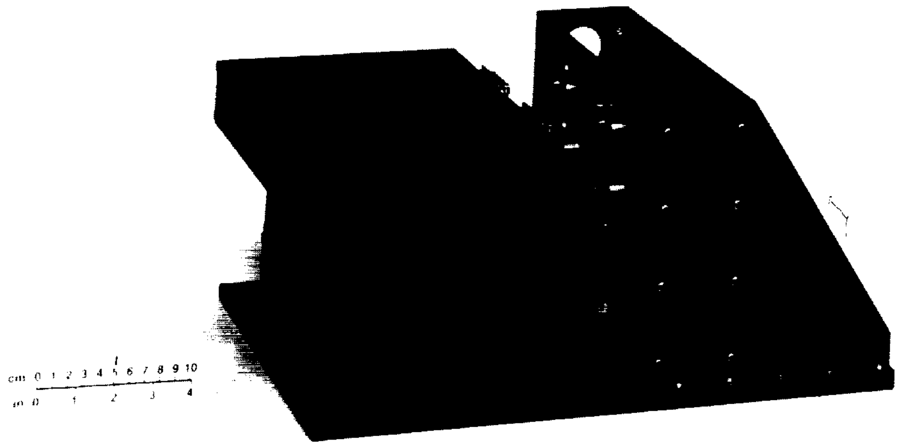
During phase B, the Space Station Program conducted surveys and workshops to establish a base of understanding of the technology available in universities, in industry, and in Government. Because there are no "off-the-shelf" systems for spacecraft advanced A & R, most of the A & R technology currently being used by industry and Government needs additional development to meet Space Station requirements. For this reason, it is important that continued resource support be given to the OAST for technology base building and to the Space Station Program for advanced development of these emerging technologies.

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

A fundamental approach to Space Station implementation is commonality (avoiding proliferation of diverse, incompatible subsystems, components, and software) in services such as power and data systems. This has benefits in capability, cost, and schedule. The underlying strategy to information management in the Space Station Program involves the following:

- Networking
- Common tools and standards
- Information resource management
- Distributed but cooperative development

Two long-lead efforts supporting Space Station information management have been identified. These two efforts, the TMIS and the SSE, were discussed in ATAC Progress Report 5 (ref. 6). TMIS is the collection of computer-based tools and processes which supports the agency in engineering and managing the program. The SSE is the collection of computer-based tools and standards which work package vendors will use to develop both flight-based and ground-based mission software.



This concept for the Hubble Space Telescope (HST) command and data handling module permits new servicing opportunities because the internal electronic boxes are designed for replacement by a teleoperated or autonomous robot. The boxes have captive screws and robot gripper accommodations, and the electrical connectors are self-aligning. (Courtesy of Goddard Space Flight Center)

In addition, the OSSA, as part of its Telescience Testbed Pilot Program, is developing initial recommendations for requirements and design approaches for the information systems of the Space Station era to develop a telescience concept for the SSP. Telescience requirements will impact the Space Station. Multiple scientific experiments, such as exploiting advanced technologies and technical approaches, are being carried out, with each emulating some aspect of science in the Space Station era (ref. 12).

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

Measures used to verify the inclusion of A & R are: performance measures, cost measures, and technology readiness measures. A set of joint OAST and OSS technology readiness measures (ref. 2) is currently being used.

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

ATAC believes the Space Station Program is following the intent of this recommendation; given consideration also for safety, reliability, maintainability, etc.

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

Because the Space Station will be evolutionary in nature, it should be developed to allow facile introduction of future A & R technology advances. It is not clear that each Space Station function, element, and subsystem will be designed to accommodate the future A & R which would lead to more autonomous station operations and improve the human/ machine interactions. Phase B contractor studies addressed these issues, and the designs should be sensitive to the A & R needs. The specification of the Data Management System (DMS) as a distributed system was a major contribution.

Space Station Program management has placed a high priority on defining the hooks and scars required for incorporating the future evolution of A & R. Management has also recognized the requirement for design knowledge capture and design for robot friendliness. However, the SSP needs to support a more dedicated effort to accomplish these tasks.

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

The OAST has continued to increase its resources and efforts devoted to A & R to include additional universities and all NASA centers. Although the increases have been modest relative to need, they have been encouraging in this period of national budget concerns. Also, the SSP level I has provided increased funding devoted specifically to advanced development in advanced automation and robotics.

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

The Office of Commercial Programs (OCP) has moved ahead with the commercialization of NASA automation and robotics technology, and it includes A & R as an area of emphasis. The OCP has also supported two centers of space commercialization specializing in A & R. The OCP plans to include a special A & R section in its *Tech Briefs* publications.

In addition, the Office of Space Station (OSS) has funded a study to assess whether Space Station A & R efforts are likely to be of benefit to U.S. industry. The study also reviewed prior successful transfers of

Government-developed technologies to the private sector to identify "lessons to be learned," which would help promote the transfer of Space Station A & R technologies.

A workshop was recently concluded at GSFC, under sponsorship of the Office of Commercial Programs, which brought together robot manufacturers, materials processing scientists, microelectronics manufacturers, and space carrier specialists (ref. 13). The purpose of the workshop was to study potential applications of robots for cost effective commercial microelectronic processes in space and to define the associated robotic requirements. The findings of the workshop identified candidate processes, robot capabilities, special requirements, and flight support facilities. As a follow-on to the workshop, a study will be initiated whose objectives are to perform cost/benefit analyses on specific processes, develop conceptual designs of a robotic ground test and space facility, and define interim small flight experiments which would test key robotic functions.

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

A new area vital to enhancing space sciences data collection is to develop instruments which can be assembled and serviced by robots. These instruments, whose size and weight preclude full assembly prior to launch, are intended to be assembled on orbit by robots. Additionally, as new sensors and subsystems are developed, the instruments can be upgraded using robotic techniques. GSFC, with the sponsorship of the Office of Space Sciences and Applications, has identified a large superconducting magnetic instrument, ASTROMAG, as a candidate to be studied for designing robot-friendly sensors and subsystems. ASTROMAG is currently being considered as an attached payload on Space Station. This will be followed by building full scale mockups to be manipulated and tested in the robot laboratory at GSFC. Eventually, a set of robot-friendly design guidelines will emerge for the general use of scientific and other payloads.

Progress in A & R Content in the Contractor Proposals for the Final Design and Development of the Space Station

During this report period, contractor teams were selected for each of the four work packages for the design and development phases (phase C/D) of the Space Station Program. Proposals were received and evaluated, contractors were selected, and fact-finding relative to the proposals and the Space Station content is proceeding. Final negotiations with the contractors will occur after the fact-finding and Program Requirements Review (PRR) have been completed. In the following, the A & R content of the proposals has been summarized for purposes of this progress report. The inclusion or exclusion of the proposed A & R content or other A & R candidates is subject to the negotiations yet to be conducted.

Work Package 1

Work package 1 (WP-1) is assigned to the Marshall Space Flight Center (MSFC). The selected prime contractor was the Boeing Aerospace Company, Huntsville, Alabama. Work package 1 calls for the Boeing contractor team to provide the U.S. laboratory and habitation modules; logistics elements; resource node structures; environmental control and life support (ECLS); ECLS common airlock systems; internal thermal, audio, and video systems; and associated software.

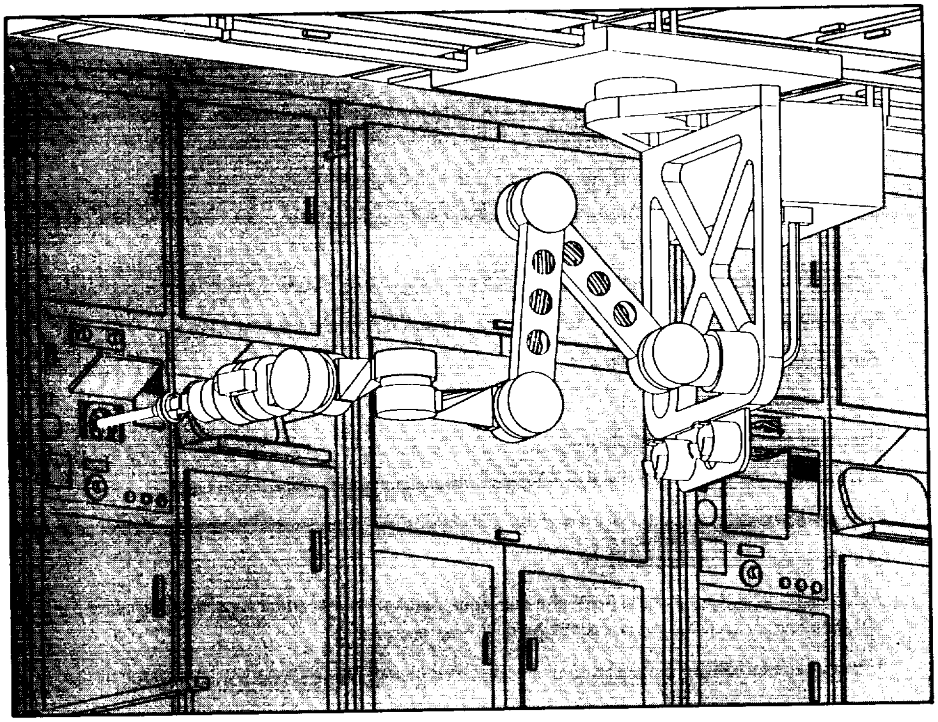
Boeing proposed to include a relatively high degree of "classical" automation in the elements and systems which they will deliver. The proposed initial capabilities will feature on-orbit automation of the Space Station utilities and inventory management. An intravehicular (IVA) laboratory-assistant robot was proposed for operation in fixed sequences monitored with teleoperation from the ground during man-tended operations, and after manned operations have begun, to offload the crew from routine operations. Boeing plans to pursue a long-term growth program to identify and evaluate innovative A & R ideas and concepts with foresight toward transferring advanced A & R technologies to the terrestrial economy.

Boeing's proposed approach provides for planned growth from low-risk initial automation to advanced automation in the various subsystems. The IVA robot concept would increase early science productivity in the U.S. laboratory. Table 4 shows the A & R applications proposed for development and implementation for the baseline and growth Space Station.

Boeing plans to utilize A & R technologies during development in their engineering and manufacturing processes. In addition, they plan to integrate and utilize automation tools to capture the rationale and analyses on which their Space Station designs are based.

TABLE 4.— PROPOSED DEVELOPMENT AND IMPLEMENTATION OF A & R APPLICATIONS — WP-1.

Program phase	Automation	Robotics
Phase C/D		
• Space	• Element OMA • Element/subsystem FDIR • Rack-level BIT/BITE • Onboard maintenance system (OBMS) • Inventory management system (IMS) • Voice input-output	• Laboratory IVA robot
Growth		
• Space	• Fault diagnosis and prediction • Adaptive fault control • Automatic scheduler • Optimizing planner • Predictive maintenance • Autonomous controller • Speech understanding • Intelligent operator systems interface	• Laboratory robot — crew proximity operations • Housekeeping robot • Logistics robot • Mobile, intelligent, dextrous robot
• Ground	• End-to-end automation for design/development • Intelligent test and verification • CIM, FMS, advanced MRP • Autonomous process and manufacturing control • Intelligent FDIR, control for transport systems	• Flexible robots



An intravehicular robot has been proposed for the Space Station laboratory module to increase early scientific productivity in the U.S. laboratory.

Work Package 2

Work package 2 (WP-2) is assigned to the Johnson Space Center (JSC). The selected prime contractor was McDonnell Douglas Astronautics Company, Huntington Beach, California. Work package 2 calls for the McDonnell Douglas contractor team to provide the integrated truss structure; mobile servicing system transporter; airlock outfitting; resource node outfitting; hardware and software for the data management system; communications and tracking system; guidance, navigation, and control system; extravehicular activity systems; propulsion system; thermal control system; and external attachment systems.

A summary of the automation and robotics applications proposed by McDonnell Douglas for work package 2 is shown in tables 5 and 6. Table 5 contains the applications proposed for the Space Station at completion of assembly, and table 6 contains the applications envisioned for an evolutionary station. The advanced automation applications focus on the implementation of an expert-system-augmented fault detection, isolation, and recovery (FDIR) capability. The FDIR applications will consist of a combination of conventional software and hardware techniques and expert system techniques, with the relative content of conventional-versus-advanced techniques being determined on a system-by-system basis and depending on required response time, safety, cost, heuristic content, etc. A high level system coordination FDIR capability is proposed for the monitor and reactive control part of the Operations Management Application (OMA), which communicates with the FDIR modules within each distributed system. Additionally, McDonnell Douglas proposes some advanced automation content in trend analysis for leak detection in the Thermal Control System (TCS), automated Extravehicular Mobility Unit (EMU) check-out, and extravehicular activity (EVA) voice recognition command.

Proposed robotics applications focus on the use of the Flight Telerobotic Servicer (FTS) for assembly and external maintenance and on a Crew and Equipment Retrieval System (CERS). Specific applications proposed for the FTS include: thermal radiator assembly, deployment and installation of boom support structures, utility installation, positioning of pallets and rotary joints for installation by the crew, and external Orbital Replaceable Unit maintenance. The proposed CERS is an unmanned retriever that is teleoperated from the station. The concept includes computing a rendezvous orbit to intercept the crewmember or equipment, capture of the crewmember or equipment with a special snare arrangement, and hand-off of the crewmember through an airlock to another crewmember.

The proposed approach to Design Knowledge Capture (DKC) includes: the use of existing engineering data bases to supply physical design data; design rationale being captured manually until the Preliminary Design Review (PDR) and in machine-interpretable form thereafter; design data being integrated with pointers from the hierarchical product structure; and expert system building tools being used to capture behavioral and functional data.

TABLE 5.— A & R PROPOSED AT COMPLETION OF ASSEMBLY — WP2

Subsystem	A & R Application	Description
Data management system	Telemetry	Automated reconfiguration for telemetry
	Fault detection	Expert system augmented fault detection isolation and recovery (FDIR)
	Monitoring	Expert system to assist in monitoring and reactive control part of OMA, communicating with the FDIR modules within each distributed system
	Scheduling	Onboard execution level scheduler will be part of the Operations Management System (OMS)
	Networking	Expert system to assist in onboard local networking and automatic reconfiguration
Propulsion system	Fault Detection	Expert system augmented FDIR
Guidance navigation and control	Fault detection	Expert system augmented FDIR
Thermal control system	Fault detection	Expert system augmented FDIR
	Control	Automated control with supervisory controller software that interfaces with the OMS
	Leak detection	Automated trend analysis for leak detection. Differences from trends used to specify control actions
Communications and tracking	Fault detection	Expert system augmented FDIR
EVA systems	EMU servicing	Automated inplace reservicing (except metal oxide cartridge removed for regeneration) within 12 hours. Replace battery and CO_2 control cartridge for 1 hour reservicing
	Communication	Helmet mounted display and support electronics that provide voice recognition and video communication capability
	Maintenance	Use of the FTS for ORU replacement and structure inspection
	Rescue and retrieval	Teleoperated system for crew rescue and equipment retrieval
Mechanical systems	Monitoring	Autonomous health monitoring and control
Integrated truss	Assembly	FTS thermal radiator assembly
	Assembly	Use of the FTS to deploy and install boom support structure
	Assembly	FTS utility installation
	Assembly	Use of a compliant end-effector for assembly (construction, maintenance, and repair) that consists of multisegmented fingers for grasping different shaped objects
	Leak detection	Automatic leak detection and isolation of the fluid management distribution system

TABLE 6.— A & R PROPOSED FOR THE EVOLUTIONARY STATION — WP2

Subsystem	A & R Application	Description
Data management	Control	Evolution of the OMA to automatic operation. Expert system will perform fault detection and reconfiguration
Propulsion system	Leak detection	Automatic leak detection and isolation
Thermal control system	Leak detection	Advanced automatic leak detection
Communications and tracking	Sensing	Smart camera for robotic applications. Intravehicular activity (IVA) astronauts will move EVA cameras by giving voice commands.
	Routing	Expert system to assist in the configuration of communication and tracking links
	Monitoring	Expert system to assist in monitoring of communication and tracking equipment
EVA systems	Servicing	Advanced automatic EMU checkout and servicing
	Communications	Natural language control of EMU
	Monitoring	Autonomous IVA monitor for EVA activity
	MMU	Enhanced Manned Maneuvering Unit (MMU) with automated functions
	FTS	FTS-derived smart front end
	Maintenance	Automatic maintenance with the growth FTS
Airlocks	Control	Automated pressurize/depressurize control

Work Package 3

Work package 3 (WP-3) is assigned to the Goddard Space Flight Center (GSFC). The selected prime contractor was the Astro-Space Division, General Electric Company (GE), Valley Forge, Pennsylvania. Work package 3 calls for the General Electric contractor team to provide a free-flying, unmanned, polar-orbiting platform which will carry scientific experiments in Sun-synchronous or other near-polar inclination orbits; and two attach points, including a pointing system, for accommodating scientific instruments on the manned base. The FTS is also a part of work package 3, but FTS work is being conducted under separate contracts and is treated in a separate section of this report. GE also is responsible for integration of the FTS to the Space Station, appropriate Space Station information system activities, associated software, and for planning NASA's role in satellite servicing. Additionally, GE is responsible for defining requirements and interfaces for a satellite servicing facility.

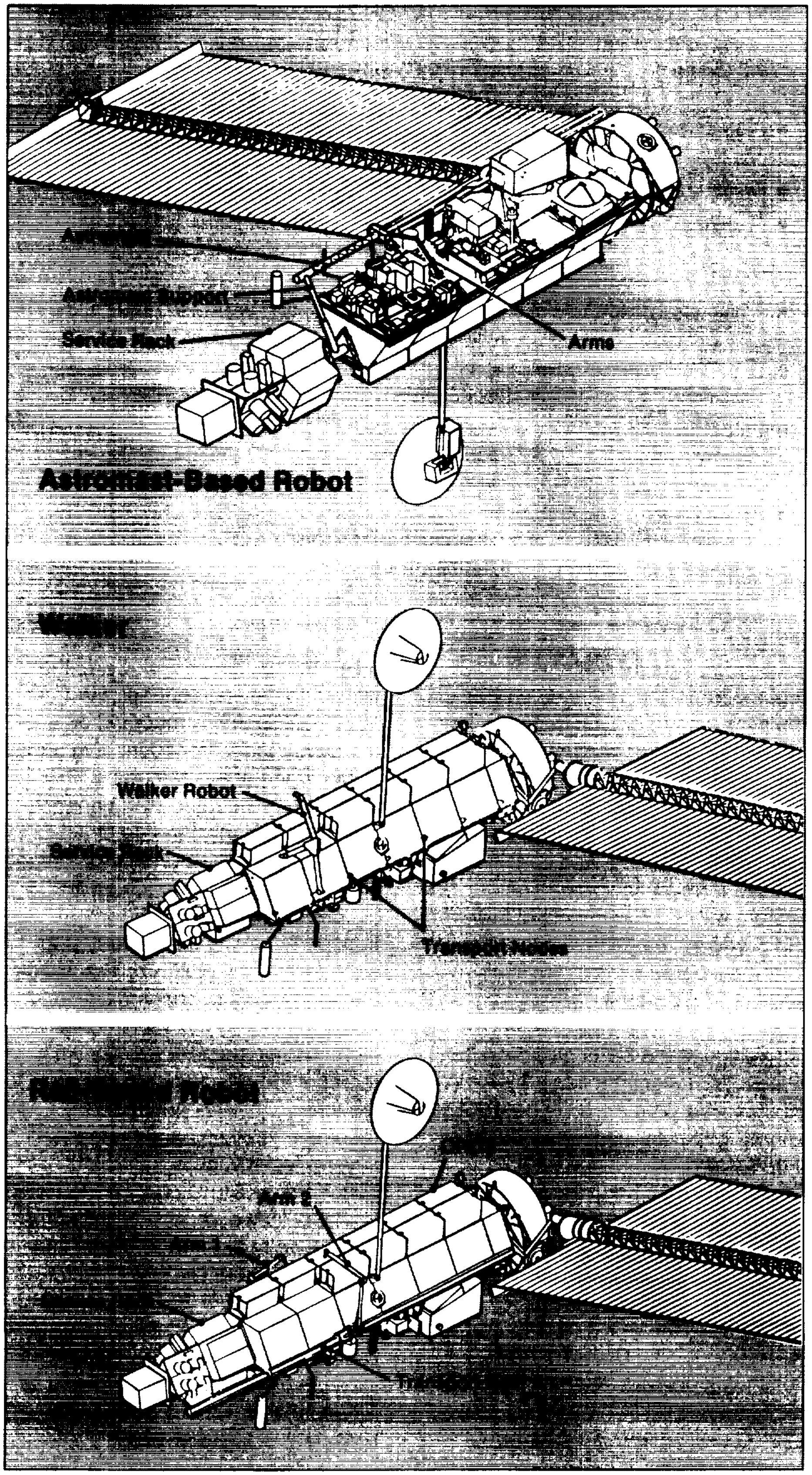
The A & R plan submitted with the proposal defined criteria for incorporating A & R in work package elements, required early incorporation of automation, and defined requirements to allow the use of robotic devices in all Space Station phases. Advanced automation concepts are incorporated in specific WP-3 deliverable products, including a knowledge-based planning and scheduling system and flight- and ground-based expert systems for platform anomaly diagnosis. Table 7 shows the typical A & R applications proposed for study by the WP-3 contractor.

The initial design knowledge capture plan defines the elements of design knowledge to be captured and suggests an approach to all electronic design knowledge capture. The approach includes studies and pilot projects to develop design knowledge capture systems that will replace traditional methods only as the systems are proven capable. The design knowledge capture system includes four elements: a systems specifications language, a data base of machine intelligible design knowledge, an integrated CAD/CAE architecture, and a library. The system will utilize elements of the TMIS and will be compatible with TMIS standards for text, graphics, and communications.

TABLE 7.— TYPICAL A & R APPLICATIONS PROPOSED FOR STUDY — WP-3

WP-3 Element	Typical A & R Applications
• Program management	• Computerized scheduling, monitoring, and information exchange
• Systems engineering	• Knowledge-based requirements traceability
• Platforms	• Expert system for anomaly diagnosis, built-in test equipment, robotic servicing, and resident robot for ELV servicing
• Attached payloads	• Monitoring and control, servicing by FTS, CSF, and mobile servicer
• Flight Telerobotic Serivcer (FTS)	• Support entire station, path planning, collision avoidance
• Customer Servicing Facility (CSF)	• Track-based manipulator, FTS storage, lighting and vision systems, self-monitoring in dormant mode
• Space Station Information Systems	• Knowledge-based planning and scheduling, expert systems

In addition to the items proposed for phase C/D, Work package 3 is studying the potential for robotic servicing of polar platforms, should the Western Test Range Space Shuttle base not be available to support the Space Station Program. This is being done as part of the Expendable Launch Vehicle (ELV) Servicing Study, which is an extension to the Space Station phase B studies by GE. The concept includes a platform-resident robot for exchanging ORU's brought up by the ELV as well as fully automated rendezvous and docking for servicing, and automated disposal of expended elements. Three concepts under study are the astromast-based robot, the rail-based robot, and the walker. In the first concept, the astromast, which is mounted on a rotatable carrier, transports two arms within reach of the item to be replaced. In the rail-based concept, manipulator arms capable of reaching the ORU's on the top of the platform and the payloads on the bottom of the platform are transported along rails mounted to each side of the platform. The walker transports itself to nodes positioned at approximately five feet intervals on each side of the platform. The final report of the GE study will compare the three concepts and make recommendations based upon several factors, including each concept's design impact on the Polar Platform. However, as a result of the work done to date, GSFC feels that the development of a polar platform "resident robot" is feasible and can be one of the technically simpler development tasks of the Flight Telerobotic Servicer. The study is to be completed, with recommendations, in the spring of 1988.



Concepts for resident robots on the Space Station Polar Platform are being studied. The concepts include a platform-resident robot for exchanging Orbital Replaceable Units brought to the platform by expendable launch vehicles, fully autonomous rendezvous and docking for servicing, and automated disposal of expended elements.

Work Package 4

Work package 4 (WP-4) is assigned to the Lewis Research Center (LeRC). The selected prime contractor is the Rocketdyne Division, Rockwell International, Canoga Park, California. Work package 4 calls for the Rocketdyne contractor team to design and fabricate the Space Station electric power system, including power generation and storage, management and distribution of electrical power, and associated software. Rocketdyne is also responsible for providing solar arrays, battery assemblies, and common power management and distribution components for the polar platform and for performing a proof-of-concept test for a possible future solar dynamic power system utilizing the "Brayton cycle" system.

In its proposal, Rocketdyne identified both automation and robotic technology candidates for application to the Electrical Power System (EPS). The automation technologies were evaluated using the set of criteria established during phase B of the Space Station Program. Those candidates which ranked as the most beneficial and were established practice were proposed for the baseline Space Station. The remaining beneficial technologies were proposed for implementation for the growth version of the Space Station.

Table 8 shows those A & R technology candidates proposed for implementation during Space Station phase C/D and growth phases. Automation technologies that were proposed for the baseline Space Station configuration were conventional algorithmic and logic strategies. The initial power systems automations involved static-state estimation of sensor data, automatic contingency analysis, simple priority of load shedding, and routine load management.

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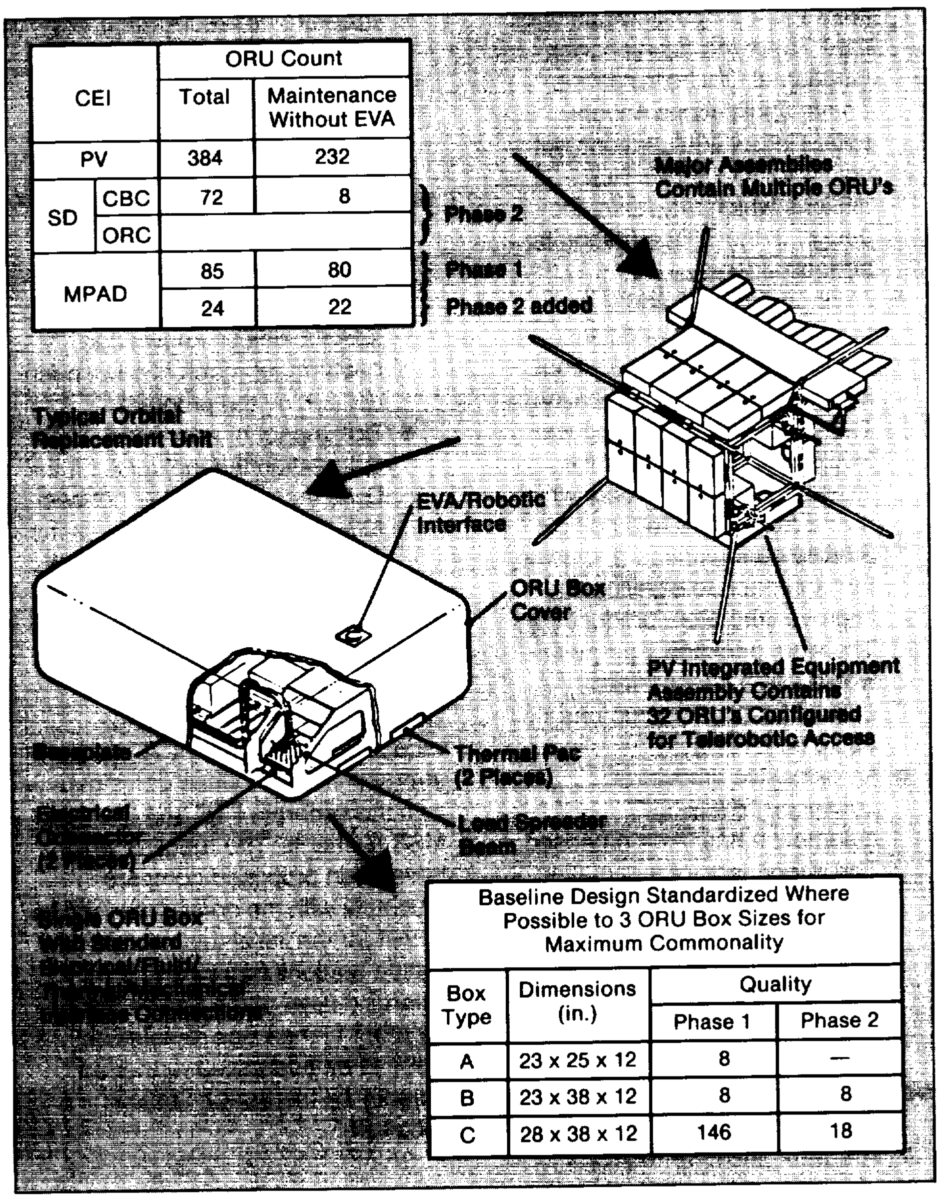
TABLE 8.— A & R TECHNOLOGIES PROPOSED FOR IMPLEMENTATION — WP4

Program Phase	Automation	Robotics
Phase C/D	• Automated system operation (incorporating proved advanced control techniques)	• Telerobotic ORU replacement
Growth and advanced phases	• Increased software sophistication and autonomy • Increased expert systems use • New diagnostic and computational • New diagnostic and computational hardware • Artificial intelligence use	• Transition to robotic replacement • Repair and maintenance using robotics



CEI		ORU Count: Total	ORU Count: Maintenance Without EVA
PV		384	232
SD	CBC	72	8
	ORC		
MPAD		85	80
		24	22

Baseline Design Standardized Where Possible to 3 ORU Box Sizes for Maximum Commonality

Box Type	Dimensions (in.)	Quality: Phase 1	Quality: Phase 2
A	23 x 25 x 12	8	—
B	23 x 38 x 12	8	8
C	28 x 38 x 12	146	18

The proposed Space Station Electrical Power System (EPS) baseline design uses Orbital Replaceable Units as the basic maintenance level to minimize extravehicular activity (EVA) requirements.

At initial operating configuration, the EPS will use advanced "classical" automated control, with provisions for manual flight crew or ground override. The processor architecture is to include reserved memory locations and processing capacity for additional and advanced sensors to permit upgrading of automated monitoring, control, and analysis functions. Electrical Power System ORU's are proposed to utilize the FTS to increase crew productivity during changeout. The contractor's proposal stipulates the use of an FTS interface element based on the RCA standard interface connector, developed as part of the work package 3 phase B effort. The primary feature of this concept is that the connector can make or break structural, thermal, fluid, and electrical connections with one operation. The robotic interface contains an end-effector attachment point for lifting and an "Acme" screw for actuation.

A cost assessment was made of the automation-focused activities. Of the proposed power system cost of $1.6 billion for the baseline Space Station, approximately 7 percent is allocated for implementing conventional automation. Implementation of advanced automation technologies are not costed in the contractor's proposal.

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ATAC Assessment

The A & R content of the work package proposals is a good reflection of the requests for proposals as assessed by the committee in Progress Report 5. The proposals, as a combined set, include extensive automation of the baseline Space Station, using "classical" automation technology. However, only one proposal, WP-2, includes significant advanced automation technology. Robotic content is stronger, as reflected by the following proposals: Use of the FTS for selected assembly (WP-2) and maintenance applications (WP-2 and WP-4), and additional robotic applications for an intravehicular laboratory-assistant robot (WP-1); a teleoperated crew and equipment retrieval system (WP-2); and a compliant end-effector for construction and maintenance (WP-2). Proposal content for an evolutionary Space Station is less defined. The committee's assessment of the strengths and weaknesses of the work package proposals is as follows:

Strengths

- Significant elements of advanced automation are included in the work package 2 baseline proposal. Specifically, expert systems are included in the onboard Operations Management System (OMS) and in several of the other subsystems interfacing with the OMS. These inclusions will not only enhance the baseline Space Station operations, but will also provide a critical driver for ensuring that the Space Station architecture will support inclusion of later advanced automation in an evolutionary Space Station for more efficient and autonomous Space Station operations. These applications focus on fault detection, isolation, and recovery (FDIR), which was identified in phase B by the work package centers as the first-priority application.
- Contractor proposals for work packages 2 and 4 contain important applications of the FTS for the baseline Space Station. The work package 2 proposal would use the FTS for the specific assembly, inspection, and maintenance applications of thermal radiator assembly, deployment and installation of boom support structures, utility installation, positioning of pallets and rotary joints for installation by the crew, and external ORU maintenance. The work package 4 proposal would use the FTS for the maintenance function of ORU changeout. These applications not only define important functions but also will provide interface designs which may drive the design of the Space Station to be robot-friendly.
- Work packages 1 and 2 proposals include additional innovative robotic applications for the baseline Space Station. The work package 1 proposal would use an intravehicular laboratory-assistant robot which leverages on FTS technology. Studies during phase B showed this approach to significantly improve laboratory productivity. The work package 2 proposal would use a teleoperated system for crew rescue and equipment retrieval.
- An extensive amount of advanced "classical" automation has been proposed. The importance of automating, even at these minimal levels, was shown in phase B to provide significant life-cycle cost benefits.

Weaknesses

- The work package requests for proposals did not require the contractors to address hooks and scars required to support incorporation of advanced A & R technology in an evolutionary Space Station. However, the OSS Strategic Programs and Plans Division (level I) has identified these requirements as a top-priority item, as have Advanced Automation and Robotics Working Groups at level II; and ATAC expects this issue will be addressed and included in the contract negotiations.
- There is wide diversity between the work package proposals in their plans for design knowledge capture. The Space Station Program has recognized this and plans to take action to resolve it in work package contract negotiations and in level II integration contractor tasks. This is perceived by ATAC to be a difficult problem, not only because of the non-uniformity of treatment by the proposals, but also because a specific design knowledge capture approach has not been defined by the program.
- The impact of advanced automation technologies on the DMS architecture has not been fully addressed from a systems level; e.g., software languages, operating systems, fault tolerance, distributed data base management, etc.

Collectively, the work package proposals are viewed by ATAC as strong in robotics when combined with the separate FTS and Canada MSS elements. The robotics which have been proposed compare favorably with the goals proposed by ATAC for the initial and evolutionary Space Stations (tables 2 and 3). Overall design of the Space Station for robot friendliness remains an issue to be addressed further and formally by the Space Station Program.

Collectively, the work package proposals are not viewed as strong in advanced automation. Only a few elements of the goals proposed by ATAC are included. However, it is encouraging that the WP-2 contractor proposed to embed a knowledge-based system in the DMS. Different, possibly incompatible, technical approaches and architectures for automation were proposed by the various prime contractors. This will need to be addressed prior to, and as part of, contract negotiations. A significant number (not all) of the applications suggested by the contractors for the initial Space Station (appendix D) during phase B have been included in the work package proposals. This includes elements that should drive the Space Station automation architecture to support future advanced automation. It will be critical for the Space Station Program to take actions in a timely manner to firm up the requirements for hooks and scars and design knowledge capture for the contract negotiations.

The committee notes that the A & R content of the Space Station Program will be subject to work package contract negotiations yet to be conducted. This will be in addition to the FTS project, international partner activities, TMIS and SSE content, user and operations requirements, and OAST and OSS research and development. There will be cost, schedule, and technical pressures to reduce the A & R content of the Space Station Program. **The committee has recommended to NASA that every effort should be made to retain the proposed A & R content and to support change requests required to provide for hooks and scars, design for robot friendliness, design knowledge capture, and the integration of A & R.**

Progress on the Flight Telerobotic Servicer for the Space Station

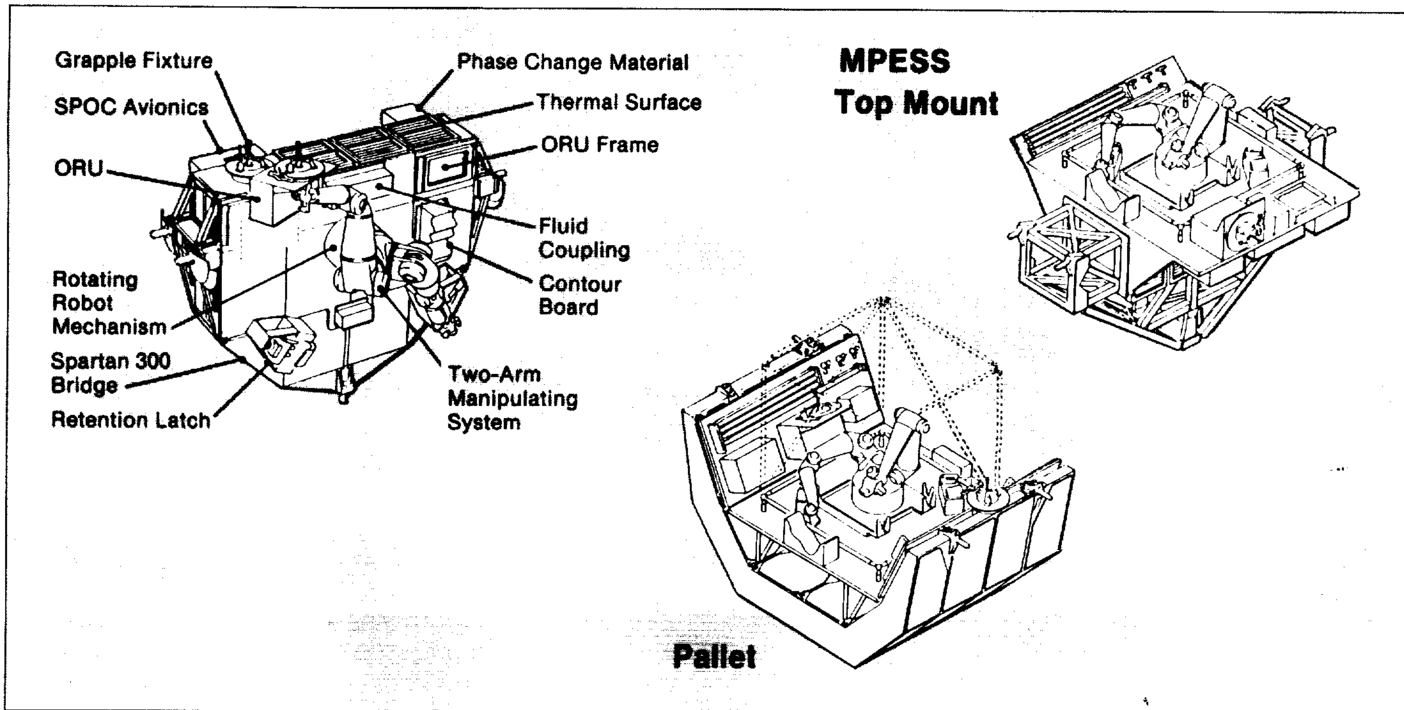
In November, 1985, Congress directed that NASA develop a flight telerobotic system, to be delivered at the time of initial Space Station operational capability, for a mobile remote manipulator for Space Station assembly and maintenance and for a smart front end on the orbital maneuvering vehicle for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

The Goddard Space Flight Center (GSFC) was assigned lead responsibility for the FTS as part of the work package 3 responsibilities. As stated in previous ATAC reports, a plan for the development and implementation of the FTS has been established. It includes the other work package centers and the support of the NASA Office of Aeronautics and Space Technology. SSP (level I) is funding telerobotic technology development to facilitate the transition of the initial FTS to the development stage as well as funding support for the evolution of the FTS.

During this ATAC report period, phase B contracts have been awarded to Martin Marietta Astronautics Group, Denver, Colorado, and to Grumman Space Systems, Bethpage, New York, to develop independent conceptual designs for the Flight Telerobotic Servicer. These contracts were awarded in December, 1987. As previously reported, the procurement approach for the FTS facilitates the development of two independent systems concepts by utilizing a continuing source evaluation board (SEB) to monitor the phase B contracts. Most contractor results and reports will be treated as SEB sensitive. Award of these contracts in December, 1987, supports the scheduled initiation of phase C/D for the FTS in early 1989, the availability of a prototype manipulator system to support a Demonstration Test Flight (DTF), and the availability of the FTS system for first element launch (FEL) of the Space Station. The two contractual studies are augmented by a parallel in-house phase B study at GSFC.

Prior to FEL, some technical and operational aspects of the FTS will be tested in a Demonstration Test Flight, conducted on the Space Shuttle. The DTF will accomplish the following:

- Provide early verification of the prototype manipulator system by demonstrating its capability to accomplish FEL-type tasks
- Provide answers to fundamental engineering uncertainties
- Influence workstation design
- Validate the FTS system architecture
- Provide in-flight training
- Develop mission planning capabilities



Concepts are being studied for packaging the FTS test configuration in the carrier bay of the Space Shuttle for a flight demonstration test. (Courtesy of Goddard Space Flight Center)

Preliminary packaging concepts are being considered for the DTF. In these concepts, a Space Shuttle bay carrier structure supports the manipulator system and all the equipment required to perform a set of carefully selected tasks in the cargo bay of the Space Shuttle. The carrier structure would also house all the support avionics required for the test, such as computers, a data management system, the power system, etc. A compact, stowable workstation will be provided for mounting in the aft flight deck of the Space Shuttle. The DTF launch is scheduled to provide results that will be available to support the FTS flight system critical design review.

The initial briefing of the GSFC in-house phase B study was held on December 14 and 15, 1987 (ref. 14). The briefing was attended by representatives of industry (including the winners of the FTS phase B study contract), universities, other Government agencies, and the NASA centers involved in this study. This in-house activity is developing trade studies to define both the Space Station interfaces and the cost drivers of systems that would:

- Meet all FEL requirements with a minimum/bare-bones system (this system would be required to provide the hooks and scars for the full-up system)
- Provide an intermediate system with several added features
- Provide all the features of an assembly-complete system

The first day of this briefing included a discussion of the NASA OAST telerobotic research activities that may be applicable to the FTS. The second day, the preliminary results of the in-house study were considered.

Design drivers that have been considered, to date, include safety, power and thermal systems, FTS mobility needs, force feedback operation, flight qualification of FTS systems, and development of the flexibility required to accept new technologies.

ATAC Assessment

ATAC continues to be supportive of the FTS initiative. Significant progress is being made in the GSFC in-house phase B studies. However, ATAC has no information on the degree of advancements that FTS will incorporate, since approaches and designs are not yet available. ATAC has concerns over questions such as timeliness of the flight demonstration test and provisions for mobility, but we are unable to make a full assessment until completion of the phase B efforts, when contractor results are available, trade studies are complete, and Space Station Program and FTS project schedules are stable.

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 from all sources in NASA. This synopsis is reported as appendix F. NASA's research and technology development program in automation and robotics is focused in the Office of Aeronautics and Space Technology (OAST).

In NASA's A & R program, the role of the Office of Aeronautics and Space Technology, Code R, is the development of fundamental A & R technology for transfer to NASA users such as the Space Station, Space Shuttle, planetary rovers, and ground operations for all missions. OAST's program in A & R, which focuses on systems autonomy and on telerobotics for servicing and assembly, began in the late 1970's and grew to a funding level of about $8 million in 1985 and to $25 million in 1988. It is part of the Civil Space Technology Initiative (CSTI). For fiscal year 1989, OAST has a new initiative proposal, Pathfinder, under which $10 million will be added to A & R to develop technology for planetary rovers and $2 million added to A & R to develop technology for assembly and construction of large space structures. OAST's program, which began at two NASA centers in the late 1970's, now encompasses work at all of the NASA centers and several universities and industrial concerns.

OAST's A & R research and development includes not only the CSTI program, but also includes:

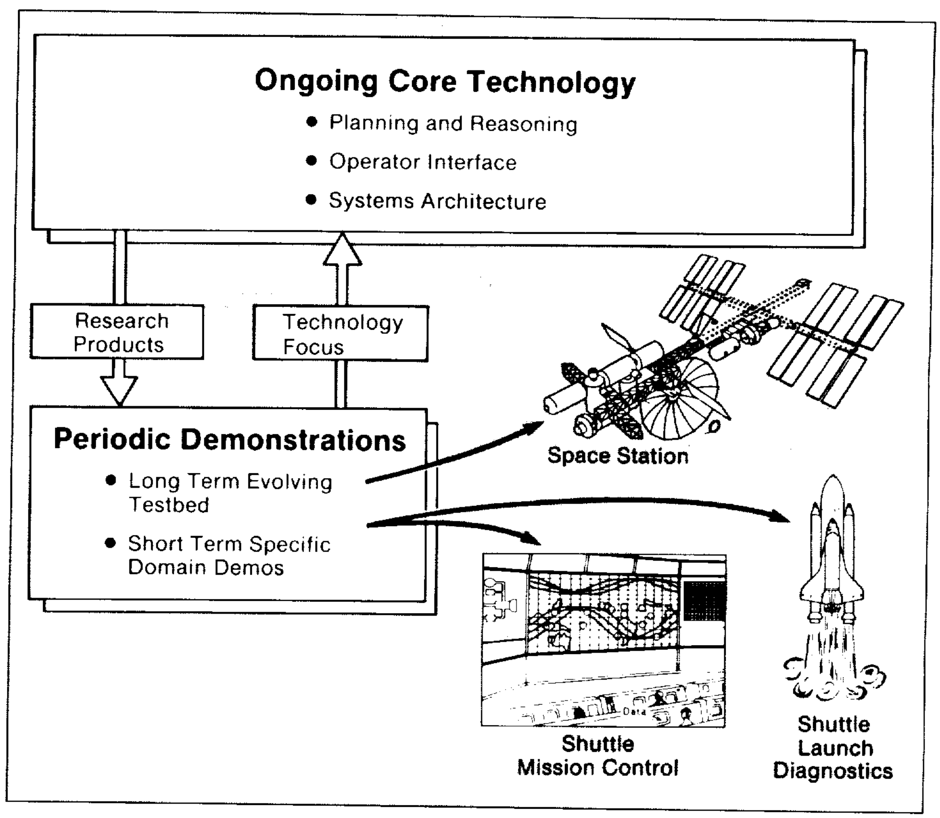
- Over 20 Small Business Innovative Research (SBIR) contracts
- A grant under the Black Universities Program
- Four contracts under the Outreach portion of the In-Space Technology Experiments Program
- A telerobotic experiment package under the Inreach portion of the In-Space Technology Experiments Program

OAST is also evaluating over 100 proposals for its new University Space Engineering Research Centers. A number of these proposals are in the A & R field.

Technical coordination of the OAST program is performed by two intercenter working groups, one for systems autonomy, and one for telerobotics. Overall strategic and policy planning for the entire program is conducted by the OAST Intercenter A & R Steering Group. The remainder of this section provides an update on the two foci of the OAST Civil Space Technology Initiative A & R program, which are the Systems Autonomy and the Telerobotics Technology Programs.

Systems Autonomy

A Systems Autonomy plan has been completed which covers a ten-year time period (ref. 15). The goal of the Systems Autonomy focus of the OAST A & R program is to advance artificial intelligence technology, especially in the areas of cooperating knowledge-based systems, knowledge acquisition, planning and



The Systems Autonomy Technology Program objectives are being accomplished by a Core Technology research program, closely coupled with several major demonstration projects. Major research areas are in planning and reasoning, operator interface, and systems architecture. There are two categories of major demonstrations: a long-term evolving testbed for automation of Space Station subsystems, and specific domain ground operations demonstrations, including Space Shuttle mission control at JSC, Shuttle launch diagnostics at KSC, and planetary unmanned spacecraft mission control at JPL.

scheduling, computer systems architectures, and validation methodologies. Major payoffs to NASA are reduced mission operations costs by automating labor intensive tasks in ground mission control centers, increased productivity by automating routine onboard housekeeping functions, and increased mission success probability by automating real-time contingency replanning.

The program objectives are being accomplished by a core technology research program which is closely coupled with several major demonstration projects. The demonstration projects provide realistic operational environments to evaluate and validate concepts developed through scientific research and engineering development of the core technology. Initially, the core technology research included the areas of planning and reasoning, and systems architecture. The first demonstrations included automation of Space Station subsystems and automation of ground mission control operations and launch processing systems.

The funding for the Systems Autonomy Technology Program nearly doubled in fiscal year 1988, and all NASA centers are now participating. Core technology was expanded to include new research elements in control execution and operator interface, in addition to planning and reasoning and systems architecture. In addition, a new demonstration project was instituted at JPL on the automation of data systems in ground control of unmanned planetary operations.

Joint activities in intelligent systems research have been initiated with the Defense Advanced Research Projects Agency (DARPA) Information Sciences Office, with the initial focus on areas of planning, machine learning, and cooperating knowledge-based systems.

A memorandum of understanding between the OAST and the OSS has been approved which facilitates transfer of technology in systems autonomy between the two Program Offices. This will complement the memorandum of understanding between the two Program Offices in the area of telerobotics described in Progress Report 4.

Core technology

The four core technology areas of Systems Autonomy are planning and reasoning, control execution, operator interface, and systems architecture.

In planning and reasoning research, there has been a fourfold expansion in the funding level of grants and contracts. This work covers the areas of machine learning, cooperation among multiple knowledge-based systems, planning and scheduling methods, validation of knowledge-based systems, causal modeling of complex systems, management of uncertainty, and knowledge of design through operations.

A new development has emerged from the research in machine learning which may revolutionize available methods for studying large data bases. It is called Autoclass and is a tool for identifying the subclasses into which a large set of data naturally falls. The initial application involving the classification of large volumes of astronomical infrared data was highly successful. Autoclass was able to discriminate among highly similar spectral data and provide statistical evidence for a new class of infrared objects.

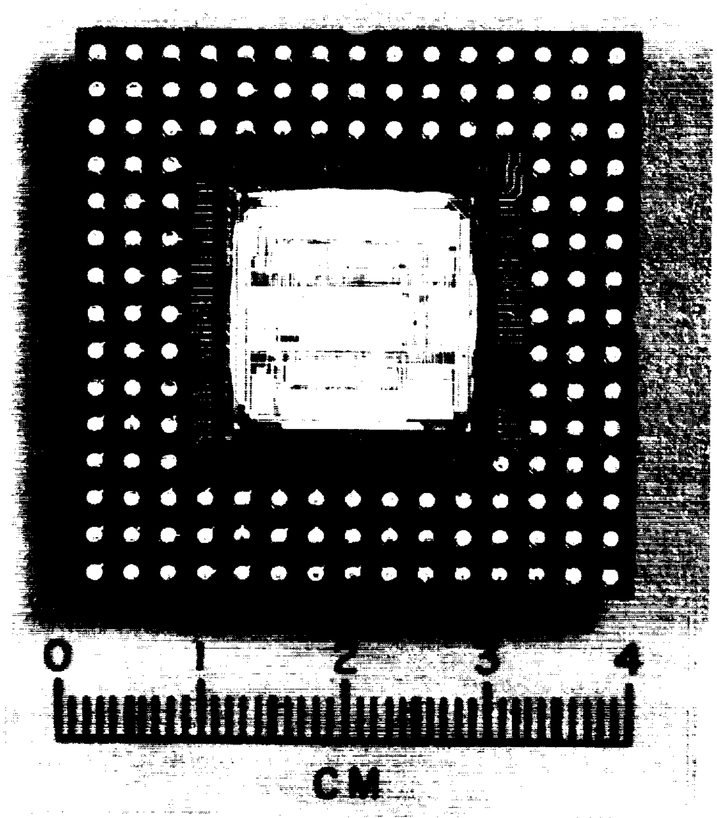
A joint effort has been initiated with DARPA for research in mutually important areas of intelligent systems research. Research efforts are under way in cooperating intelligent agents, with the initial application focus on cooperating intelligent agents for planetary outpost construction and operation. Additionally, new fiscal year 1988 core research elements have been initiated in behavioral nets and validation methodologies for knowledge-based systems, in design data capture, and in management of large distributed knowledge bases.

Control execution research was added as an element in fiscal year 1988. It focuses on the interface between high-level AI planning and supervision levels and the real-time arithmetic levels where commands are executed and system behavior measured.

Operator interface research was also added as a new element in fiscal year 1988 to determine the best ways to build the interface between humans and automated systems. Specific research products will include:

- Design decision aids and rapid prototyping tools
- More natural human-computer dialog systems
- Advanced display/control concepts
- Computer aided interface design systems

In systems architecture research, a contract was awarded in 1987 to initiate development of a Spaceborne Symbolic Processor System to execute both numeric and symbolic processing for large knowledge-based systems. Included in this Symbolic Processor will be a 32-bit general purpose processor. NASA and the USAF have agreed on a joint development project for this Symbolic Processor. The initial milestone is a concept design and development of a flight-qualifiable breadboard unit. It is anticipated that this effort will lead to development of a space-qualified "super-chip" family of functional modules for application in standardized modular



The Phase I concept definition phase of an effort for the development of a space-qualified symbolic VHSIC multiprocessor chip will be completed in April 1988. The prototype chip shown above was developed as part of the Phase I effort and includes a working symbolic processor, memory, and data communications on the chip. This effort will lead to the delivery, in 1995, of a space-qualified multiprocessor, including a "super-chip" family of functional modules for application in standardized modular systems. (Courtesy of Ames Research Center)

systems. The concept definition phase will be completed in April 1988 and has included development of a prototype processor chip, as shown in the accompanying illustration. Phase II contract award is expected in late 1988 for development of three brassboard units. Target delivery of the space-qualified unit, in phase III, is in early calendar year 1995.

Space Station related AI demonstrations

The Systems Autonomy focus of the OAST program includes a sequence of increasingly complex ground demonstrations of systems autonomy technologies applicable to the operation of the Space Station. This element ensures the near-term relevance of the OAST program to the Space Station, provides a technical focus for the validation and demonstration of the autonomy technology developed under the core technology program, and helps establish credibility and user confidence in that technology.

The first demonstration, which will occur in 1988, will be of an expert system for control of the Space Station thermal system. It will take place on the Space Station Thermal System testbed at JSC and is a joint effort of ARC and JSC. This demonstration is significant in that it will be one of the first knowledge-based systems to control a large complex system in real time with real operational hardware. Prototype expert system software and two initial incremental expansions of the knowledge base have been completed.

The second demonstration, in 1990, is a joint effort between ARC, LeRC, JSC, and MSFC to show coordinated control of both the Space Station Thermal Control System (TCS) and the Electric Power System (EPS). The power system autonomy demonstration will provide stand-alone expert system management of the EPS testbed at LeRC with the MSFC core module power management and distribution system as a load source. For purposes of the 1990 demonstration, the TCS will appear as a "cooperating user" of the EPS output and a "smart" load to the EPS. The EPS will incorporate real-time expert system control for failure detection, classification, isolation, and system restoration. In addition, the demonstration will include a real-time planner and scheduler for rescheduling loads in the event of an EPS failure or other anomaly.

In support of the 1990 demonstration, the OMS/DMS testbed will provide the interface between three cooperating expert systems; the first supporting the EPS, the second supporting the TCS, and the third, the Expert Controller, performing integration and control management of the other two expert systems. The OMS/DMS testbed provides the global level management services into which the Expert Controller is to be inserted for the 1990 demonstration.

Ground operations AI demonstrations

Along with the core technology element and the Space Station AI-related demonstration sequence, a third element of the System Autonomy Technology Program includes a set of demonstrations of the capability of current artificial intelligence technology to increase the efficiency and operational capability of current techniques for ground operations and control. Two of these are described here.

A rule-based integrated communications officer (INCO) is being developed and demonstrated at JSC in Space Shuttle ground operations in 1988. Initially the system will be used in parallel with conventional systems during Space Shuttle simulations, and also during the next Space Shuttle flight (STS-26). After the system completes its validation phase and confidence in the system has grown, INCO will be implemented on-line as the ground operations communications system for the Space Shuttle. This is significant in that it will be the first expert system used by flight controllers to monitor real-time telemetry during an actual Space Shuttle mission.

Another ground operations demonstration is being conducted at Kennedy Space Center (KSC) for autonomous diagnostics and control of Space Shuttle launch processing systems. Two previously existing sets of expert system software are being combined into a more generic and more powerful knowledge-based system for Space Shuttle launch and payload processing. This is planned to be the first expert system in operational use for a NASA mission.

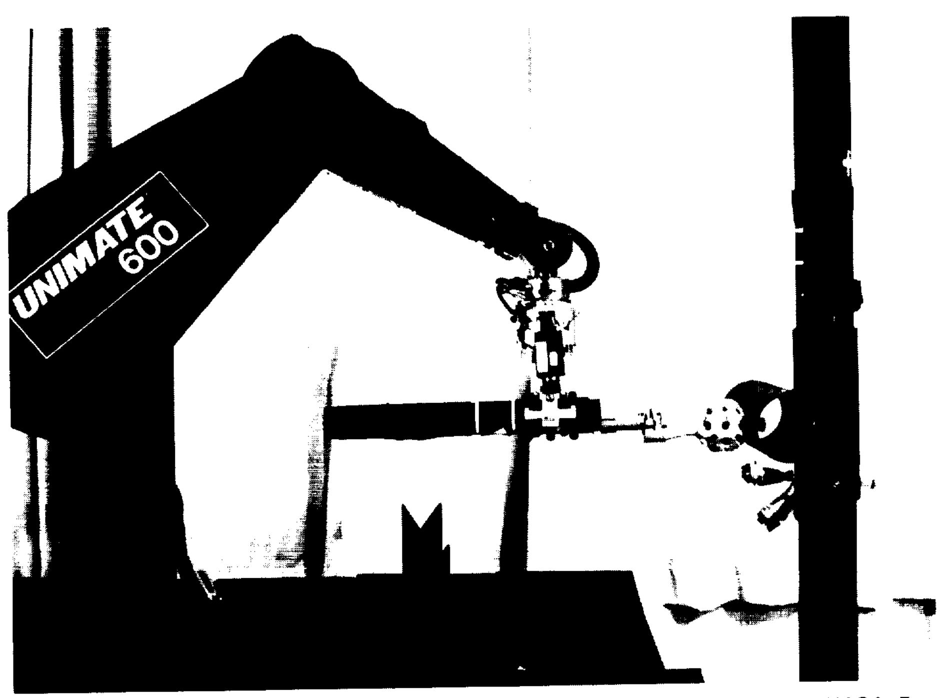
The Space Station level I is jointly funding the OAST demonstrations at JSC and LeRC and is also supporting the technology development activity at ARC through the Space Station advanced development program. The funds are used primarily to increase the fidelity of the OAST applications software to an engineering development level and to modify the JSC and LeRC Space Station testbeds to permit the incorporation of advanced automation. The lessons learned from these modifications and the demonstrations themselves will be invaluable in developing both specific requirements for advanced automation as well as the design data necessary for the work package contractors to implement these systems.

Telerobotics

Telerobotics is the second focus of the OAST A & R program. While the Systems Autonomy focus emphasizes the application of artificial intelligence technology to the cognitive (monitoring, controlling, planning, problem solving) aspects of space operations, the Telerobotics Technology Program focus emphasizes the physical remote manipulation aspects of space operations. Telerobotics combines the immediacy of execution of teleoperation (the replication at a distance of the physical motions of the operator) with the efficiency and precision of supervised robotic autonomy (the accomplishment of assignments through machine task decomposition and interpretation of sensor information). One of the key goals of this approach is the achievement of a smooth transition between teleoperation and supervisory autonomy.

Note that the overall field of telerobotics covers the continuum from teleoperation to robotics and encompasses three types of manipulators for space operations:

- Cranes, such as the Space Shuttle Orbiter's Remote Manipulator System, for transfers of large masses
- Servicers, primarily aimed at the assembly and servicing of those items that otherwise would be done by an astronaut during an extravehicular activity sortie



Automated assembly techniques for the Space Station are being investigated by NASA. For example, this photograph shows the final step in connecting a strut to a node, using Space-Station-type hardware and a single robotic arm. This assembly step is performed automatically, using closed-loop force-torque information for the robot servo control. (Courtesy of Langley Research Center)

- Planetary rovers, which are necessarily the most autonomous of the three, and which are designed for traversing a planetary surface in order to gather and send back data

A rover may, for example, need the capability to take rock samples, analyze them and store them for later return. The Telerobotics Technology Program being described here is devoted to research and development on the second category, servicers, but much of the work being done is also applicable to cranes and rovers.

Studies conducted over the last four years show that benefits from the application of telerobotics will accrue in three areas: increased payoff from space operations by freeing human resources from routine maintenance for dedication to productive activities in experimentation and observation; decreased cost of space operations by reducing the number of humans needed for a given task; and improved safety by minimizing the exposure of humans to the space environment and to hazardous operations.

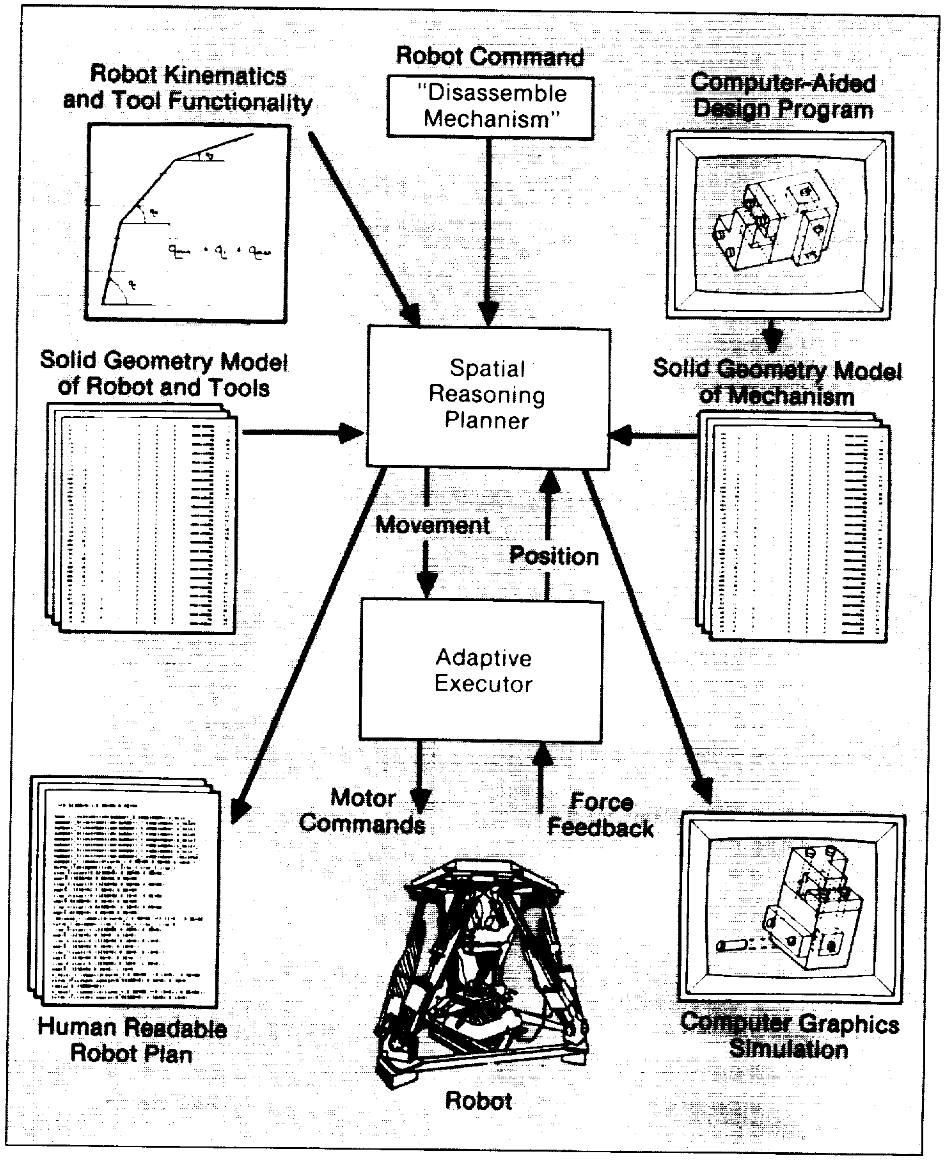
The five core technology areas of Telerobotics are sensing and perception, planning and reasoning, control execution, operator interfaces, and systems architecture and integration.

The OAST Telerobotics research and development program involves a dozen universities, five Centers, and a number of commercial firms. It is designed to advance this technology and develop it for application to space missions. It consists of three thrusts:

- A scientific research core to investigate fundamental research issues and, through artificial intelligence technology, to advance the state of the art in computer vision, autonomous control, teleoperation, task planning, and sequencing
- A sequence of ground demonstrations to validate research results through integration in experimental operating systems into a telerobotic testbed
- A series of studies leading to applications to space experiments and space missions

Recently several advances, most notably in automatic vision and in force and torque feedback, have been integrated and demonstrated in the program's first major ground demonstration. In this demonstration, three new functional capabilities were achieved:

- The same physical structure and control architecture performed in teleoperation and in supervised autonomy modes.



This diagram shows the basic inputs and outputs of an automatic robot planner and executor. Basically, the planner inputs a high-level command plus the geometry and kinematics of both the robot and task hardware and outputs a robot plan. The executor adjusts the plan while operating the robot to make corrections based on real-time sensor inputs. (Courtesy of Goddard Space Flight Center)

- The vision subsystem tracked a complex object (a satellite model spinning at up to 10 rpm).
- The integrated system, consisting of the vision, manipulation, and supervisory control subsystems, tracked and grasped the satellite, and stopped it with a smooth motion.

Current development work is focused on achieving:

- Smooth trading of control between human operator and machine
- Autonomous acquisition of objects by the vision system
- Greater levels of "robustness" (the ability of the autonomous system to overcome unplanned circumstances, e.g., calibration drift and execution time failures) by advances in the interpretation of sensor data

A demonstration of these capabilities is scheduled for 1989.

Another important set of results reported recently establishes qualitative and quantitative comparisons between the performance of humans in a buoyant facility and teleoperation. Comparisons, including supervised autonomy and teleoperation in space, will follow.

OAST is also sponsoring work at GSFC which is aimed at developing design concepts for robot serviceable hardware that is coupled with a design capture knowledge base which permits robots to autonomously plan and execute assembly and servicing sequences. The only human input would be a command to assemble a system or to replace a given component or subsystem. The accompanying illustration shows the overall logic flow for a robot to autonomously plan and execute an assembly or servicing sequence from a single high-level command, a geometry knowledge base, and routine sensor input.

ATAC Assessment

In reviewing the programs and progress of the OAST, the committee believes the OAST has taken positive initiatives to provide an advanced A & R program for development of new A & R technologies. The SS level I co-funding of OAST efforts in advanced automation and robotics has significantly improved the likelihood that these technologies will be incorporated into the Phase I Space Station and that the necessary hooks and scars to support the increased future use of A & R in the growth and evolution phases will be designed into the baseline Space Station. These new technologies will be available not only to NASA, but also to the commercial sector of the U.S. economy. These initiatives are viewed by the committee as responsive to the intent of Congress.

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

The Technology Utilization Program within the Office of Commercial Programs (OCP) has moved ahead with the commercialization of NASA automation and robotics technology. OCP, in conjunction with the Technology Utilization Offices at each NASA Center and with the Research Triangle Institute's Technology Applications Team, has under way or planned, a number of A & R-related applications engineering projects with industry, including the following:

- Knowledge-based Autonomous Test Engineer (KATE) expert system transferred to both the Electric Power Research Institute (EPRI) and the Institute for Textile Technology (ITT) for application in nuclear power plants and textile processing. KATE provides system testing, fault diagnosis, and expert-system-directed response.
- Utilization of a NASA robot computer simulator, ROBOSIM, for teaching purposes and for personal computer (PC) workstation applications.
- Industrial implementation of an Expert Weld Inspection System.
- Teleoperator control concepts and navigational and avionics expertise applied to remotely piloted vehicles for utility lines inspection.
- Unique NASA actuator applications to Hydraulic Control System for Body-Powered Upper Limb Prostheses.
- Development of an expert system for a Custom Footwear Fitting Process.
- Further development of an Intelligent, High-Performance, Jaw Robotic Gripper.
- Extension of NASA inspection and design techniques to an Industrial Computed Tomography/Computer-Aided Design Integration.
- Design for an Infrared Communications System to be applied in warehousing environments.
- Research and development leading to commercialization of an Optical Correlator/Remapper.
- Development of a hardware/software architecture for a Generic Flexible Manufacturing Cell Controller.

The Kennedy and Johnson Space Centers, Marshall and Goddard Space Flight Centers, and Ames Research Center are all contributors to these projects.

OCP is also supporting a Center to provide a mechanism to assist U.S. industrial firms in acquiring appropriate (especially NASA) automation techniques, robotics, and artificial intelligence for application in computer integrated manufacturing (CIM) systems. The National Space Technology Laboratories (NSTL) have joined with the University of Southern Mississippi to initiate the Center activities.

A partnership of JSC, the University of Houston at Clear Lake, and AdaNet Corporation, West Virginia, is also being supported by OCP to establish a base of Ada software and software engineering resources that will be applicable to flexible CIM applications.

While technology transfers are only beginning to evolve from Space Station planning and programs, it is anticipated that development of the FTS, robotics on other platforms, and overall Space Station automation and system intelligence will eventually contribute substantially to U.S. commercial competitiveness in automation and robotics. OCP has taken an initial step by planning to include a section on A & R in NASA's *Tech Briefs* publication, which is distributed to a readership of over 800,000 in the U.S. It is hoped that innovative technology disclosures from Space Station will be an important part of this section.

The Office of Space Station recently funded a study to assess whether the Space Station A & R program is likely to enhance the use of A & R technologies and applications by terrestrially based U.S. industries. The study included a significant outreach effort to obtain the views of A & R leaders from industry, academia, and Government. Although few in industry, academia, or Government expect Space Station A & R spin-offs to provide revolutionary advancements in the state of the art, many foresee potential benefits in areas including the following:

- The use of lightweight materials for robotics
- Improvements in AI-based diagnostics, control, and monitoring applications
- Improvements in collision avoidance capabilities
- Providing the experience and training in A & R technologies to industry, university, and Government personnel

ATAC Assessment

ATAC considers the transfer of A & R technology to the U.S. economy to be fundamental and strongly supports the initiatives of the OCP and the OSS in this most important area.

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 1988 in a format similar to previous reports. The substantial funding increases for advanced A & R in the Space Station and across the agency apparently reflect an increased awareness of the potential benefits of advanced A & R. The basis for this increase in Space Station will be examined in the next reporting period. The details of the Space Station funding increases were not established in time for ATAC's consideration in this report.

TABLE 9.— NASA FUNDING FOR AUTOMATION AND ROBOTICS

[Fiscal year funding, millions of dollars]

Office and activities	FY 85	FY 86	FY 87	FY 88
Space Station	5.8	18.1	24.9	40.6
Definition phase	(5.8)	(8.1)	(4.9)	—
Advanced development	—	—	—	(20.6)
Flight Telerobotic Services augmentation	—	(10.0)	(20.0)	(20.0)
Aeronautics and Space Technology	N/R	10.2	18.0	25.4
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	N/R	4.6	4.5	9.7
Robotics				
OMV servicing and refueling				
Automation				
Space Science and Applications	N/R	0.7	0.8	2.5
Information system and telescience				
Servicing				
Payload carriers and pointing systems				
Space Operations	N/R	1.0	1.2	4.0
Space Tracking and Data Systems				
Commercial Programs	N/R	N/R	N/R	3.8
Commercial use of space				
Technology utilization				
Small business innovation research				
Total NASA funding, approximately	—	34.6	49.4	86.0

N/R — Data was not requested by ATAC

APPENDIX A

NASA Advanced Technology Advisory Committee

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

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

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

J. Stuart Fordyce, Director of Aerospace Technology, Lewis Research Center (LeRC)

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

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

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

Henry Plotkin, Assistant Director for Development Projects, Goddard Space Flight Center (GSFC)

Carl Solloway, Automation and Robotics Manager, Strategic Programs and Plans Division, Office of Space Station, NASA Headquarters

Giulio Varsi, Manager of Automation and Robotics Office, Jet Propulsion Laboratory (JPL)

Consultants

Dr. Saul Amarel, Department of Computer Science, Rutgers University

Dr. Takeo Kanade, Acting Director of the Robotics Institute, Department of Computer Science, Carnegie-Mellon University

Executive Secretary

Kelli F. Willshire, Automation and Robotics Coordinator for Space Station, Langley Research Center

APPENDIX B

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APPENDIX C

Acronyms

A & R	automation and robotics
AI	artificial intelligence
ARC	Ames Research Center
ARP	Automation and Robotics Panel
ATAC	Advanced Technology Advisory Committee
C & T	communications and tracking
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacturing
CBC	closed Brayton cycle
CEI	contract end item
CERS	Crew and Equipment Retrieval System
CIM	computer-integrated manufacturing
DARPA	Defense Advanced Research Projects Agency
DKC	design knowledge capture
DMS	Data Management System
DTF	Demonstration Test Flight
ECLSS	Environmental Control and Life Support System
ELV	expendable launch vehicle
EPS	Electrical Power System
EVA	extravehicular activity
FDIR	fault detection, isolation, and recovery
FMS	flexible manufacturing system
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
MSFC	Marshall Space Flight Center
MSS	Mobile Servicing System
NASA	National Aeronautics and Space Administration
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
ORC	organic Rankine cycle
ORU	orbital replaceable unit
OSS	Office of Space Station
OSSA	Office of Space Sciences and Applications
OTV	orbital transfer vehicle
PDR	Preliminary Design Review
PMAD	power management and distribution
PRR	Program Requirements Review
PV	photovoltaic
R&D	research and development
RFP	request for proposal
SD	solar dynamics
SS	Space Station
SSE	Software Support Environment
SSIS	Space Station Information System
SSP	Space Station Program
TCS	Thermal Control System
TMIS	Technical and Management Information Systems
VHSIC	very high speed integrated circuit
WP	work package

APPENDIX D

Recommended Applications for the Initial Space Station

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

Knowledge-Based (Expert) Systems

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

Robotics

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

Advanced Automation

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

APPENDIX E

Priorities for Implementation of A & R on the Space Station

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

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

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

Advanced Automation

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

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

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

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

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

3. Resource management

4. Performance management

5. Training and instruction

6. Maintenance

Robotics

1. Servicing

2. Inspection and maintenance

3. Assembly and construction

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

5. Customer accommodation
   - Installation and removal
   - Materials handling

6. Astronaut rescue

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

APPENDIX F

R & D Activities Related to Automation and Robotics

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

Institution	Objectives of the research	Potential Space Station use	Level
Category 1.1—Knowledge			
Ames Research Center	Representational issues including —Time (duration and causality) —Actions and their effects —Spatial information (models, computer-aided design (CAD)) —Truth maintenance Decision-making under uncertainty Learning Fault diagnosis Integrated decision-making for distributed expert systems	Astronaut and equipment scheduling System operation Construction Autonomous robots	2-3
Ames Research Center	Automated design data capture	Systems engineering	3-4
Goddard Space Flight Center	Geometric knowledge base Autonomous reasoning for assembly/disassembly/replacement	Servicing and assembly	4
Goddard Space Flight Center	Development of standard formats	Autonomous robot servicing	5
Goddard Space Flight Center	Integrated scheduling of independent resources via a network of distributed systems	Payload data flow control Space and ground network scheduling	1
Jet Propulsion Laboratory	Knowledge-based subsystem development and integration —Configuration planning —Global schedule planning —Failure diagnosis and reasoning —Execution monitoring	System autonomy Telerobotics Ground operations Automation	2-6
Jet Propulsion Laboratory	Knowledge-based system development tools —Blackboard —Conditions model —Memory model —Process model —Reasoning engine design language —Graphics debugging —Time representation model	Expert system development	2-4
Johnson Space Center	Development of trajectory simulations which use logic structures as the basic building blocks	Trajectory analysis	2
Langley Research Center	Distributed artificially intelligent system for interacting with the environment (DAISIE): planner/controller interaction	Control	3

Institution	Objectives of the research	Potential Space Station use	Level
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
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 sensing	3
Jet Propulsion Laboratory	Force and torque sensing Proximity sensing Tactile sensing Sensor fusion	Telerobots	6 3 3 1
Johnson Space Center	Utilization of optical correlators to identify objects and to estimate their positions and attitudes	Robotic control systems Proximity operations	4
Johnson Space Center	Development of coordinate transformation algorithms for an image processor operating at video rates	Computer vision for proximity operations	4
Kennedy Space Center	Development of adaptive control systems and software	Tracking and mating of objects having relative movement	
Langley Research Center	Laser-based image and rate/ranging systems	Autonomous robots	3
Langley Research Center	Focal plane preprocessing for improved sensitivity and speed	Autonomous robots	4
Lewis Research Center	Techniques for sensor-failure detection, isolation and accommodation	System monitoring	4
Lewis Research Center	Develop sensors and algorithms to predict, detect, and isolate electric power system	Load-prioritized fault tolerant power system	1

Institution	Objectives of the research	Potential Space Station use	Level
Lewis Research Center	Accurate position, force, and acceleration sensing and control of flexible arms using a controlled laser system	Robotic sensing and control	2
Marshall Space Flight Center	Utilization of high-accuracy charge injection device (CID) sensors in a hardware adaptive target-tracking system	Orbital maneuvering vehicle (OMV), orbital transfer vehicle (OTV), and Space Station docking, berthing, servicing	3-4
Marshall Space Flight Center	Vision sensor for a robotic system to remove solid rocket booster thermal protection during rework	Automated processes in the space environment	6
Marshall Space Flight Center	Optimization of lighting, video camera control, and transmission for OMV rendezvous and docking (through flat-floor simulation studies)	OMV and OTV operations and remote viewing	6
Marshall Space Flight Center	Development of vision system for automatic docking using TV box scan and syntax pattern recognition	Autonomous docking and servicing	3
Category 1.3—Actuation and Manipulation			
Ames Research Center	Real-time control of limber manipulators with end-point sensing	Manipulators, robotics, and servicing	2-3
Goddard Space Flight Center	"Smart" parallel gripper with force feedback Wrist-activated automatic change system	Telerobotic technology	4
Goddard Space Flight Center	Ground telerobotic system for technology evaluation	Telerobotics and robotics	3
Goddard Space Flight Center	Lightweight extravehicular activity (EVA) tools	Spacecraft servicing	5
Jet Propulsion Laboratory	Two-arm force-reflecting hand controller "Smart" hand development Distributed control for space telerobot mechanization Hybrid (position and force/torque) control Dual-arm manipulation Multifinger hand and controller	Telerobotics technology	2 4 2 2 2 2
Johnson Space Center	Define algorithms and computers for controlling two coordinated manipulator arms	Assembly Launch, retrieval, and handling of payloads	3
Johnson Space Center	Design and develop a testbed on the Shuttle for manipulator controls experiments —Test control algorithms —Use simulated payloads —Evaluate human/manipulator interaction	Retrieval and rescue Payload launch, retrieval, and handling Assembly and servicing	2
Johnson Space Center	Anthropomorphic hand manipulator	More efficient exravehicular activity	3
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	Robotic servicing via task automation including —Active compliance control —Static and dynamic force limiting	Automation of robotic servicing, ORU replacement, berthing	5
Marshall Space Flight Center	Inflatable end effectors which expand inside large, irregularly shaped space structures and thereby distribute the force loads evenly	Assembly, maintenance, and repair of space structures	4
Category 1.4—Human/Machine Interface			
Ames Research Center	Telepresence information and environments Procedural aids for system automation Models of human vision, voice input/output, command language	Improved human/machine interface	2-3
Ames Research Center	Development and evaluation of artificial intelligence (AI) technologies for autonomous systems	System and subsystem automation	3-4
Goddard Space Flight Center	Guidelines data base for development of user interfaces to expert systems	Expert systems	3
Goddard Space Flight Center	Expert assistant for designers of user interface management systems	Command and control displays	3
Jet Propulsion Laboratory	Evaluation and analysis tools to assess the merit of automating various functions and to decide where the human/machine interface should be	Optimal extent of automation and robotics utilization	4
Jet Propulsion Laboratory	Fused sensor displays Force feedback evaluation Predictive displays Analysis of human factors associated with operating a telerobot in zero gravity Operator interface to dual-arm telerobot	Teleoperation	2-4
Johnson Space Center	Graphic knowledge displays to aid in interface with intelligent systems	Crew and ground workstations	1
Johnson Space Center	Graphics system with animated displays in which data and objects can be manipulated	Interface to command and control systems	6
Johnson Space Center	Optimized interface to advanced displays, controls, and computers	Crew and ground workstations	1
Johnson Space Center	Laboratory testbed and experiments in the linkage of eye, brain, and task	Interface to command and control systems	4
Kennedy Space Center	Advancement of design capability by human/machine (CAD) interface	Improved human/machine interface	

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

Institution	Objectives of the research	Potential Space Station use	Level
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	Incorporation of 6-DOF hand controller used to operate manipulator arm	Control of remote servicer, OMV, telerobotic servicer (TRS)	6
Marshall Space Flight Center	Use of force-reflecting hand controller to return force and torque information to operator	Telepresence control of servicing	5
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
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 model for estimating the cost of Space Station software	Software development; cost control	3
Johnson Space Center	Automated reasoning tool in Ada	Mission operations	2
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	

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

Institution	Objectives of the research	Potential Space Station use	Level
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
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/ Marshall Space Flight Center	1990 demonstration of automated control of TCS and electric power system (EPS)	Automatic control and monitoring of multiple subsystems	2

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

Institution	Objectives of the research	Potential Space Station use	Level
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	Workstation for automated generation of programs	Software development	3
Kennedy Space Center	Development of a robotics testbed 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 Testbed 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

Institution	Objectives of the research	Potential Space Station use	Level
Lewis Research Center	Development of power system testbed 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
Lewis Research Center	Develop detailed electrical power system simulation models using hybrid computer simulators; apply the reduced-order models to autonomous control	Electrical power system automation	2
Lewis Research Center	Electric power system designs with reduced sensitivity to faults, including self-healing components and assemblies	Fault tolerant electrical power system	1
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	Autonomous management of large spacecraft power system	Electrical power system automation	5
Marshall Space Flight Center	Autonomous cooperative fault management and load-shedding management AI systems	Space Station module power management and distribution system automation ground support advisory system	4-5
Marshall Space Flight Center	Determination and evaluation of potential expert systems for mission planning on Space Station	Mission planning	1
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	Hardware system for autonomous docking utilizing high-accuracy solid-state sensors	OMV and Space Station docking and berthing	3-4
Marshall Space Flight Center	Expanded simulation capability to support studies of the OMV, of free-flyers, and of the core module	OMV and OTV payload berthing Space Station maintenance and inspection	3-5
Marshall Space Flight Center	Demonstration of telerobotic servicing including —Task-primitive automation —Reflexive manipulator control —Sensor fusion —High-fidelity task simulator —Prototype hardware	Evaluation of ORU designs, servicing techniques, sensors, controllers	2-3
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	Expert systems to monitor and control the thermal testbed	Development of the thermal control system	4-6
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
Johnson Space Center	Expert systems for monitoring and control of communications and tracking system	Communications and tracking	4
Johnson Space Center	Knowledge-based system for monitoring and controlling exercise in health maintenance facility	Crew health maintenance	6
Johnson Space Center	Expert system to analyze data from flight simulations	Flight software development	6
Johnson Space Center	Define the partitioning of functions of Space Station distributed subsystems for an operations management expert system	Operations management system	3
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
Kennedy Space Center	Expert systems for weather forecasting for Space Shuttle launch and landing	Logistics planning	2
Lewis Research Center	Hierarchical power system control structure framework for integrating numerical algorithms with expert system techniques	Autonomous control of electrical power system	1

Institution	Objectives of the research	Potential Space Station use	Level
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 —State estimation —Configuration —System monitoring —Fault and trend analysis	2
Lewis Research Center	Expert system for probabilistic structural analysis	Structural and component design	2
Lewis Research Center	Expert system for composite load spectra	Structural and component design	2
Lewis Research Center	Procurement advisor expert system to increase productivity	Program management	3
Lewis Research Center	Expert system for finite-element modeling and structural analysis	Structural design	2
Lewis Research Center	Expert systems for polymer synthesis	Construction materials	2
Marshall Space Flight Center	Automatic math modeling of Space Shuttle main engine and joint fault isolation and event scheduling AI systems	Real-time simulation and fault isolation of subsystems	3-4
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	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	Engine technology testbed advisory system	Subsystem operation advisory systems	2
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	Definition of a plan for a telerobotics flight experiment	Crew rescue, equipment retrieval, servicing, and repair	2

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

Institution	Objectives of the research	Potential Space Station use	Level
Johnson Space Center	Definition of crew and robotics tasks for assembly and maintenance —Requirements —Criteria —Tests —Interfaces	Assembly and maintenance	3
Johnson Space Center	Robotics for autonomous retrieval and rescue	Retrieval and rescue	2
Johnson Space Center	Development of a system for constructing synthetic views from a CAD data base	Computer vision systems	3
Johnson Space Center	Development of robot-friendly designs for space structures	Structural designs Assembly and maintenance	5
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	Interchangeable tools for use by manipulator arm in servicing, assembly, and maintenance	Servicing, assembly, and maintenance	3-4
Marshall Space Flight Center	Development of OMV and ORU interface mechanisms	Repair and resupply	5

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16. Abstract

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

A further requirement of the law was that ATAC follow NASA's progress in this area and report to Congress semiannually. This report is the sixth in a series of progress updates and covers the period between October 1, 1987 and March 1, 1988.

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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