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

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Advanced TechnologyAdvisory Committee
National Aeronautics and Space Administration

Submitted to the
United States Congress
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NASA
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Space Administration

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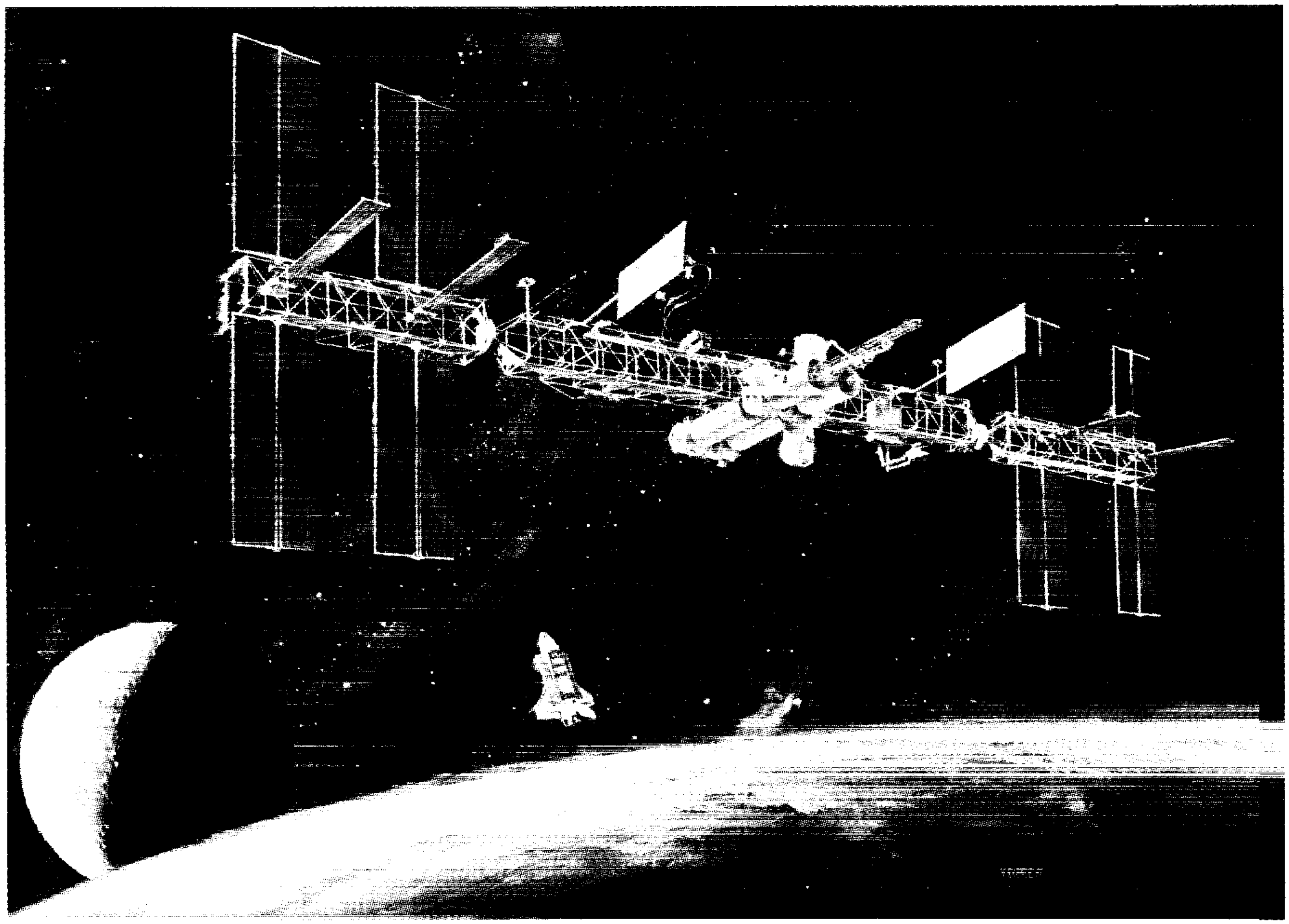


## Space Station *Freedom*

The Space Station Freedom will be a multipurpose facility for conducting scientific research, developing advanced technologies, and stimulating commercial activities in space. The permanently manned space station features a 508-foot-long transverse boom, to which the other elements are attached. In the center of the boom are four pressurized modules where the 8-person crew will work and live. The modules are connected by resource nodes which, in addition to connecting the modules, house the space station's command and control systems. Arrays of solar cells will provide 75,000 watts of power to the station. Space Station Freedom will circle the Earth every 90 minutes and will be located at an inclination of 28.5° to the equator at an altitude of 250 miles. Designed to operate in space for 20–30 years, the station is being designed to evolve. The inclusion of automation and robotics will help to expand the ability of humans to operate in space. Space Station Freedom is a bulding block investment in our future and the next logical step into the space frontier.

# 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 Freedom systems which advance automation and robotics (A & R) technologies. In April, 1985, as required by Public Law 98-371, ATAC reported to Congress the results of its studies (ref. 1). The initial ATAC report proposed goals for automation and robotics applications for the initial and evolutionary space station. Additionally, ATAC provided recommendations to guide the implementation of automation and robotics in the Space Station Freedom program.

A further requirement 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 Freedom program to assess the application of A & R technology with consideration for safety, reliability, schedule, performance, and cost effectiveness (including life-cycle costs). Based upon these assessments, develop recommendations to enhance A & R technology application, review the recommendations and discuss their implementation with NASA management. Report assessments and recommendations twice annually to Congress.**

The Space Station Freedom program (SSFP) is charged to develop a baseline station configuration which provides an initial operational capability and which, in addition, can be evolved readily to support a range of future mission scenarios in keeping with the needs of space station users and the long-term goals of U.S. space policy.

ATAC has continued to monitor and to report semiannually NASA's progress in the use of automation and robotics in achieving this goal. To a lesser extent, ATAC has reported other NASA program-sponsored activities in A & R which are related to Space Station Freedom and are transferrable to the U.S. economy. The reports are documented in ATAC Progress Reports 1 through 7 (refs. 2–8). Progress Reports 1 through 5 covered the definition and preliminary design phase (phase B) of the Space Station Freedom program. Progress Reports 6 and 7 covered the start up of the design and development phase (phase C/D) of the Space Station Freedom program. Phase C/D leads to a permanently inhabited station, to be operational in the mid-1990's.

This report is the eighth in the series of progress updates and covers the period of August 15, 1988, through February 23, 1989.

To provide a useful, concise report format, all of the committee's assessments have been included in the section "ATAC Assessments." Summaries of progress in A & R in the NASA Office of Space Station (OSS) and the Flight Telerobotic Servicer (FTS) are provided as appendices. Appendices covering progress in other NASA program-sponsored activities in A & R will be included on an annual basis; thus, appropriate appendices for this purpose were presented in Report 7 and will also be contained in Report 9. In addition to the individual efforts of ATAC members to understand and assess the application of A & R in the Space Station Freedom program, ATAC held a review February 22–23, 1989, for the purposes of additional dialogue, understanding of the progress, and formulating the points of this assessment.

# ATAC ASSESSMENTS

The ATAC assessments for this reporting period are based upon the committee's appraisals of progress in advanced automation and robotics for Space Station Freedom.

### A & R Policy

As reported in ATAC Progress Report 7, the Office of Space Station has adopted a policy to encourage the use of A & R where it is technically appropriate, where the technology is sufficiently mature, and where there is a favorable benefit-to-cost ratio (ref. 8). As indicated by this policy, the program is committed to using A & R in the station, because these technologies offer significant promise in reducing problems faced in the design and operation of Space Station Freedom.

Space station A & R requirements are addressed in the various requirements documents including the Program Requirements Document (PRD) and the Program Definition and Requirements Document (PDRD). (These documents are undergoing revision for revised requirements and consistency.) As part of the space station A & R organizational infrastructure, focal points have been established within Level I, Level II, and each of the four work package Level III offices. In addition, there are three levels of planning documents under development. These are the Level I A & R Plan, the Level II A & R Implementation Plan, and the WP Contractor A & R Plans. To date, these documents exist in various draft forms. At present, there is a lack of clarity and specificity in the roles and responsibilities of the various focal points in implementing the A & R policy. The planning documents should specifically address this issue. Specific ATAC recommendations for the roles of the focal points are contained in the next section.

**ATAC's assessment is that the top level management of the Space Station Freedom program is genuinely committed to the application of automation and robotics in program activities and has adopted a clearly defined policy to promote appropriate A & R applications. The planning documents which will describe the details of the policy's implementation have been in preparation for some time. These planning documents need to be brought to completion in the near future (even if they will need to be updated later) so they can be used as a basis for decisions in the program. Delay in completing versions of these plans could erode the necessary commitment to A & R in development and operation of the Space Station Freedom.**

### A & R Organization and Responsibilities

Until firmly established in the planning documents, the relative roles and responsibilities of the different groups and focal points in identifying and making decisions to implement specific A & R applications must be assessed by observation and are therefore subject to varying interpretations—including differences of opinion on the appropriate authority which should be vested in the people assigned as A & R focal points at the various program levels. In the following paragraphs ATAC will present its understanding of the A & R implementation infrastructure, assess some of the issues which have been raised concerning the structure, and recommend a modified approach.

The Space Station Freedom A & R roles and responsibilities are divided among the three program management levels, I-III. Level I A & R responsibility lies in the Strategic Programs and Plans Division (Code ST). This office has identified Level I A & R requirements of an overall and general nature for inclusion in the Program Requirements Document (PRD). In addition the office oversees a development program focused on the initial station and an evolution advanced development program aimed at the evolutionary station. For A & R, Code ST acts as an external interface, interagency focal point, intra-agency focal point, and advocate and in this capacity provides a liaison member to the ATAC.

The Associate Director, Space Station Freedom program office, is assigned as the Level II focal point for A & R. He coordinates the A & R efforts of the line organizations in Level II. In executing this responsibility, he has at least four identified people to work with him in the areas of operations, systems engineering and integration for robotics and for automation, and implementation of artificial intelligence. (As of this writing, the organization at Level II is being revised. Indications are that operations and systems engineering robotics people will keep their same functions, but that automation related functions may be distributed.) There are three working groups in Level II, whose members come from most Centers, including the Work Package Centers, which are used to advise and work A & R issues: the Robotics Working Group; the Automation Working Group; and the Artificial Intelligence, Expert Systems, and Technology Working Group.

The Work Package Level III focal points are in charge of technical definition, technical cost trade studies, and advocacy of A & R applications within the scope of each work package responsibility.

### Implementation of the A & R Organization

While this organizational approach clearly encourages use of A & R in Space Station Freedom, there are some significant issues with respect to its practical implementation. Lack of resolution of these issues results in the failure to achieve the desired emphasis, at least in the case of automation, for Space Station Freedom.

A significant issue is the degree of responsibility and authority which should be assigned to the focal points. Specifically, should the focal points at each level have unique responsibility to ensure that the A & R goals of the next higher level are met and should they have the authority to direct the implementation of A & R activities to satisfy this responsibility? Vesting the A & R focal points with this authority would allow them to implement the activities that would ensure incorporation of A & R applications. Nevertheless, while it would appear to encourage accomplishment of A & R goals, this approach is not recommended, since for the reasons given below, it would violate the sound management principle of having a direct, unambiguous chain of command.

Automation and robotics technologies are not functions themselves, rather they will be applied in a wide variety of contexts within the Space Station Freedom. They, especially automation, provide means to an end or approaches to implement parts of functions such as the power, guidance and control, life support, and data management systems. Automation should not be used for the sake of having automation, but because, in each work package, automation is an effective and efficient way to implement the work package functions.

Since the WP head and the chain of command (both up and down) is principally responsible for achieving the results of that WP, the ultimate implementation of A & R must be determined by that person and that person's direct supervisory chain. The focal points (at the contractors, work packages, and Level II) are not in that chain of command - nor should they be, since that would create dual lines of responsibility. The A & R focal points should act as advisors to identify and promote high-payoff A & R applications to those with the ultimate project responsibility.

**ATAC's assessment is that the Space Station Freedom program has vested the focal points with the appropriate amount of authority. The responsibility of the automation focal point at each organization is to help identify potential applications areas, help define the payoff from successful use of automation, encourage actual implementation activities, coordinate information exchange on the use of automation, and finally, to act as a key advisor to the people with ultimate responsibility for implementation. For robotics, the role of the focal point should be to determine applicability of robotics for specific tasks, identify necessary modifications of tasks to accommodate robotics, and to promote acceptance of the use of robotics in accomplishing those tasks.**

While this organization is appropriate, it does not provide for a direct line of responsible accountability for reporting on automation or for transferring results of Level I advanced automation development activities to Level II and on to the WP contractors. **To facilitate the effectiveness of these A & R focal points in accomplishing these tasks, ATAC recommends a modification of the existing structure. This modification would create a hierarchy of the identified**

**Level I, Level II, Level III, and work package contractor focal points for a limited scope of responsibility. The responsibility of this hierarchy would be limited to (1) reporting on A & R accomplishments and plans, and (2) to the implementation of a program promoting A & R applications in a manner patterned after the Level II high leverage prototyping activity described in the subsequent section on A & R accomplishments.** While there is considerable evidence of informal person to person coordination, the accomplishment of specific results would be considerably enhanced by establishment of an explicit hierarchy for the purposes stated.

### A & R Priority

The focal points have a valuable role to play in promoting A & R applications. Unfortunately, for a number of reasons, they are not always able to adequately perform that role. For example, it is not clear that all A & R focal points have adequate visibility into negotiated decisions that are made, e.g., between the work packages and their prime contractors. If they are to fulfill their assigned role, they need both visibility into decisions that are being made and the opportunity to advise those with implementation responsibility as to the impact of that decision on A & R technology application. Failure to achieve these conditions will result in less than the desired application of advanced A & R. Specifically, when funds are cut, A & R coordinators are not always in position to defend the A & R activities, and since A & R requires advanced technology, program leaders may cut A & R in favor of proven technology. There is some evidence that this situation is already being experienced in WP1 and WP2. While program redirection to maintain costs is clearly the prerogative of the program management, they should at least be made aware of the impact of their decision on A & R technology applications. The same situation occurs in relation to personnel. The Space Station Freedom program is experiencing a personnel shortage, so that people with A & R responsibilities (both focal points and people working A & R tasks) are being pulled off A & R and put to work on higher priority projects.

**ATAC feels that the identification of focal points should be kept rigorously current despite changing assignments and that the people identified as focal points not be so burdened with other assignments that promotion of A & R technology becomes an assignment of secondary importance. Moreover, the focal points should be given sufficient visibility into program decisions to assess and advise program management of the impact of the decisions on the applications of A & R.**

The main reason for lower priority of A & R technology implementation, particularly for automation, is that the benefits have not been demonstrated to the degree that A & R has been accepted by space station development managers. One area in which A & R potentially can help is in reducing life-cycle costs for the station.

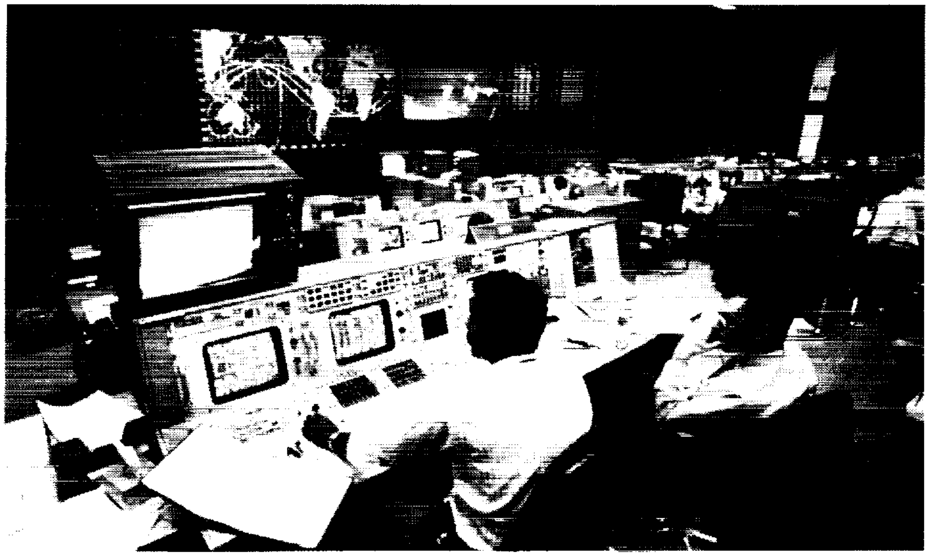
**ATAC's assessment is that increased emphasis on life-cycle cost analysis will help to demonstrate the potential benefits of A & R technology. ATAC has discussed this issue in previous reports (refs. 5–7) and has not seen much progress in this area. The planning requirements documents indicate that the decisions regarding application of A & R technologies in the SSFP ground and on-orbit systems shall be based on developed criteria, including the safety, productivity, and life-cycle cost benefits that are provided. ATAC urges the Space Station Freedom program and project managers to apply resources to determine the payoffs of A & R implementation in terms of station life-cycle costs. These cost benefits studies involve not only systems development and integration costs, including verification and validation, but operational costs as well. Failure to adequately consider the operational costs weighs decisions against A & R technology. Moreover, during the C/D phase, there should be clear direction to include those cost considerations and to provide for later incorporation of advanced A & R technology.**

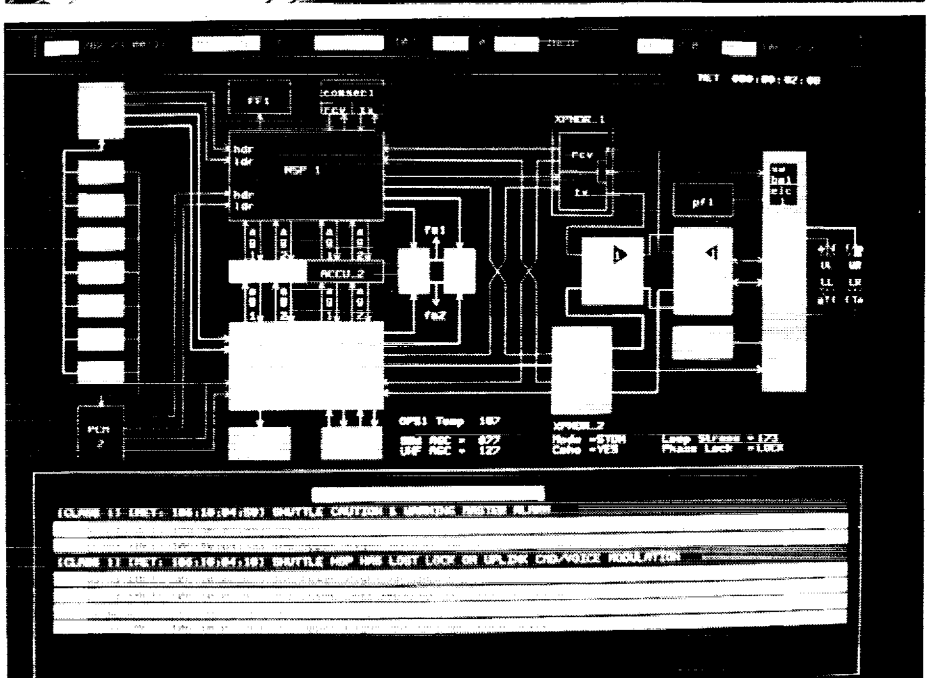
Another way to demonstrate the benefits of A & R and to minimize the applications risks is to develop some A & R prototypes for space station testing. This effort is discussed in the A & R Achievements section, below.

### A & R Achievements

Despite the issues described above, the people responsible for implementing A & R activities have made a concerted effort to make effective use of A & R on the station. Specific praiseworthy achievements are described below:

Level I has used 100 percent of its FY89 Advanced Development funds for A & R activities.






Major changes are being made to the Space Shuttle Mission Control Center (MCC) to incorporate advanced automation technologies. The role of automated telemetry monitoring, utilizing expert system technology, is being expanded as a direct result of the expert system demonstration performed during the STS-26 mission in September, 1988.

Expert systems have been developed in four applications areas: Communications, Main Engines, Mechanical/Hydraulics and Flight Instruments. All four of these systems were used by flight controllers during the STS-29 flight in February, 1989.

During STS-26 and STS-29 activities, confidence was developed in these expert systems and a decision was made to use them as prime operational tools on STS-30 in April, 1989. Display hardware from some older display consoles has been removed and replaced with the expert system workstation display units. The expert systems have been certified for use in making flight critical decisions and flight rules regarding their use have been written and approved. These systems are directly contributing to safety of flight and improving flight controller effectiveness.

Expert systems are also being developed in other areas of Mission Control including Guidance, Navigation and Control (GN&C), On-Orbit Propulsion, Electrical Power, and Life Support. This effort is jointly funded by the Office of Aeronautics and Space Technology (OAST), the Office of Space Flight (OSF), and the Office of Space Station (OSS).

The top photograph shows the MCC with the Integrated Communications Officer (INCO) in the foreground. The middle photograph shows the INCO with the expert system in the background. The INCO expert system was evaluated in parallel with the earlier technology during the STS-26 mission. The bottom photograph shows one display from the INCO expert system.

Starting with the themes of (a) improved productivity and (b) reduction of life-cycle costs, Level I has funded a significant number of tasks—all of which are related to automation and robotics (e.g., power management and distribution, intelligent computer-aided training, data management system advanced automation, knowledge-based system verification and validation, a space-qualified symbolic processor, and telerobotic technology).

Level I also undertook and published a study of the test beds which are involved in development of the station (ref. 9). There are at least four space station test beds which are operational to some degree or close to it. These test beds can be used in the development and testing of advanced automation for the station and include the following: the JSC Data Management System test bed, the JSC and ARC Thermal test bed, the Electrical Power System test beds at LeRC, MSFC, and JSC, and the JSC Control and Monitor test bed which is part of the Communications and Tracking System. For each of the individual test beds, specific applications of automation have been identified.

The JSC data management system test bed was established to evaluate data management, processing, and system control techniques in a distributed system environment in support of SSFP requirements (ref. 9). It is to be the host facility for the operations management system prototype target activities of commanding, monitoring, and controlling flight systems. Two prototypes currently being used are the integrated status assessment and the procedures interpreter prototypes, both of which involve the use of expert systems, advanced displays, and other advanced automation technologies.

The JSC/ARC thermal test bed is a complete thermal system of various test articles which are being evaluated and compared. An expert system has been developed to monitor, control, and diagnose problems on the test bed and is currently being evaluated.

The Electrical Power System test bed at LeRC consists of prototype electrical power system hardware which is being integrated with software to automatically control the system operation. One of the first expert system software programs being developed provides fault detection and isolation. JSC has a breadboard version of a data management system interface to the electrical power system, which has been developed with LeRC. The MSFC portion of the electrical test bed concentrates on power management and distribution. This test bed has been under definition for the last four years. An initial demonstration of capability was performed in 1988, and further capability is scheduled to be demonstrated in 1990. Initial demonstrations have already been performed which use three cooperating knowledge-based systems: a loads priority list management system, loads scheduler, and a fault recovery and management expert system.

The Control and Monitor test bed is used to develop and evaluate candidate communications and tracking system software. A local controller fault manager expert system and central processor resource manager have been implemented.

**ATAC's assessment is that a number of advanced automation applications are being developed and will be evaluated in the test beds. This approach should lead to a number of advanced automation applications in the Space Station Freedom program.**

Level II has identified an excellent program to provide candidate automated systems for the Station. This program, known as high-leverage prototyping, is particularly noteworthy in that it promotes application of A & R without requiring task managers to make a premature commitment to A & R. Moreover, it is designed to minimize the difficulty in transitioning successful results to WP test beds and thus facilitate inclusion in baseline program activities and planning. In this approach, automation prototypes are to be developed for specific applications where the program has elected to baseline more conservative approaches because of the high risk in requiring an automated system. The automated prototypes are to be developed at Level III Centers and work packages in parallel to the baseline system development. When complete, the automation prototypes are to be evaluated on the test beds to permit assessment of their performance relative to the baseline approaches. Where their performance warrants, these automation systems can be made part of the baseline system. While a considerable amount of work would still be required in applying these systems, their use in the Space Station Freedom program will be more readily accomplished since they are already implemented on the test beds.

The prototype candidates for this program have been informally coordinated with the projects in the Level I Advanced Development Program and proposed at a minimal level of funding. **Since it seems to directly address the practical problems of incorporating automation on the Space Station Freedom, ATAC's assessment is that this activity deserves significant praise. To achieve maximum impact, ATAC encourages a more formal proposal solicitation process for this program which would provide a wider base of candidates for eventual selection. Selection criteria keyed to the A & R implementation criteria which evaluate potential benefits to the Station also would be desirable.**

Two activities of the Level II Robotics Working Group are also commendable. The first is development of a draft document titled "Robotic Systems and Interface Standards" (ref. 10). The document is currently undergoing revision, but its progress indicates NASA and Space Station Freedom Office recognition that both EVA astronauts and robots will be working on the space station and the desirability of design commonality of the tools and orbital replacement units (ORUs) for both modes of operation.

The second commendable effort is the Robotics Working Group study of hand controller commonality. The objective of this study being conducted by McDonnell Douglas and Honeywell is to recommend common hand controller configurations to reduce volume and crew training requirements for both free flyers and manipulators. To date, the results of the study indicate that two six degree-of-freedom hand controllers which can operate in rate, position, and force reflecting modes are required. Further tasks are planned for this study: systems engineering trade studies, prototype development and testing, and definition of equipment specifications.

It is also commendable that Level II is looking at ways to use A & R for Space Station Freedom operations. Specifically, the Level II Operations and Utilization Office is developing operational scenarios, beginning with first element launch through mature operations. These scenarios include assembly operations, visual inspection of elements, attached payload servicing, external ORU maintenance, servicing, and contingency operations. Potential robotic tasks are being identified with the help of the Robotics Working Group and a process to rank and select them is being developed. Automation applications being examined include a test control and monitoring system for prelaunch systems checkout, logistics support, and the operations management system.

### Progress on the Flight Telerobotic Servicer

During this reporting period, The Flight Telerobotic Servicer (FTS) Phase C/D (final design and development) request for proposals was issued. Two proposals were received by January 1989 and are being evaluated currently. Contract selection is expected to take place in June 1989. As part of the preceding and overlapping Phase B effort, both contractors started preliminary design of the first FTS flight experiment, called DTF-1. The winning contractor will continue design and development efforts after contract award to meet the DTF-1 launch deadline of approximately mid-1991. Meanwhile, the FTS project office at Goddard Space Flight Center continues to evaluate the contractor's progress, develop an in-house integration and test facility, and coordinate requirements with Level II, especially through the Robotics Working Group.

ATAC has significant concerns with the FTS program. The first is the impact of any contract award delays on the DTF-1 schedule. This schedule is already extremely tight and cannot absorb any further delay. Interruption of continued funding for FTS development and laboratory tests for any reason, could prevent adherence to the DTF-1 schedule. Specifically, if the issue of FTS commercialization is not resolved prior to the scheduled milestones for source selection and completion of negotiations, there will be a definite impact on the success-oriented DTF-1 schedule. Development of the second FTS flight demonstration, DTF-2, should start and should include laboratory demonstrations as an opportunity for robotics technology experiments. Further, more progress needs to be made for flight integration and processing of DTF-1 with Kennedy Space Center. This requires flight integration funding. Both DTF flight activities should be designed to include relevant technology experiments on a noninterference basis.

Another major concern is that FTS still needs to be better integrated with the work packages. A block change request, which inserted FTS requirements throughout the PDRD has been approved, and work package assessments of those requirements are in progress. However, ATAC has no indication that these assessments and their implementation is progressing in a timely manner. Moreover, there are still no explicitly defined tasks for the FTS. **ATAC's assessment is that commendable efforts have been made to better define FTS tasks and requirements for payloads. The FTS project office has been attempting to do this through their mission** utilization team efforts, but more coordination, including more inputs from the potential users (with WP2 (JSC) as potentially the prime initial user), is required and encouraged. The mission utilization efforts should be expanded to include participation from the other Centers. Moreover, consideration should be given to having work packages define specific performance requirements for the FTS which would make it effective in accomplishing specific tasks required in the development and operation of the Space Station Freedom.

GSFC Robotics Development, Integration, and Test Facility.

Two Gantry robots, with 6 degrees of freedom and two-ton capacity, being acceptance tested. The nearer robot is carrying a test load.

# ATAC RECOMMENDATIONS

I. Complete the A & R Program Plan at all levels within six months, realizing that the plan may change in the future. The plan should explain the A & R goals and organization, and should indicate resources and priorities required to complete implementation of the planned A & R activities. Without this overall plan, there is very little hope for evolution and integration of A & R. Delay in completing the plan reflects a perception of low priority for A & R. (Section 3.7 of the PDR states that such a plan is to be developed.)

II. Establish a hierarchy of the A & R focal points in Levels I, II, III, and the work package contractors for the purposes of (1) reporting on A & R accomplishments and plans and (2) implementing a high-leverage prototyping activity. While this process has already been initiated by Level II, the process should be formalized in terms of organization and calls for proposals. Consideration should also be given to a higher level of funding for this activity.

III. Identified focal points should be kept rigorously current despite changing assignments, and the people identified as focal points not be so burdened with other assignments that promotion of A & R technology becomes an assignment of secondary importance. Moreover, the focal points should be given sufficient visibility into program decisions to assess and advise program management of the impact of the decisions on the applications of A & R.

IV. Develop criteria for assessing the merits of A & R activities and for prioritizing and choosing high-leverage prototype candidates. This will require studies which include systems engineering and integration, verification and validation, systems operations, and life-cycle cost. Specific attention should be given to evaluating the payoff of A & R activities in reduced overall life-cycle costs and incorporating those advanced A & R activities which provide significant life-cycle cost benefits.

V. The efforts of the FTS Mission Utilization Team to define FTS compatible tasks are commendable, but the process is missing a prime user; JSC should participate, and either endorse the set of tasks used as the design basis or define specific performance requirements for the FTS which would make it effective in accomplishing specific tasks.

VI. Continue funding to permit FTS development and laboratory tests. Make flight integration funding available as soon as possible. Start developing DTF-2 experiments and conduct laboratory tests as opportunities to demonstrate robotics technology. Both DTF flight activities should be designed to be pertinent to specific FTS tasks as defined by the work packages and other users and to include relevant technology experiments on a noninterference basis.

VII. Continue and expand development of the Robotic Systems Integration Standards to include all space station robots and adopt it as a space station applicable document.

# Appendix A

# OSS A & R Progress

The Space Station Freedom program (SSFP) A & R policy reflects a commitment to apply A & R technologies in the design and development of the baseline Space Station Freedom where these technologies are found to be appropriate within the framework of the overall system design, have a favorable cost-to-benefit ratio, and where the enabling technology components are sufficiently mature. The Office of Space Station Freedom (OSS) recognizes that automation and robotics disciplines are experiencing rapid change, exhibiting varying levels of technology readiness, and with attendant challenges in their integration with conventional design approaches and system engineering methodologies. Consequently, an important component of the OSS A & R policy is the provision of design accommodations to fully capitalize on anticipated A & R advances during the development and evolution of the Space Station Freedom. The OSS intends to take full and complete advantage of the significant momentum in A & R research and technology development within the academic, government, and commercial sectors during all phases of the SSFP.

Progress has been made by the SSFP in each of these program areas and will be discussed in the following sections.

## A & R Progress Within The Baseline Space Station Freedom Program

Since the last reporting period, Level II has made significant progress in planning for the implementation of A & R within the baseline program. The following sections provide highlights of the last six months.

### High-Leverage Prototyping Program

A high-leverage prototyping program has been established to evaluate potential A & R candidates for inclusion in the baseline. The program will promote applications of A & R by demonstrating benefits and reducing risks through prototyping of selected candidates. The proposals are planned to be funded at a moderate level and will maximize use of planned SSFP test beds to facilitate transition to the baseline. In response to this program, approximately 25 proposals were received from the centers. The proposals cover a wide range of applications in robotics research, artificial intelligence, and expert system applications.

The proposals were reviewed at Level II by the Robotics Working Group, the Advanced Automation Working Group, and the Artificial Intelligence, Expert Systems, and Technology Working Group. The Program Director will be briefed on the proposals with the highest potential to contribute to the baseline program in A & R.

### Systems Engineering and Integration (Robotics)

The Robotics Working Group has developed a draft document, "Robotic Systems Integration Standards," that specifies "robot-friendly" design standards for the Space Station. The final standard will include requirements for robot safety, structured environment, work sites, hardware and equipment designs, and design for maintainability.

Hand controller commonality for the various robotic devices on SSF is desirable for training, logistics, operational effectiveness, and safety. The Robotics Working Group coordinated a study by McDonnell Douglas/Honeywell to address commonality of hand controllers for all space station telerobotic manipulators. The "Hand Controller Commonality Study," completed in February 1989, identified the equipment to be controlled, defined the location and work station of the controllers, identified candidate hardware configurations, and recommended common configurations.

The Robotic Task Integration Process (RTIP), under development by the Robotics Working Group, will provide a standardized process for contractors to analyze assembly, maintenance, and servicing tasks for robotic performance. For the Preliminary Design Review, the RTIP will provide a framework for verification of conformance with the robotic system integration standard.

A Flight Telerobotic Servicer (FTS) requirements update to the PDRD was completed. The changes include design reference tasks, transportation capabilities, operational and control modes, workstation requirements, work site requirements, work piece/FTS/EVA compatibility, emergency shutdown and collision avoidance, and storage requirements.

The Robotics Working Group has also been actively involved in developing the requirements for Mobile Servicing System (MSS) performance. The results will be incorporated into the PDRD.

Systems Engineering and Integration (Advanced Automation)

The A & R section of the PDRD was revised to reflect greater consistency with the A & R requirements in the Level I Program Requirements Document. Center review of the revisions is in progress and will be followed by systems engineering review. The Operations Management Application (OMA) requirements are currently under revision to incorporate potential knowledge-based system applications.

Information Systems

Work is proceeding on standardization of information system services for interoperability, transportability, commonality, and reduced life-cycle cost. A system engineering approach has been initiated for defining needed expert system support in this area. Program-wide requirements for expert system services will be analyzed, and standard expert system tools, rules, and processes will be defined. This work will result in an Expert System Interface Definition (ESID), which will include development services (production systems and support tools), test services (test bed accommodations and verification/ validation), execution services (operating system services, database services, communications, and information processing architecture), and process requirements (knowledge engineering standards and software support environment rules).

Operations

Operational scenarios, from first element launch through mature operations, are being developed in support of robotic device/EVA task assignment. Operations addressed include assembly operations, visual inspection of elements, attached payload servicing, external Orbital Replacement Unit (ORU) maintenance, Man-Tended Free Flyer (MTFF) servicing, and contingency operations. From these operational scenarios, potential robotics tasks are being identified. A decision process to rank the capability of potential robotic devices to perform tasks, and to select candidates, is in preparation.

Automation applications under development for operations include the Test Control and Monitoring System (TCSM) for prelaunch systems checkout. In the logistics support area, automation applications include historical maintenance data capture, systems trend analysis and prediction, and supportability analysis. For the Operations Management System (OMS), an evolution plan, which presents an approach for development and activation of automated OMS capabilities, has been developed and distributed.

Planning

Preparation of the Level II A & R Implementation Plan is proceeding and is currently in the process of revision internal to Level II, incorporating changes and clarifications in A & R roles and responsibilities in the management structure. Development of decision criteria for determining the benefits of application of A & R technologies is continuing, based on the results of an evaluation test case that used program criteria mandated by the Program Requirements Document and recommended by ATAC. Decision criteria include development cost, operations cost, crew productivity, safety, development risk, implications for resource requirements, spin-off potential for terrestrial applications, growth potential, and most effective use of SSF budget and personnel. These criteria and the methods to determine the benefits of A & R will continue to be refined.

### A & R Within the Transition Definition Program

The Space Station Freedom program, recognizing the importance of growing and evolving the baseline Space Station Freedom and its dedicated ground support facilities during the projected thirty year life of the Station, established the Transition Definition Program to define, develop, and implement a Program to enable space station evolution in keeping with the needs of users and the long term goals of the United States. The Transition Definition Program is managed by the Strategic Plans and Programs Division, Office of Space Station Freedom, and involves all of the NASA centers and each of the SSFP Work Packages.

The primary thrusts of the Transition Definition Program are to define Reference Evolution Configurations which are consistent with projected user requirements, national space policy, and SSFP constraints; define and incorporate Baseline Design Accommodations, often referred to as "hooks and scars," which satisfy the requirements associated with the Reference Evolution Configurations; and, develop advanced technology that insures technology readiness to enhance space station capabilities and enable evolution.

The Transition Definition Program is divided into two separate, but nonetheless interconnected components, Evolution Studies and Advanced Development. ATAC Progress Report 7, Appendix B, "Overall Plan for Applying A & R to the Space Station and for Advancing A & R Technology," provided a detailed overview of each and emphasized their A & R content. The following paragraphs describe progress made in both areas during this reporting period.

Several Evolution Studies were initiated in FY 1989 to examine the potential of A & R technology to address projected evolution mission requirements as well as identify A & R technology needs that enable space station evolution. The study topics are Advanced Robotics for In-Space Vehicle Processing, Advanced Automation for In-Space Vehicle Processing, and Data Systems Evolution. These studies will provide detailed "hooks and scars" requirements prior to the Preliminary Design Review and will directly influence the Space Station Advanced Development Program content. The studies will also develop long-range technology need data which will be provided to the Office of Aeronautics and Space Technology to support planning activities associated with their Artificial Intelligence and Telerobotics Programs. The results of the Data Management System Technology Transparency study have been briefed to the Associate Administrator, Office of Space Station, and the Data Management System Working Group. The technical recommendations it contained are currently under evaluation by Level II and Work Package 2 for incorporation in the development program.

The primary goals of the Advanced Development Program are to enhance baseline Space Station Freedom capabilities with an emphasis on increasing productivity and reliability while reducing operations costs and, to enable space station evolution by providing mature technology in areas required to support advanced evolution missions.

Presently, the Advanced Development Program has two major categories: Application Development and Demonstration, and Technology Development and Evaluation. Sub-categories under Applications Development and Demonstration include On-Orbit Systems Control, Ground Operations Support, and the Space Station Information System. Under Technology Development and Evaluation, the subcategories are Advanced Automation Software Development, Advanced Automation Hardware and Human Factors, and Telerobotic Systems Technology.

The products of the Advanced Development Program range from ground and flight demonstrations and evaluations of technology at a near-operational level of readiness to detailed requirements, performance specifications and mature technology components which are suitable for transition to NASA centers and/or contractors for final implementation during the development and evolution of the Space Station Freedom.

In FY 1989, the Advanced Development Program investment of $8M is completely dedicated to A & R prototype application development and technology maturation. Knowledge-based system (KBS) prototypes have been initiated (or accelerated) for the Power Management and Distribution System at Work Packages 1 and 4, the Life Support System at Work Package 1, the Data Management System and Operations Management System at Work Package 2, and the Platform Management System at Work Package 3.

These KBS applications, which augment conventional techniques, are primarily aimed at system status monitoring, fault diagnosis and isolation, and system reconfiguration in the event of malfunctions and/or anomalies. Each prototype will be demonstrated and evaluated on the baseline development test bed associated with it's specific application. Successful applications will be transitioned for additional refinement to either the Level II high-leverage prototyping program or directly to the System Development Manager at the appropriate Work Package center for incorporation into the development program.

The Advanced Development Program is building upon the application of KBS technology to the Space Shuttle Mission Control Center at Johnson Space Center (JSC) funded by the Office of Aeronautics and Space Technology and the Office of Space Flight. The Integrated Communications Officer (INCO) expert system which has successfully performed real-time monitoring, fault detection, and system reconfiguration in support of STS-26 and STS-29 is being used to derive detailed hardware and software architecture requirements and operations concepts for the Space Station Control Center. The principal benefits expected will be improved operational performance, reduced manpower requirements and training expense, and a Control Center architecture that more readily accepts the insertion of advanced technology.

A programming tool which permits the development of sophisticated Intelligent Computer-Aided

Training (ICAT) applications was recently demonstrated at JSC. This task has been jointly funded by the Advanced Development Program, the Office of Space Flight, and the United States Air Force to address the significant time and expense associated with the training of Mission Control Center personnel. The ICAT tool will also be evaluated as an on-board training aid for Space Station Freedom crewmembers. This task has secured commercial participation to develop it as a tutor for high school physics and has been successfully demonstrated in this capacity. Additional educational topics such as math and chemistry will be added during an evaluation period. The ICAT tool has high potential as a successful commercial spinoff.

A prototype KBS software development tool which produces Ada target code has been demonstrated at JSC. This task was co-funded by the Advanced Development Program and the United States Air Force. This is a significant development as it represents the first time a major LISP-based KBS development tool has been converted to support the Ada language and programming methodology. Both Level II and Level III Software Support Environment (SSE) personnel are participating in this task and using the results obtained to aid in the development of detailed requirements and performance specifications associated with the development of Ada-based KBS standards and tools.

A KBS application jointly funded by the Advanced Development program and the Office of Space Flight which dramatically improves the productivity of conventional software development has also been successfully demonstrated at JSC. The Automated Software Development Workstation uses KBS techniques to intelligently search libraries of previously developed Ada software components and assist the programmer in the integration of "new" software which reuses the existing code. This capability is currently under evaluation for use within the SSE and also for transition to the private sector for commercial applications.

A telerobotics technology demonstration effort has been initiated with the Jet Propulsion Laboratory (JPL) and Kennedy Space Center (KSC) to transfer JPL path planning and robot control software to the Robotics Application Laboratory at KSC. The software has been transferred from JPL to KSC and is being modified for the demonstration later this year on a Payload Assist Module (PAM) high fidelity mockup. The end application is the operation of a large robot in the Vertical Payload Bay Inspection Facility at KSC. A datalink will be established between JPL and KSC to permit the teleoperation of the Payload Bay Inspection Robot from JPL with time delay equivalent to that experienced from earth to the Space Station Freedom. This will allow the refinement of advanced algorithms for planning, sensing, perception, and shared control as well as display techniques appropriate for safe teleoperation with significant time delay. The results of this activity will be directly transitioned to the Flight Telerobotic Servicer (FTS) Program.

A study entitled "A Review of Space Station Freedom Program Capabilities for the Development and Application of Advanced Automation" was completed in December 1988. The results were briefed to the Associate Administrator, Office of Space Station, and formally distributed to Levels I, II, and III in January 1989. The study examined design and research facilities, operational and support facilities, and many existing advanced automation prototypes and identifies critical issues associated with the development and evolution of advanced automation applications for the Space Station Freedom. A copy of this report will be forwarded with the transmittal of ATAC Progress Report 8 to Congress.

This effort was expanded during FY 1989 and is currently updating the previous survey of test beds and advanced automation applications, developing advanced automation evolution plans for each of the space station development test beds, and is also producing a detailed plan for the integration of the individual test beds to permit the development and evaluation of distributed KBS applications which address the Operations Management Systems functional requirements. Key Level II and Level III personnel are participating in each facet of this effort. The individual planning documents produced by this activity will be integrated with the A & R planning documents currently under development at Levels I and II.

Progress continues in each of the other Advanced Development Program tasks and it is expected that major accomplishments for them will be reflected in the next ATAC reporting cycle. The FY 1990 budget for the Advanced Development Program is currently projected at $17M. The focus on A & R will continue with the addition of applications in Guidance Navigation & Control, Communications and Tracking, EVA/Manned Systems, and Laboratory Module scientific experiment support. Additional disciplines to be addressed will include optical communications and data processing and on-orbit cryogen storage and fluid transfer. Planning and preparation for expanded ground and flight demonstration of applications and technology will also continue.

As evidenced by the frequent references to jointly funded activities, it can be seen that the Advanced Development Program is aggressively leveraging applied research and technology development efforts initiated by the Office of Aeronautics and Space Technology (OAST). The existing Memoranda of Understanding (MOU) and Memoranda of Agreement (MOA) Concerning Telerobotics and Advanced Automation are being updated to reflect progress within OAST's and OSS's respective programs. These documents will provide a formal mechanism for the coordination of joint efforts, the transition of OAST-sponsored technology, and the provision of long-range technology requirements to support OAST's planning process. Additionally, an MOU between OSS and the Office of Space Flight (OSF) has been drafted to permit a more formal coordination between the respective Advanced Development Programs of each organization.

# APPENDIX B
# FLIGHT TELEROBOTIC SERVICER PROGRESS

The following information represents the current status of the FTS Project.

### FTS Prime Contract

The FTS Phase B Study contracts performed by Grumman Aerospace in Bethpage, NY, and Martin Marietta in Denver, CO, were completed in September 1988. The Phase C/D Request for Proposals (RFP) was formally released in November 1988, and proposals were received January 3, 1989. As anticipated, Grumman and Martin were the only proposers. The FTS Source Evaluation Board (SEB) is currently operating on schedule with contractor selection scheduled for June 1989, and contract award scheduled for July 1989.

As discussed in the next section, there were also two interim contracts issued to Grumman and Martin Marietta to avoid loss of schedule time on the DTF-1 mission.

### Development Test Flight (DTF-1)

The DTF-1 mission has four primary objectives: (1) to evaluate the FTS robot manipulator design and control approach; (2) to evaluate the FTS workstation design approach; (3) to correlate fundamental engineering relationships of system performance in space with ground simulation and analysis predictions; and (4) to evaluate human-machine interfaces and operator fatigue.

DTF-1 is currently manifested aboard the Atlantis as part of the STS-49 mission as a complex secondary payload with a scheduled launch date of August 1, 1991.

It is clear that the DTF-1 flight schedule is a very tight one. Therefore, the time between Phase B completion and Phase C/D contract award (9 months) could not be lost. To make maximum use of this valuable time, a contracting approach was formulated, approved, and implemented that awarded new, independent (as opposed to Phase B extensions) contracts to Grumman and Martin Marietta for the purpose of completing the DTF-1 preliminary design. These contracts include initiating long-lead procurements necessary to meet the schedule requirements. Each contractor will complete his preliminary design for the DTF-1 mission and prepare for a preliminary design review. The selected Phase C/D contractor will then proceed with the preliminary design review and the rest of the FTS prime contract activities while the losing contractor's effort will be terminated.

These preliminary design contracts are funded at $4.5M each, and were initiated in September 1988, with a completion date of June 1989. All data and purchased hardware under both contracts will be delivered to the Government.

The direction of these contracts is being accomplished in parallel with the competition for the Phase C/D implementation contract. Both activities deal with SEB sensitive information and must not influence each other. This has created the need to establish a civil service team independent from the procurement activity. This team includes FTS project management and technical specialists from GSFC, the STS payload integration specialists from JSC, representation from the Astronaut Office, and appropriate support from KSC and NASA Headquarters.

Martin and Grumman each presented a mid-term design briefing at their facilities in February as part of these contracts.

A Payload Integration Review was held at JSC in December which resulted in release of the Preliminary Payload Integration Plan (PIP). This review formally initiated the STS/DTF-1 integration process.

DTF-2 called the Demonstration Test Flight, is scheduled to fly in November of 1993, approximately 2 years before the First Element Launch of Space Station Freedom. This mission will include a mature version of the entire FTS system and will demonstrate FTS capabilities to perform actual space station tasks.

### FTS/Space Station Freedom Integration

There has been significant progress toward the integration of FTS as a formal space station element. A major FTS Block Change Request (CR) to the Space Station Preliminary Design Requirements Document was written and accepted. This CR defined FTS performance (in terms of capabilities to perform six tasks that were specified in the FTS Phase C/D RFP), its operating modes, the accommodations required for the telerobot at eleven specific work site locations and accommodations for FTS storage. Achieving approval of this Block Change Request required coordination with the other Space Station Freedom Work Packages and evaluations of cost impacts, and was considered a significant achievement.

A second integration milestone has been the development of an interface control document between the Canadian Mobile Servicing Centre (MSC) and the FTS. Driven by the early Canadian PDR schedule, development of this document forced out issues associated with the FTS/MSC interfaces and operational modes. This also proved to be a catalyst in the development of a beneficial working relationship between the FTS and the MSC projects. This is important because the MSC is the primary system used for the deployment of the FTS during space station operations.

### Mission Utilization Team

The Mission Utilization Team (MUT) at GSFC, which was established to script, simulate, and formalize operational scenarios for tasks utilizing the FTS, has completed the development of a formal methodology for task analysis. The team then applied this methodology to the six baseline FTS tasks, plus scenarios for tasks on the second through fifth space station assembly flights (MB-2 through MB-5), and a scenario for power system radiator panel installation as suggested by the JSC Work Package-2 prime contractor (McDonnell Douglas). Additionally, scenarios for Orbital Replacement Unit (ORU) exchange were developed in close association with LeRC Work Package-4. The work of the Mission Utilization Team has become an integral part of the FTS project and represents the FTS project interface for all potential applications of the FTS.

### Development Integration and Test Facility

The Development Integration and Test Facility (DITFAC) is located at GSFC and is part of the Engineering Directorate support to the FTS Project. The effort in the facility has two primary components; the Engineering Test Bed and the Functional Simulator.

The work in the Engineering Test Bed will focus on advanced robot control techniques. Experimentation and testing will be performed in the following areas: (1) redundant degree of freedom algorithms; (2) bilateral force reflection performance; (3) dual arm coordinated control; and (4) force and active compliance control. Robot safety system development and autonomous sub-task technique development and testing will also be key efforts worked in the Test Bed. The Engineering Test Bed will be configured according to the NASREM architecture.

The work done in the Engineering Test Bed will serve to verify concepts developed by the FTS prime contractor making GSFC a smarter buyer and possibly anticipating or experiencing problems before the prime encounters them. Another primary function of the Engineering Test Bed is to support the evolution of the FTS. It will serve as the entry point for technology elements from outside sources so that integration and feasibility testing can be performed before these elements are flight configured for future installation on the FTS flight system.

The basic elements of the Test Bed have been procured and are in the DITFAC. They are: two Robotics Research Corp. manipulator arms mounted on a common pedestal; two Kraft force reflecting hand controllers; control computers; and required sensors and cameras.

The other major component of the DITFAC, the Functional Simulator, has an entirely different and complementary purpose from that of the Engineering Test Bed. While the Engineering Test Bed focuses on the internal control problems of the robot, the Functional Simulator will be used for simulation and testing of robot applications. The focus of the Functional Simulator activities will be in the areas of task procedure development, camera and lighting testing, end-effector development, task/work-piece design, operator interface development and operations support.

The primary elements of the Functional Simulator are: the dual-masted gantry robot (now installed in the DITFAC); a dual-arm, bilateral force reflecting system from Kraft Telerobotics Inc.; a simulated aft flight deck workstation; and numerous task mock-ups. The Kraft system is currently being procured and the workstation is under construction. Several of the task mock-ups have already been built.

# APPENDIX C
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# APPENDIX D

## Acronyms

| | |
|---|---|
| A & R | Automation and Robotics |
| ARC | Ames Research Center |
| ATAC | Advanced Technology Advisory Committee |
| EVA | Extravehicular Activity |
| FTS | Flight Telerobotic Servicer |
| JSC | Johnson Space Center |
| LERC | Lewis Research Center |
| MSFC | Marshall Space Flight Center |
| NASA | National Aeronautics and Space Administration |
| ORU | Orbital Replacement Unit |
| OSS | Office of Space Station Freedom |
| PDRD | Program Defintion and Requirements Document |
| PRD | Program Requirements Document |
| SSFP | Space Station Freedom Program |
| WP | Work Package |

## APPENDIX E

## NASA Advanced Technology Advisory Committee

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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 Freedom 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 eighth in a series of progress updates and covers the period between October 1, 1988, and March 31, 1989. NASA has accepted the basic recommendations of ATAC for its Space Station Freedom 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 Freedom 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 Freedom study contractors. It also describes research in progress, and it makes assessments of the advancement of automation and robotics technology on the Freedom space station.

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