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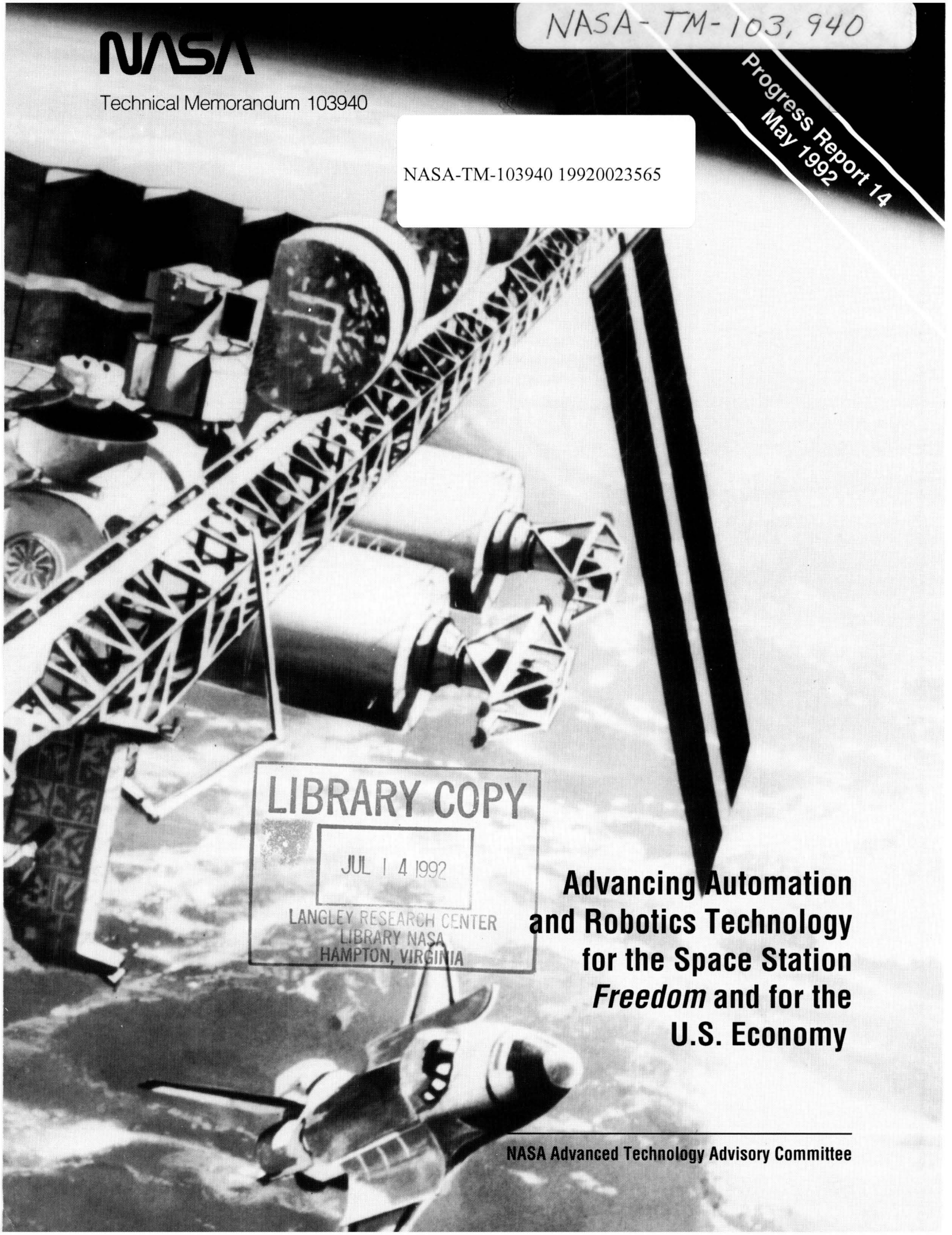

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Advancing Automation and Robotics Technology for the Space Station *Freedom* and for the U.S. Economy

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Technical Memorandum 103940

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

Progress Report 14
August 15, 1991 through February 27, 1992

Submitted to the Congress of the United States
May 1992

Advanced Technology Advisory Committee
National Aeronautics and Space Administration

NASA
National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

Cover: Space Station Freedom
Permanently Manned Capability

Insets: Lunar Base
Planetary Exploration

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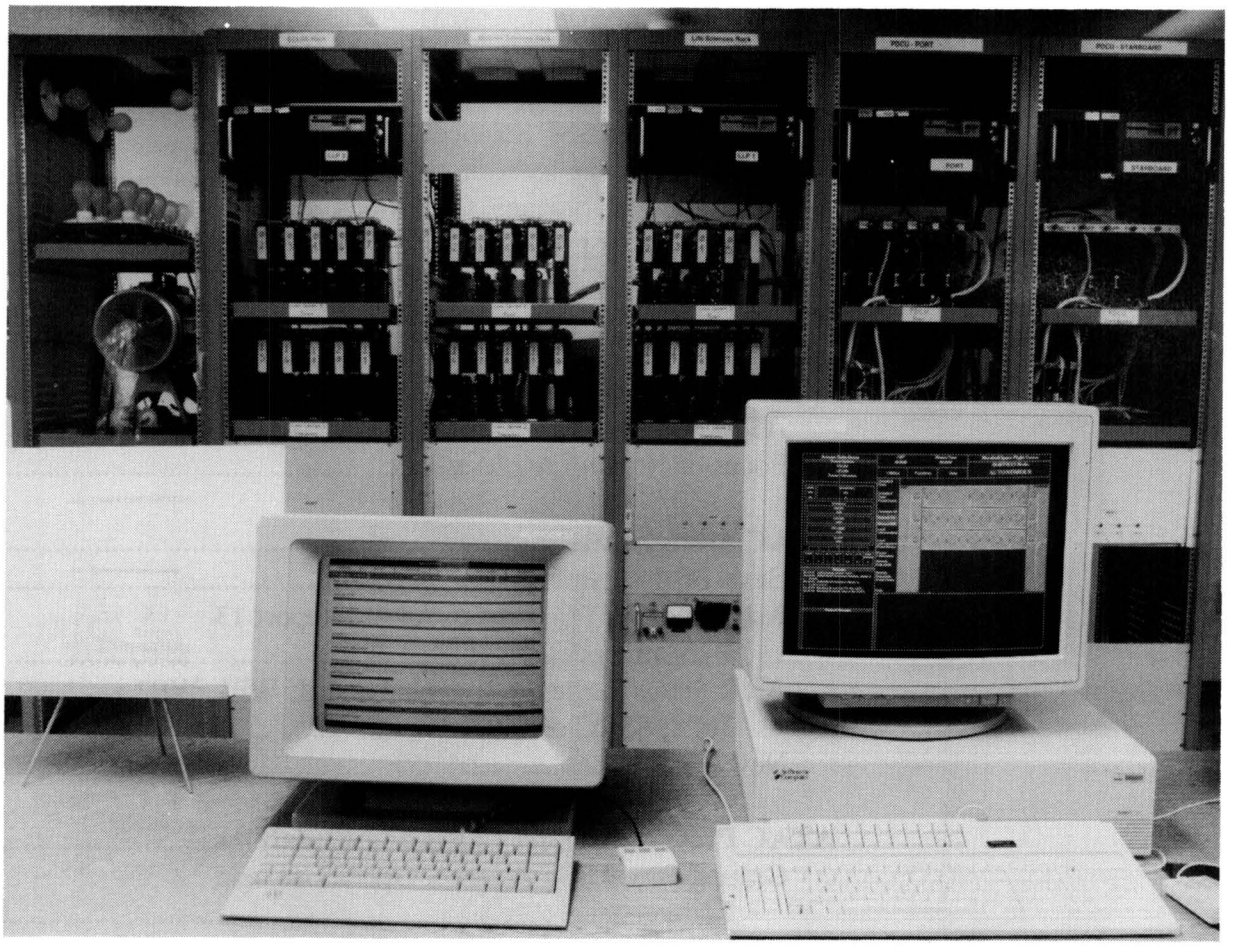

SSF automated module/power management and distribution testbed

The SSF Automated Module/Power Management and Distribution (PMAD) testbed is located at Marshall Space Flight Center. The project is developing and demonstrating advanced technology for autonomous monitoring, control, and fault management of power for the SSF habitat and laboratory modules. Design accommodations are being identified for SSF baseline and for evolution.

The advanced automated PMAD technology will provide enhanced safety, increased reliability, and increased productivity for SSF science, operations, and maintenance. If funding becomes available, the technology will be implemented first in SSF ground mission control centers and eventually migrated to SSF on-board systems.

Executive Summary

Background

Congress has directed NASA to develop and implement an A&R program with the intent to focus and transfer the A&R technologies into the U.S. industrial sector and economy by using Space Station Freedom as the focused application.

In response to the mandate of Congress, NASA in 1984 established the Advanced Technology Advisory Committee (ATAC) to review, assess, and report NASA's progress in carrying out its Congressional mandate. This is the fourteenth in the series of progress updates and covers the period of August 15, 1991 through February 27, 1992.

Recommendations

Ground-Based SSF Science, Operations, and Maintenance

Space Station Control Center

The ATAC Report No. 13 indicated that SSFP funding would not support the implementation of automation within the Space Station Control Center (SSCC). Current plans are for Level I to support the development of a Testbed which would encourage demonstration and potential migration of automation products being developed in the Level I Engineering Prototype Development program. In addition, the SSCC Testbed would provide potential for demonstration and migration of products being developed within the OAST Artificial Intelligence program, and the OSSD Advanced Development Program.

ATAC recommends that the Level I Engineering Prototype Development manager coordinate an SSFP effort with OAST to assure that applicable existing automation technologies are considered for the SSCC baseline system, and present a specific plan for the effort at the July 1992 ATAC review.

Payload Operations Integration Center

Current planning for development of the SSF Payload Operations Integration Center (POIC) includes the use of state-of-the-art software development tools and a distributed computer architecture. However, plans do not include specifically development and implementation of automation tools in the POIC baseline design. Plans are to use the existing Spacelab planning and scheduling system through SSF MTC, with development of a new system in 1995 through 1998 which will be available for use during PMC. The use of existing planning and scheduling tools for on-board SSF operations may not allow efficient use of the limited manned operations during the early stages of the SSF program.

ATAC recommends that SSF Level I Engineering Prototype Development manager determine if one of the existing advanced planning and scheduling tools being developed within their program or one being developed within the OAST program could be implemented for the POIC baseline operations.

On-Board SSF Science, Operations, and Maintenance

Science Productivity

Science activities on-board SSF could be greatly enhanced through the use of automation and robotics, especially the use of on-board automation during the unmanned operational phase of the SSF. SSFP should be more proactive in providing expert A&R consultation to the science community. It is SSFP's responsibility to provide sufficient capabilities within the SSFP laboratory infrastructure to enhance and promote its effective utilization by the science community during the MTC operational phase.

ATAC recommends that SSFP coordinate and implement an integrated effort to facilitate and enhance the effective utilization of the SSF laboratory facilities for the conduct of material and life sciences during the MTC phase.

A&R Technology Evolution

Migration of Advanced Automation On-Board SSF

The current SSFP Level I program does not address the advanced development of automation technologies that will provide the ability to migrate automation from ground operations to SSF on-board operations; which was the SSF program plan proposed in the 1991 restructuring exercise. Without the development of a specific plan to address automation development for SSF on-board operations, automation will not be available for the Permanent Manned operational phase, which may greatly reduce the efficiency of SSF operations.

ATAC recommends that SSFP develop a plan including migration of advanced automation technology from ground control centers to on-board SSF to address supporting automation advanced development for the SSF PMC operational phase, and present the plan at the July 1992 ATAC review.

Flight Telerobotic Servicer Technologies

The FTS contractor, along with various FTS subcontractors, has made substantial progress in developing a technology base for a space telerobotic infrastructure. The last significant action to disseminate information from this technology base to U.S. industry was an Industry Briefing in 1990. The substantial resources invested in FTS warrant a focused activity to collect and disseminate to US industry and academia all of the worthwhile technology developed by the program.

ATAC recommends that SSFP strongly encourage OAST to organize and implement a timely process to preserve and disseminate to U.S. industry the technologies developed during the FTS Program.

Introduction

Background

Congressional Mandate

Congress has directed NASA to develop and implement an A&R program with the intent to focus and transfer the A&R technologies into the U.S. industrial sector and economy by using Space Station Freedom as the focused application.

ATAC Establishment

In response to the mandate of Congress, in 1984 NASA established the Advanced Technology Advisory Committee (ATAC) to prepare a report identifying specific Space Station Freedom (SSF) systems which advance automation and robotics (A&R) technologies. In March 1985, as required by Public Law 98-371, ATAC reported to Congress the results of its studies (ref. 1). The first 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 (SSFP).

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.

ATAC Mission

Review, assess, and report NASA's progress in carrying out its Congressional mandate for A&R technology development and application to Space Station Freedom. Specifically, independently review 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, and review the recommendations with NASA management for their implementation. Report assessments and recommendations twice annually to Congress.

The Space Station Freedom Program is charged with developing a baseline station configuration that provides an initial operational capability and which, in addition, can be evolved 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.

The ATAC has continued to monitor and prepare semiannual reports on NASA's progress in the use of automation and robotics in achieving this goal. The reports are documented in the ATAC Progress Reports 1 through 13 (refs. 2-14). Progress Reports 1 through 5 covered the definition and preliminary design phase (Phase B) of Space Station Freedom. Progress Reports 6 through 10 covered the startup of the design and development phase (phase C/D) of the SSF. Reports 11 and 13 have covered the Restructured design of SSF which was required by Congress in late 1990. Phase C/D will lead to a completely assembled station to be operational in the late-1990's.

ATAC Progress Report 13, as previous ATAC reports, received wide

dissemination. ATAC Progress Report 13 was distributed in the following categories:

Congress	25 copies
NASA	235 copies
Industry	110 copies
Universities	50 copies
CSA, ESA, NASDA	5 copies
GAO	2 copies
Oversite Committees	23 copies
Total	450 copies

This report is the fourteenth in the series of progress updates and covers the period of August 15, 1991 through February 27, 1992. To provide a useful, concise report format, all of the committee's assessments have been included in the section "ATAC Assessments." This section of the report includes comments on SSFP's progress in responding to the ATAC recommendations in Report 13. Also, a summary of progress in A&R in the Space Station Program Office as written by SSFP is provided as an appendix. In addition, appendices are included on the Flight Telerobotic Servicer technologies. The report draws upon individual ATAC members' understanding and assessments of the application of A&R in the SSFP and upon material presented during an ATAC meeting held February 25-27, 1992, at MSFC for the purposes of reviewing the SSFP A&R activities and formulating the points of this report.

Climate

ATAC reported in its November 1991 Report (Report No. 13) that it was concerned that the Space Station Control Center (SSCC) had "...not taken full advantage of the technology work being done in support of shuttle ground mission operations ... and the evolution of advanced automation technologies into the SSCC are not clearly provided for, which could result in flight controller productivity that is lower ... than is presently achievable with shuttle ground mission operations systems."

ATAC is now pleased to report that SSFP has initiated plans towards the implementation of advanced automation technologies into the SSCC which may result in a more cost-effective implementation of the SSCC over the life cycle of the SSFP.

In addition, the computational environment for SSCC has now been redefined resulting in a system design with interfaces to accommodate evolving technologies such as the capability for systems fault detection and analysis. This environment will provide for the validation of advanced automation technologies in an operational environment and will provide technology validation prior to on-board implementation.

During this period ATAC reviewed the development efforts at MSFC for the Payload Operations Integration Center (POIC). The POIC will provide Principal Investigator access to data and support facilities for many of the experiments to be flown on the Space Station. Many of the data system designs appear to be adequate at this time. However, SSF Level I should work with the POIC managers to determine if existing Agency advanced planning and scheduling software tools can be implemented into the POIC baseline operations. The area of advanced planning and scheduling had not been adequately researched for the initial design phase. ATAC was encouraged by the openness of the MSFC design team in expressing their ideas and concepts to the committee, and their willingness to discuss ATAC comments and suggestions for advanced techniques that should be considered in their upgrade plans.

ATAC Concerns

Ground-Based SSF Science, Operations, and Maintenance

Although the SSCC has made some progress in the definition and development of a program plan to incorporate advanced automation technologies into the baseline system, the **implementation phase has been impeded by the lack of validated software proposed for the advanced automated subsystems.** An SSCC Testbed, sponsored by SSFP Level I, has been proposed to accelerate the validation process and aid in the transition of the advanced automation technologies into the SSCC operational environment. However, ATAC is concerned that

1) There is no evidence of long-term funding committed to this effort to make it a successful venture

2) **There is not an SSFP/OAST Automation Program coordinated and integrated for ground-based operations to insure the readiness of promising technologies for SSCC's baseline and evolutionary phases.**

It is the opinion of ATAC that the use of advanced automation technologies for the SSCC and the POIC will be cost effective for the SSFP and will increase the science and engineering productivity over the lifetime of the program.

As such, ATAC is concerned that the Agency still does not have an integrated advanced automation technology program which addresses the needs of SSCC, the POIC, and the SSFP scientific investigators.

On-Board SSF Science, Operations, and Maintenance

ATAC has received several briefings on proposed scientific uses for the SSFP laboratory. There has been interest expressed by the life sciences and material sciences research communities in using the SSFP laboratory during the MTC phase.

It is ATAC's opinion that the SSFP laboratory can be effectively utilized during the MTC phase provided that an integrated plan is developed and coordinated by SSFP to facilitate and enhance the effective utilization of the SSF laboratory facilities for the conduct of life and material sciences experiments.

At the current time, the potential scientific users do not have an SSF advocate nor does an integrated Agency A&R plan exist to provide the needed technologies to support their long-term experiment requirements.

Significant progress has been made in the baselining of the Robotic System Integration Standards (RSIS), Volumes I and II, with specific robotic operational functions defined. SSF Level II and III organizations have been active in implementing and integrating the robotic interfaces with Canadian Space Agency/ SPAR for ORU replacement.

ATAC is concerned, though, that there is little progress being made in standardizing or integrating the NASDA and ESA space robotic elements with the RSIS format which, if not done, may lead to additional costs for operation, maintenance, and training.

A&R Technology Evolution

SSFP has made considerable progress towards the development of a plan for the utilization of advanced automation technologies into the SSCC.

However, ATAC is concerned that there is not an integrated Agency plan to evaluate, validate, and migrate the advanced automation technologies to the SSF on-board systems for the PMC phase.

In addition, several unique technology components were developed during the course of the FTS contractual effort.

It is the opinion of ATAC that the technologies developed during the FTS effort should be preserved and disseminated to the U. S. industry for potential use in the commercial sector.

Focus of Next ATAC Meeting

The next ATAC meeting and report, Progress Report 15, will focus on detailed review of the DMS design simplification status, plans for the SSCC automation testbed, the OAST A&R Program, the progress towards robotic standards which apply to all workpackages and international partners, and the SSFP plans for migrating advanced automation technologies to on-board systems. The meeting will be held in July, 1992 at Johnson Space Center.

ATAC Assessments

Basis of 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 following the implementation of restructuring. A review of the progress toward the recommendations from ATAC's most recent report, Progress Report 13, will be discussed first, followed by a review of topics explicitly addressed during the February 25-27, 1992 ATAC meeting, and then a discussion of new A&R issues.

It is ATAC's understanding that the Congress provided funding for NASA's overall A&R program with the specific intent to focus and transfer the A&R technologies into the U. S. industrial sector and economy by using Space Station Freedom as the focused application. Due to the congressional budget constraints, the SSFP, as currently restructured, is unable to comply with the SSFP part of the intent. OAST is responsible for a major part of the NASA A&R technology development program; as such, ATAC will review and assess the OAST contributions to SSF at the next ATAC meeting.

Assessment of Progress on ATAC Report 13 Recommendations

Recommendation I: Space Station Control Center Automation.

"The SSCC software development team evaluate and implement applicable portions of the Level I Advanced Development expert systems into the baseline SSCC prior to MTC."

SSFP Response to ATAC:

"Following the semi-annual meeting of ATAC at the Johnson Space Center (JSC) (August 13-15, 1991), the Mission Operations Directorate, Space Station Ground Systems Division (SSGSD) prepared an integrated indepth review regarding the SSCC project schedules and plans relative to automation capabilities for the SSCC. This information was reviewed with ATAC members on December 10, 1991, and progress relative to that plan is discussed below."

"The approach proposed by the SSCC development project included four major areas of emphasis:

a. Detailed review and analysis of existing Level I Engineering Prototype Development activities which may provide early expert system models for SSCC evaluation/use.

b. Initiate an early analysis of commercial off-the-shelf (COTS) technology. This will include assessment of specific products of Artificial Intelligence (AI) development and run time environments to establish a most likely candidate for near term and future

use within the SSCC testbed and operational system.

c. Establish SSCC automation testbed capability for early stand alone development and assessment of AI Tools and to determine which existing expert system applications are suited for control center utilization.

d. Expand AI testbed functionality to allow for running expert system applications in parallel with realtime flight operations, as a means to verify expert systems for eventual operational use."

"The SSGSD has initiated efforts in each of the above areas. Initial assessments of Level I Engineering Prototype Development models for the thermal control system, electrical power system, and environmental control and life support system indicate potential applicability; however, existing models vary significantly in their use of AI environments. The Model Assessment Team (MAT) and the NASA SSCC development project are continuing their analysis and will make recommendations for SSCC rehost of specific Level I prototype models in the coming months. Since the ATAC review in December, the SSCC development personnel have met with NASA Headquarters/Code MT, and Ames Research Center (ARC) personnel to discuss SSCC prototype evaluation plans and SSCC Test Bed funding issues. In addition, the SSCC development project has established an early testbed activity in the SSCC facility to serve as the initial infrastructure for an AI assessment capability and to achieve compatibility between early prototyping and future operational system environments."

"The JSC Information Systems Directorate will conduct an independent assessment to establish the AI environment best suited for control center utilization assuming advanced development funding can be provided for that purpose. The SSCC testbed and expert systems model prototype assessment plan was reviewed with Level I and a tentative schedule and cost for the initial test bed capability was identified. A better understanding of the Level I Prototype Modeling activities was achieved and plans for continuing the assessment of these models were discussed. The final area of review was the potential for continuing Research and Development (R&D) tasks in the area of Mission Operation Automation, and for exploring potential tasks in this area for future funding with the Ames Research Center (ARC). It was concluded that the SSCC development project would identify the tasks which would best support the SSCC AI development approach and submit requests for R&D funding to the appropriate NASA offices."

"An initial meeting was also held with ARC personnel in December and a strawman list of potential research tasks was established. The areas considered most probable included status and control automation, and Fault Tree to Digraph conversion automation. It was concluded that some effort could be provided by ARC within scope of their current activities, but that some co-funding may be needed once a better understanding of the tasks is achieved. The SSGSD feels that progress has been made in each of the major areas of emphasis."

ATAC Assessment

SSFP does not currently evaluate and implement advanced automation functions in SSCC such as knowledge-based systems for fault detection and diagnosis, monitoring, and control prior to MTC as desired by ATAC. However, the SSCC has made excellent progress since August of 1991 in the development and initiation of a long range plan to incorporate advanced automation technologies into SSCC. An SSCC plan for knowledge-based system implementation and use has been initiated. Implementation of this plan will require additional monies which are difficult to obtain in the constrained budget climate. The SSCC AI Test Bed and knowledge-based system prototype evaluation efforts are positive steps. The current SSCC schedule does not show operational use of knowledge-based systems until PMC in 1999, some three years after MTC, which is overly conservative. With help from Level I Engineering Prototype Development, the OSSD Advanced Program Development, and the OAST AI efforts, it may be possible to accelerate this schedule sufficiently to have one or more knowledge-based systems evaluated and implemented in the SSCC by the MTC phase. ATAC urges this schedule reduction be addressed and accomplished, if feasible.

Recommendation II: Science Productivity.

"SSFP increase the level of expert consultation and assistance to the currently proposed life and material sciences experimenters on advanced A&R technologies to enhance science productivity and make the payload community more knowledgeable of A&R benefits."

SSFP Response to ATAC

"The SSFP is responsible for the design, development, and operation of a space-based facility that provides a set of users with the resources (e.g., power, volume, crew time, and computational

services) needed to perform scientific experimentation. It is left to the discretion of each user how to best maximize the resources allocated for their experiment and to select the appropriate technologies required to meet experiment objectives."

"The role within the Agency of advancing technology and highlighting its potential uses belongs to the Office of Aeronautics & Space Technology (OAST). This activity has the overall responsibility to showcase the benefits of A&R technology to the multitude of potential users within NASA. This includes, among others, users from the Office of Space Science & Applications."

"The SSFP is evaluating the benefits of payload automation to determine performance benefits and design accommodations required to support an increased level of automation. The Level I Engineering Prototype Development activity is sponsoring two projects with goals of introducing the payload community to the benefits of automation. The first is called the Astronaut Science Advisor and is a prototype Knowledge Base System advisory experiment protocol manager being developed at Ames Research Center and the Massachusetts Institute of Technology for a Spacelab-based vestibular physiology experiment, the Rotating Dome. This prototype has demonstrated that KBS techniques can significantly improve an astronaut's ability to perform in-flight science and provides protocol flexibility, detection of interesting phenomena, improved user interface for experiment control, real-time data acquisition, monitoring, and on-board trouble shooting of experiment equipment. Results of this task are being used to influence design requirements for Space Station Freedom laboratory experiment interfaces to ensure that analogous capabilities can be provided during MTC and PMC. The second involves analyzing Data System Management standard services and procedures needed to support SSF payload operations. This task is supporting the definition and demonstration of proposed payload interfaces, processors, and software development approaches. Results of these activities are shared with the payload community through forums like the Space Station Science Applications Advisory Subcommittee and symposiums like the Utilization Conference sponsored by the Space Station Utilization & Operations Division."

ATAC Assessment

The SSFP position is that they are responsible for the design, development, and operation of the space-based facility and the users should decide how best to maximize the resources allocated for their experiments. ATAC agrees with this position, however, **ATAC strongly encourages SSFP to take a more proactive role in explaining the features and performance capabilities of the baselined data system design and in providing consultation to the payload community.**

The science community is just now acquiring a basic understanding of the interface and operational constraints of the restructured SS particularly for the man tended phase. The Space Station Freedom Payload Accommodations Handbook (SSFPAH) and the Integration Requirements on Payloads (IROP) Documents are only in the planning and development stage with review scheduled for later this year. Early coordination and communication of the preliminary SSFPAH, IROP, the Engineering Prototype Development activities, the results of the SSF unmanned Operations Assessment, and the technologies being developed in the OAST A&R program to the OSSA committee will increase the technology transfer and application of advanced A&R for payload operations.

ATAC sent a representative to the Space Station Science and Applications Advisory subcommittee (SSSAAS) meeting in February. Some of the major issues and concerns were data recording, communications and payload interface to SSF, particularly the DMS and software development requirements.

The two examples given above are indications of the state of technology and awareness that exist in the science community relative to the use, capabilities and uncertainties of the Space Station Freedom. ATAC Report 13 attempted to address these concerns. In general, the science community users do not understand the interfaces, restrictions and capabilities of a system as complex as the Space Station. They do not recognize the benefits that automation may provide to assist them in the conduct of their experiments from a remote Earth-based workstation. Level I EPD is sponsoring the Astronaut Science Advisor and a Payload Software Development Initiative which specifically address the use of automation for payloads. Level I also has several activities that consider the data management system processor and network capabilities for the initial Station and its growth and evolution. Through these efforts and the ongoing close association with all Work Package contractors, the SSFP is the most logical choice to provide consultation to the science community on all aspects of the Station, including expert consultation services. This was not meant to imply that the SSFP should be involved in development, or review, of A&R functions wholly contained within an experiment. But, the SSFP should be taking a more active role in explaining the features of the baselined data system

design and the future plans for growth and enhancement. When there is an issue relative to the interface or integration of an experimenters A&R component to the Station facility services, the SSFP should be taking an proactive approach in expert consultation and assistance to the payload community.

Recommendation III: Robotics and EVA SSFP Maintenance.

"SSFP insure that external ORUs are robotic compatible and developed with standardized robotic interfaces on the assumption that SPDM will have the capability to support ORU changeout."

SSFP Response to ATAC

"On December 4, 1991, RSIS Volume II which specifies standardized robotic interfaces was baselined at the Level II Space Station Control Board (SSCB). In addition to the CSA/SPAR design H-Handle and Micro Interfaces, the WP2 requirement for a "micro-conical" interface was also baselined. One result of the SSCB was the selection of 118 Work Package 2 ORUs to be accommodated robotically in an end-to-end fashion. This could potentially save 83 EVA hours per year. These ORUs will be listed in Table 3-55 of the PDRD and will eventually become part of JSC 31000. A Level I Directive for funding to support incorporation of the RSIS Volume II interfaces for all ORUs identified in Table 3-55 is currently in preparation. An SPDM Interim Review with CSA is being conducted March 26, 1992 in Toronto, Canada to ensure that SPDM has the capability to support changeout of these ORUs. In addition, CSA/SPAR has conducted Technical Interchange Meetings with WP2 and WP4 to ensure that ORU designers are fully aware of planned SPDM capabilities and that SPDM designers are aware of ORU design requirements."

ATAC Assessment

On December 4, 1991 Space Station Level II baselined robotic maintenance compatibility for 42% of its external Orbital Replacement Units which represents over 50% of the projected EVA time required for maintenance. Due to the late decision, increased types of robot interfaces and tools will now be required to obtain this compatibility. However, at this point in time, the decision is a good one trading robot compatibility for design change costs.

Recommendation IV: SSRMS and SPDM Accommodations.

"SSFP insure that an appropriate process is established to fully integrate SSRMS and SPDM design into SSF plans."

SSFP Response to ATAC

"The SPDM is being integrated into SSF plans through joint CSA/NASA development of an SPDM System Requirements Document (SRD). Development of this document is being conducted in close coordination with all work packages and their contractors to ensure that the SPDM meets requirements for external ORU replacement tasks. Assistance in the design of Robotic Compatible ORUs will be provided as part of the "Robotic Integration Technical Area Management Plan" being developed jointly by Level II and the JSC A&R Division. In addition, NASA and CSA are negotiating an agreement to establish a "Robotic Systems Architect" to have Level II oversight of assembly and maintenance task integration and design worthiness/flight readiness certification for all SSFP Robotic Systems. These negotiations were scheduled to be completed at a meeting between the Deputy Director, SSF Program and Operations, and the Director General, Canadian Space Station Program, on February 27, 1992."

"WP2 hosted a four day activity in September, 1991 with CSA to redesign the Mobile Remote Servicer Base System (MBS) in an effort to make the MBS more consistent in function and capability with the "Restructured Station." One of the major outcomes of the redesign effort in terms of robotics and maintenance is the ability to service most of the WP2 ORUs designated for robotic accommodation with the SPDM directly from the MBS without the use of the SSRMS. The MBS can now be positioned by the Mobile Transporter (MT) on each Pre-Integrated Truss (PIT) segment inboard of the alpha joints and will serve as the berthing point for both the SSRMS and SPDM for most scenarios. In situations where the SPDM cannot reach the worksite when directly attached to the MBS, the SPDM will be operated from the end of the SSRMS. This latter situation has been minimized through the ORU robotic accommodation selection process in WP2 as very few of the ORUs are not on the Truss faces accessible by the SPDM/MBS combination. The MBS redesign was reviewed at the November 6, 1991 SSCB at which time the decision was made to implement the redesign with core system changes as proposed by WP2/CSA."

"In January 1992, the CSA/WP2 Bilateral Meeting was held at JSC to address and resolve common problems with the Mobile Servicing System

(MSS). This bilateral was significant for dextrous manipulation because the SPDM was elevated to "Team" status thus getting the recognition and management attention not seen in past bilaterals. Among the items agreed upon affecting the SPDM was the scheduling of a Technical Interchange Meeting (TIM) in February to be held at the WP2 prime contractor facility. This meeting will allow the robot provider and the ORU designer to discuss problems with robotic accommodation. Additionally, SPDM viewing requirements which surfaced at the SRD review were resolved and actions levied to resolve: SPDM micro-conical interface tool functionality and provision; the requirement for multiple speeds on the ORU Tool Changeout Mechanism (OTCM); and the development of a plan and schedule for the identification of the SPDM performance parameters."

ATAC Assessment

SSFP has aggressively initiated the writing, revising, and incorporating of Robotic System Integration Standards which establishes a process integrating the SSRMS and SPDM into Space Station Freedom maintenance plans. Assembly flight planning and simulation also incorporates robot capabilities.

Recommendation V: Level I Engineering Prototype Development.

"SSFP increase the Level I Engineering Prototype Development Program support for A&R technology contributions to the SSF baseline configuration."

SSFP Response to ATAC

"The FY92 Engineering Prototype Development (EPD) activity demonstrates cost, schedule, and technical risk reduction options and identifies minimum impact design accommodations. It is funded at the discretion of the Director, Space Station Freedom. While the EPD budget dropped by 5% in FY92, the approved funding level of $7M still represents an increase of almost 16% over the FY90 allocation. This activity is occurring in an era when the overall program was completely restructured in response to a major budget reduction. The EPD activity is reviewed and evaluated by the Director at least twice a year and sustains funding on the basis of its ability to show continued success in meeting its technical objectives and impacting baseline design, development, test, and evaluation."

"The EPD activity attempts to leverage joint funding from other NASA Codes and government organizations. Specifically, cooperative arrangements have been made with the Office of Aeronautics and Space Technology, Office of Space Systems Development Advanced Program Development, and the Defense Advanced Research Products Agency. Typically, the funding from these organizations pay for the advanced technology development while the EPD funds focus that technology development on Space Station applications. The EPD funds tend to cover the implementation and integration overhead associated with technology transfer. The activity also aggressively participates in those industrial Independent Research & Development (IR&D) and Small Business Innovative Research (SBIR) programs which address complimentary objectives of Engineering Prototype Development. This joint funding and coordination significantly augments the amount of resources devoted to building SSF A&R applications and enables EPD to have considerably greater impact within the Station program than its funding level would indicate."

ATAC Assessment

While the Level I Engineering Prototype Development (EPD) Program has not received any funding increase due to budget constraints, it continues to be highly productive in advanced A&R technology contributions and transfers to the SSF baseline configuration (see later section on A&R Status Review Assessment of Level I for some examples).

> **The Director, Space Station Freedom, is commended for support of advanced A&R technology transfer to, and inclusion in, the SSF. However, additonal EPD support for the SSCC testbed is needed in both the near and far term.**

ATAC feels additonal near term support would shorten the schedule for the SSCC evaluation and implementation of expert systems to the time frame of MTC.

A&R Status Review of Levels I and II; WP1, WP2, WP4; SSCC and POIC

Assessment of Level I.

The objectives of the Level I Engineering Prototype Development Program (EPD) are to enhance baseline

SSF flight and ground systems capabilities (through advanced A&R technologies) and to provide enabling (A&R) technology for SSF evolution. This program is the primary mechanism of advanced A&R technology transfer to, and inclusion in, the SSF. This program was approved for FY92 at a very modest level of funding, but it is still very productive.

Four examples of current EPD enhancement of baseline SSF flight and ground systems capabilities are: (1) optimization of the design of the Environmental Control and Life Support System (ECLSS) on-board sensor and instrumentation placement for better monitoring and diagnosis, (2) development and use of the Failure Environment Analysis Tool(FEAT), which provides fault modeling for Failure Modes Effects Analysis and supports diagnosis by ground controllers, with its use across the SSF by Level II and in realtime operations in SSCC, (3) development and use of a flat alignment target design for improved robotic system operations with less weight and easier access, and (4) development and transfer of Intelligent Computer Aided Training (ICAT) systems to the Space Station Training Office for use in the Space Station Training Facility, to provide cost effective training.

A major pending EPD enhancement of baseline SSF ground systems capabilities is the SSCC plan for expert systems using a SSCC AI Testbed as a transfer mechanism. This would capitalize on one or more of the EPD knowledge-based system testbeds: Electrical Power System Management and Control, Space Station Module/Power Management and Distribution, Thermal Control System Advanced Automation, Environmental Control and Life Support System, and the DMS Architecture Testbed. It may also leverage the EPD, OAST, and OSSD supported Real-Time Data System (RTDS) technology. This SSCC plan for expert systems needs Level I EPD funding to reduce the schedule to be compatible with MTC operational use of expert systems.

The SSCC AI Testbed should also be a focal point for the AI efforts of the OSSD Advanced Program Development and of the OAST AI program to enhance advanced automation technology transfer to the SSCC.

Two other pending EPD enhancements of baseline SSF flight and ground systems are the Integrated Station Executive(ISE) Advanced Scheduling System and the Automated Robotic Maintenance of SSF activity. Both address reducing costs of major operations aspects of SSF.

In summary, ATAC is encouraged at the Level I advanced automation insertion and pending insertions into the baseline SSF flight and ground systems as enhancements, which Level I EPD is producing, and urges its continuation and expansion if possible.

Assessment of Level II.

Major progress was achieved since the last ATAC report when the Level II Space Station Program approved for baselining the Robotic System Integration Standards (RSIS) Volume II. RSIS Volume I provides robotic accommodation requirements and the newly baselined Volume II provides robotic interface standards including drawings and design information for specific interfaces. These documents provide for robotic compatibility of 42% of Space Station Freedom's external Orbital Replacement Units (ORUs) which represents greater than 50% offloading of maintenance from Extravehicular Activity (EVA) to robotics. The $25 million cost impact of these changes has been forwarded for approval at Space Station Level I. This effort specifically addresses the ATAC Report 13 recommendation to ensure robotics compatibility for external ORUs. Although ATAC would like to see more than 42% of the Orbital Replacement Units made robot compatibile, this represents an acceptable programmatic tradeoff between robot compatibility and cost impact from design changes. However, a lesson can be learned from this process. If robot compatibility of Orbital Replacement Units had been required from the beginning of the Space Station Program, more Orbital Replacement Units would be robot compatible and require little special tooling at negligible cost. Most of the $25 million cost of making the ORUs compatible is for changing interfaces, tools and existing designs for ORUs which were not designed to be robot compatible. If standards and requirements are adopted earlier in a program, the redesign costs should be negligible.

The baselining of 50% of external Space Station maintenance requires an update of the Robotic Systems Integration Standards Volume I (requirements) which will be completed in the second quarter of 1992. Interface testing of designs for Robot-to-Orbital Replacement Unit compatibility is in progress at JSC/Oceaneering Systems and at Canadian Space Agency/SPAR Aerospace. The Space Station Level III organizations have been working with Canada in developing robot interfaces. ATAC expects the designated Orbital

Replacement Units will be made robot compatible and be successfully integrated into the program.

ATAC has recommended robot compatibility and standard interfaces since its first report to Congress in March of 1985, and is pleased that it has finally been incorporated into the program.

ATAC has several new and continuing concerns with Space Station Level II's Automation and Robotics Program. As ATAC has repeatedly pointed out, there is no defined Level II Automation Program. The SSCC plan for expert systems supports possible migration of these expert systems onboard through its operational use of these systems, but does not address migration onboard as a specific objective or element of the plan or schedule. Before the plan is finalized, ATAC urges Level II to adopt such an objective and coordinate the other required development activities to enable accomplishment.

ATAC is also concerned that Level II has decreased its workforce and time devoted to robotics. The Robotics Working Group, which was very active and successful in FY91, has been dormant in FY92. Although a Robotics Working Group "Splinter Group" was formed to address the feasibility and impact of Telerobotic Ground Control, little progress is evident. There are no schedule, goals, or milestones in the effort and it is ATAC's assessment that the Splinter Group effort will probably have little or no impact to the baseline program. ATAC has been flagging ground robot operations as a capability for Space Station since technical feasibility was established. The cost and impact of incorporating this capability will increase as the decision is pushed out further in time. This pattern is reminiscent of the ORU compatibility vicissitudes described at the beginning of this section.

The SPDM is being integrated into SSF plans through joint CSA/NASA development of a SPDM System Requirements Document (SRD). NASA and CSA are discussing a plan to establish a "Robotic Systems Architect" to have Level II oversight of assembly and maintenance task integration and design worthiness/flight readiness certification for all SSFP robotic systems. It is thus apparent that a process is now in place to integrate the SSRMS and SPDM into SSFP plans and to ensure an effective working relationship between WP2 and CSA.

Standardization progress was made in the change incorporated by the Japanese for the ORU "Option B" interface which allows ORUs to be picked up by the SPDM as well as the Japanese Small Fine Arm. This is a necessary capability and the leadership of Level II and cooperation by the Japanese is recognized as a good step forward. However, ATAC is concerned that not sufficient progress is being made in standardizing and integrating the NASDA space station robots. The end effectors and control systems are different which will result in different modes of operation, capabilities, control station layout, and "feel" of the robot system in operation. Multiple robot interfaces and control systems will complicate astronaut training, operations and maintenance.

The Space Station needs standards for robotics which apply to all work packages and all international partners.

The RSIS volumes are an outstanding start on these issues. However, the need for standards must be pushed to incorporate international partners as well as all work packages to simplify training and maintenance and to increase safety.

The Space Station Level II End-to-End EVA/EVR Maintenance Study to address maintenance task requirements including Unpressurized Logistics Carrier interfaces and operations concepts, ORU transport to and from worksites, and robotic setup/teardown of astronaut worksites is proceeding well. A schedule of milestones indicates study results will be available and reported to the Space Station Control Board by the end of April. Emphasis should be placed on making all logistics carriers and payloads robot compatible.

Assessment of Work Package 1

At the ATAC review meeting, Work Package 1 presented work at MSFC being supported by the Space Station Level I Engineering Prototype Development Program.

Excellent presentations and tours were given describing the advanced work being done to develop prototypes on the Space Station Environmental Control and Life Support System (ECLSS) Testbed and the Secondary Power Management And Distribution (PMAD) Testbed. The testbed shows a real possibility of deploying these technologies and aid supporting those Space Station subsystems from the SSCC and ESC. Details on the progress of these tasks is provided in Appendix A - Level I A&R Progress.

A lingering concern of ATAC is the elimination of "soft switches" from the laboratory power systems, requiring manual reset of circuit breakers. During MTC, circuit breakers cannot be reset until the crew returns.

Lack of a reset capability through the use of "soft switches" will constrain the utilization of the SSF laboratory environment by the science community during the MTC phase.

Work Package 1 did not present in any detail its support or interface for robotic interface standards. In particular, Work Package 1 needs to consider robotic compatibility with payloads on the Unpressurized Logistics Carriers. ATAC feels consideration should be given for unloading and handling Cryogenic supplies, dry supplies, and replacement ORUs by robotic systems.

Assessment of Work Package 2

Work Package 2 has made progress, in three areas, in addressing concerns expressed in previous ATAC reports. RSIS Volume II, which specifies standardized robotic interfaces, has now been baselined by the Level II Space Station Control Board (SSCB). A Level I directive for funding to support this action is currently in preparation. This action baselined 118 WP2 ORUs, which are thought to require 83 EVA maintenance hours per year, for end to end robotic accommodation. Robotic set up of EVA worksites to reduce EVA overhead is also baselined. The WP2 requirement for a "micro-conical interface" was also baselined in addition to the CSA/SPAR design H-Handle and Micro Interfaces. Work Package 2 hosted a meeting in September, with CSA, to redesign the Mobile Remote Servicer Base System (MBS) in order to make the MBS more compatible, in function and capability, with the restructured station. As a result of this redesign effort the Special Purpose Dextrous Manipulator (SPDM) will be able to service most of the 118 WP2 ORUs, that are baselined for robotic accommodation, directly from the MBS without use of the Space Station Remote Manipulator System (SSRMS). In servicing those ORUs for which the SPDM lacks sufficient reach, the SPDM will be mounted on the end of the SSRMS. These latter cases have been minimized by the WP2 ORU robotic accommodation selection process. Work Package 2 has conducted numerous meetings with CSA to establish and maintain a process to fully integrate the Canadian robotics into SSF plans.

The WP2 contractor maintains approximately a 2 1/2 person complement in advanced automation and robotics. This includes a modest amount of work in completing three advanced automation tasks. Some of this activity is expected to lead to improvements in flight software.

In summary ATAC perceives gratifying progress in the WP2 efforts to baseline robotic accommodation of ORUs and to integrate the Canadian robotics into SSF assembly and maintenance plans.

Assessment of Work Package 4

The Electrical Power System (EPS) consists of a flight support system onboard to control safety and time critical functions and ground-based dispatchers to perform the command and control decision-making activities to maximize productivity. The flight support system includes a significant level of automation for monitoring and control of the power and thermal condition of the EPS. Nominal operations are automatic including; detection, isolation, and reconfiguration of the system for failure control. Caution and warning conditions are automatically determined and enunciated. The ground controllers task is to maximize productivity of power management by load scheduling throughout the envelope of changing operational configurations including remedial options after a fault has occurred.

LeRC is developing an automation program to assist the ground control operators and engineers in the planning and decision making associated with power management control. In addition, as part of the Engineering Prototype Development Program they are integrating the power system testbed, the Engineering Support Center (ESC), and the automation products. Demonstrations of the automation products for failure detection and diagnosis and rescheduling after reconfiguration are being made within the testbed. These automation products will be used in the ESC if the prototypes prove their acceptability. ATAC views this as a significant activity that can lead to the incorporation of automation in an area of the SSFP that has potential for considerable cost avoidance.

ATAC commends the WP4 group for their effort in designing and testing the EPS ORUs for telerobotic replacement capability.

Their design approach was to utilize telerobotic manipulation for ORU replacement with EVA as a backup. Over 80 percent of the EPS ORUs will be robot compatible. WP4 have been an active participant in the Robotics Working Group effort to establish the Robotic Systems Integration Standards (RSIS) and are actively implementing the RSIS revisions with the goal of minimizing cost impacts to the SSFP.

Assessment of Space Station Control Center

This assessment is based on an integrated in-depth review prepared by the JSC Mission Operations Directorate and reviewed with the ATAC on December 10, 1991 and an update presented on February 25, 1992. Excellent progress has been made in regard to a more open-systems distributed workstation architecture for SSCC. Also, a SSCC expert systems plan has been initiated with prototype evaluation and AI Testbed activities. The SSCC is commended for its responsiveness and early progress.

ATAC's assessment of the SSCC expert system progress and lack of plans for implementation in operations prior to MTC is given in detail in the section on ATAC Assessment of ATAC Report 13 Recommendation I.

For robotics, the SSCC plan includes a console for (1) monitoring the Space Station Remote Manipulator System (SSRMS) and Special Purpose Dexterous Manipulator (SPDM), and (2) simulation modeling in advance of planned maneuvers. Plans for implementing collision avoidance and SSF "world" model verification and updating have not been reviewed by ATAC. Verification testing plans of the SSRMS/SPDM and their use in maintenance operations are other important aspects of robotics and SSCC of interest to the ATAC. Due to the issue of CSA/NASA roles and responsibilities which is being addressed by SSFP at Level II, the fidelity of the models available to SSCC for rehosting is unknown at this time.

Since SSFP has not identified a requirement for ground control of the SSF robotic systems, the SSCC has no plans for such a function. ATAC believes ground control may be needed and the SSCC baseline design may have to be modified to support implementation of ground control. However, ATAC did not review the progress of the ground control splinter group of the Level II Robotics Working Group. Therefore, an adequate assessment of this facet of the SSCC design could not be accomplished.

Assessment of Payload Operations Integration Center (POIC)

The review of the planning for the POIC was a major emphasis of the ATAC meeting held at MSFC on February 25-27. A full day was devoted to the POIC. The POIC will be located at the Huntsville Operations Support Center (HOSC) which is a facility that provides support to several programs.

The HOSC has been developed using a generic systems implementation philosophy. Each program's requirements are assessed to determine the similarities with other programs and implement configurable generic systems that meet common requirements. This minimizes the need for custom hardware and maximizes the use of general purpose, off-the- shelf system elements. The implementation of common requirements leads to: significant cost savings in development, operations and maintenance; and reliable efficient systems and operations. This approach is applied to all aspects of the HOSC; facilities, systems, and operations.

Although the Space Station will have considerable requirements for the HOSC, they will be incorporated into the generic system as another user. ATAC recognizes that this is a very cost effective methodology, but it provides only a limited opportunity to employ advanced automation technologies.

Each user will interface with the POIC system via a well defined and structured interface. The user or experimenter will be able to utilize his own hardware/software as long as it matches the interface. This provides the capability for the users to employ any automated systems that they desire or require. Space Station payload "users" have not yet been educated to the benefits of advanced automation tailored for their payloads.

The scheduling/planning software in the POIC will be an extension of that presently utilized on Spacelab-type missions. This system has been workable, but could be more automated. The POIC personnel are involved in an effort to assess the scheduling/planning technologies that are available within NASA. This may lead to enhancements of the POIC system in the future.

In summary, the POIC is being developed in a reasonable manner considering the very constrained funding limitations. However, advanced automation technologies that are available are utilized only to a limited extent.

New A&R Issues

Ground-Based SSF Science, Operations, and Maintenance

Space Station Control Center

The ATAC Progress Report 13 indicated that SSFP funding would not support the implementation of automation within the Space Station Control Center (SSCC). Subsequent to the Report 13 activity ATAC held discussions with the SSCC management and the manager of the Level I Engineering Prototype Development program. Current plans are for Level I to support the development of a Test Bed which would encourage demonstration and potential migration of automation products being developed in the Level I Engineering Prototype Development program, the Office of Aeronautics and Space Technology (OAST) Artificial Intelligence development program, and the Office of Space Systems Development (OSSD) Advanced Development Program.

ATAC recommends that the Level I Engineering Prototype Development manager coordinate an SSFP program effort with OAST to assure that applicable existing automation technologies are considered for the SSCC baseline system, and present a specific plan for the effort at the July 1992 ATAC review.

Payload Operations Integration Center

Current planning for development of the SSF Payload Operations Integration Center (POIC) includes the use of state-of-the-art software development tools and a distributed computer architecture which should allow the smooth implementation of automation techniques into the POIC operations and greatly reduce the ground support manpower. However, current plans do not include specific development and implementation of automation tools in the POIC baseline design. This is especially true of the use of new planning and scheduling tools where current plans are to use the existing Spacelab system through SSF MTC, with development of a new system to take place in 1995 through 1998 which will be available for use during PMC. It currently takes twelve hours for a re-plan function using the Spacelab planning and scheduling tool. The use of this tool for on-board SSF operations may not allow efficient use of the limited manned operations during the early stages of the SSF program.

ATAC recommends that SSF Level I Engineering Prototype Development manager determine if one of the existing advanced planning and scheduling tools being developed within their program or one being developed within the OAST program could be implemented for the POIC baseline operations.

On-Board SSF Science, Operations, and Maintenance

Science Productivity

During the ATAC review in August 1991, documented in Report 13, it was indicated that the science activities on-board SSF could be greatly enhanced through the use of automation and robotics, especially the use of on-board automation during the unmanned operational phase of the SSF. At the February 1992 ATAC review, it became evident that there has been little, if any, progress towards implementation of applicable automation and robotics technologies within the SSF Science operations and maintenance program to facilitate and enhance the scientific utilization of the SSF laboratory facilities during the MTC phase. ATAC concurs that it is not the responsibility of SSFP to provide "expert consultation and assistance to the currently proposed life and material sciences experimenters on advanced A&R technologies to enhance science productivity." However, ATAC feels that it is SSFP's responsibility to provide sufficient capabilities within the SSFP laboratory infrastructure to enhance and promote its effective utilization by the science community during the MTC operational phase.

ATAC recommends that SSFP coordinate and implement an integrated effort to facilitate and enhance the effective utilization of the SSF laboratory facilities for the conduct of material and life sciences during the MTC phase.

A&R Technology Evolution

Migration of Advanced Automation On-Board SSF

The ATAC Progress Report 13 recommended that SSFP increase the Level I Engineering Prototype Development Program support to assure that as much automation as possible be developed and implemented into the SSF baseline ground operations program. The current Level I program does not address the advanced development of automation technologies that will provide the ability to migrate automation from ground operations to SSF on-board operations, which was the SSF program plan proposed in the 1991 restructuring exercise. Without the development of a specific plan to address automation development for SSF on-board operations, automation will not be available for the Permanent Manned operational phase, which may greatly reduce the efficiency of SSF operations.

ATAC recommends that SSFP develop a plan including migration of advanced technology from ground control centers to on-board SSF to address supporting automation advanced development for the SSF PMC operational phase, and present the plan at the July 1992 ATAC review.

Flight Telerobotic Servicer Technologies

The FTS contractor, along with various FTS subcontractors, have made substantial progress in developing a technology base for a space telerobotic infrastructure. The contractors have taken numerous actions to disseminate information from this technology base to US industry. The last significant action was an Industry Briefing in 1990. The substantial resources invested in FTS warrant a focused activity to collect, and disseminate to US Industry and Academia, all of the worthwhile technology developed by the program.

ATAC recommends that SSFP strongly encourage OAST to organize and implement a timely process to preserve and disseminate, to U.S. industry, the technologies developed during the FTS Program.

ATAC Progress Report 14 Recommendations

Ground-Based SSF Science, Operations, and Maintenance

Recommendation I: Space Station Control Center (SSCC)

"The SSFP Level I Engineering Prototype Development manager coordinate an SSFP program effort with OAST to assure that applicable existing automation technologies are considered for the SSCC baseline system; and present a specific plan for the effort at the July 1992 ATAC review."

Recommendation II: Payload Operations Integration Center (POIC)

"The SSFP Level I Engineering Prototype Development manager determine if one of the existing advanced planning and scheduling tools being developed within their program or one being developed within the OAST program could be implemented for the POIC baseline operations."

On-Board SSF Science, Operations, and Maintenance

Recommendation III: Science Productivity

"SSFP coordinate and implement an integrated effort to facilitate and enhance the effective utilization of the SSF laboratory facilities for the conduct of material and life sciences during the MTC phase."

A&R Technology Evolution

Recommendation IV: Migration of Advanced Automation On-Board SSF

"SSFP develop a plan to address supporting automation advanced development for the SSF PMC operational phase, and present the plan at the July 1992 ATAC review."

Recommendation V: Flight Telerobotic Servicer (FTS) Technologies

"SSFP strongly encourage OAST to organize and implement a timely process to preserve and disseminate to U.S. industry the technologies developed during the FTS Program."

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Appendix A

Space Station Freedom Program A&R Progress

The Space Station Freedom Program (SSFP) is applying A&R technologies to the design, development, and operation of the baseline Space Station when found to be appropriate within the context of overall system design, to have a favorable cost-to-benefit ratio, and where the enabling technology is sufficiently mature. A&R technologies are experiencing rapid change, exhibiting varying levels of technology readiness, and have unique requirements for successful integration with conventional design approaches and system engineering methodologies. Consequently, the provision for design accommodations and mature technologies which permit the program to fully capitalize on A&R advances during the development and evolution of Space Station Freedom is an important consideration. As such, the program intends to leverage the significant momentum in A&R research and technology development within NASA, other government agencies, industry, and academia.

Progress by the SSFP is described in the following sections.

Level I Engineering Prototype Development

The Advanced Programs activity at Level I was initially divided into two major components, Evolution Studies and Advanced Development. A detailed overview of Advanced Programs was provided in ATAC Progress Report 7, Appendix B, "Overall Plan for Applying A&R to the Space Station and for Advancing A&R Technology." Additional information can be found in ATAC Progress Report 8, Appendix A, "OSS A&R Progress," and ATAC Progress Reports 9, 10, 1, 12, and 13 Appendix A. Advanced Programs has been reorganized within the Level I Space Station Engineering Division to reflect the priorities resultant from Program Restructuring. The Advanced Development Program has been retitled Engineering Prototype Development and placed within the Systems Development Branch of Level I Engineering. This move more closely ties advanced technology developments to baseline issues and concerns and facilitates the opportunity to insert new technology where appropriate. Evolution Studies has been placed within the Systems Engineering and Analysis Branch to more closely align growth and evolution concepts with baseline scenarios.

The Engineering Prototype Development activity enhances baseline Station flight and ground systems capabilities by prototyping applications of advanced technology. These improvements will lead to increased system productivity and reliability, and help constrain operations and lifecycle costs attributable to technological obsolescence. The activity evaluates and demonstrates technologies needed for Freedom's flight and ground systems. This is accomplished by building user/technologist teams within flight and research centers, developing applications using a mix of conventional and advanced techniques, addressing transition and implementation issues, and evaluating performance and documenting design accommodations for technology insertion and implementation. Specifically, cooperative arrangements have been pursued with the Office of Aeronautics and Space Technology; the Office of Space Systems Development Advanced Programs Development activity; the

Office of Space Science and Applications; DARPA; and other DoD programs.

As a result of these efforts, the SSFP is acquiring mature technologies, tools, and applications for key systems. In addition, performance specifications and design accommodations are being developed for the insertion of advanced technologies in both flight and ground systems.

Currently, the majority of the Engineering Prototype Development FY92 budget of $7.0M is dedicated to A&R applications and technology demonstration. Tasks are focused on fault detection and management, planning and scheduling, realtime telemetry distribution, advanced data management architectures, system and software engineering, and robotics. Twenty tasks are divided between four work elements; Flight and Ground Systems ($2.25M), Space Station Data Systems ($2.3M), Advanced Software Engineering ($1.125M), and Telerobotic Systems ($1.325M). Fourteen of the tasks are leveraged by joint funding from the Office of Aeronautics and Space Technology (OAST), the Office of Space Systems Development Advanced Programs Development, and the Defense Advanced Research Projects Agency (DARPA). The joint funding adds $7.4M to the tasks and enables Engineering Prototype Development to have considerably greater impact within the Station program than its funding level would indicate. Also worthy of note is the significant participation of Work Package contractors within the activity. Several have focused their own internal Independent Research and Development funding to address complimentary objectives of Engineering Prototype Development. The Small Business Innovative Research (SBIR) program is another significant facet of Engineering Prototype Development. Many of the activity's task managers participate in the SBIR program as proposal reviewers and task monitors. This joint funding and coordination significantly augments the amount of resources devoted to building SSF A&R applications, and facilitates technology transition to the baseline station.

In the Flight and Ground Systems area, advanced fault detection and management applications are being developed for Power Management and Distribution (PMAD) and Environmental Control and Life Support System (ECLSS) for Work Package 1, the Thermal Control System (TCS) and applications for the Mission Control Center (MCC) and Space Station Control Center (SSCC) at Work Package 2, Power Management and Control (PMAC) at Work Package 4, and a Spacelab scientific experiment. The applications focus heavily on Fault Detection, Isolation and Reconfiguration (FDIR) and provide a range of support in system status monitoring, safing, and recovery. All are a mix of conventional and Knowledge-Based System (KBS) techniques and each provides a powerful user interface to support interactions in an advisory mode. The primary benefits of these applications are improved system monitoring, enhanced fault detection and isolation capabilities, and increased productivity for SSF mission control personnel and crew members. Increased system reliability via the detection and prevention of incipient failures, reduced IVA maintenance time, and better monitoring with fewer sensors are added benefits of advanced FDIR techniques.

These tasks provide an understanding of the design accommodations required to support advanced automation (e.g., instrumentation, interfaces, control redundancy) and identify KBS simplementation issues (e.g., integration of KBS and conventional algorithmic techniques, processing, data storage, communication requirements, and software development, testing, and maintenance procedures) required for KBS development and support. As more and more functions are scrubbed to a ground implementation, the value and importance of these tasks increase, for they provide the necessary R&D foundation to develop ground-based capabilities and to later migrate those functions back to space. The most significant accomplishments of this reporting period follow.

Advanced fault management knowledge based systems have been hosted on the WP4 Power Management and Distribution (PMAD) testbed and are currently supporting baseline evaluations of the primary power distribution system. The capability of scheduling an initial load set and then reprioritizing that set to produce a new schedule after faults have been detected has been demonstrated. This FDIR application is also serving as a bridge between the baseline testbed and the LeRC Engineering Support Center which will support SSF power system operations.

Advanced fault management knowledge based systems have been hosted on the Marshall Space Flight Center (MSFC) PMAD testbed and are currently supporting MSFC assessments of the baseline secondary power distribution system. This capability complements the WP1 prime contractor's evaluation of secondary PMAD.

Advanced fault management techniques are currently supporting the ECLSS Predevelopment Operational System Test (POST). POST activities have concentrated on the ECLSS Air Revitalization Subsystem. A knowledge-based system, with a powerful user

interface, has been added to the POST testbed to support baseline system performance evaluations. Advanced technology from JPL to improve the placement of ECLSS sensors and provide predictive monitoring capabilities has been well received and is currently being used to effect design trades. An overall sensor placement framework which uses monitorability and diagnosability metrics has been developed.

The Thermal Control System (TCS) advanced fault management project has been integrated into the baseline TCS testbed at Johnson Space Center to support the TCS verification process. Communications between the DMS-like software and the thermal testbed data collection software have been established and tested during ambient and thermal vacuum tests. The knowledge based system has already shown worth by improving the TCS test engineer's ability to detect and diagnose system anomalies. Different colors within the high fidelity simulator schematic (fig. A1) represent either fluid phase changes or valve position. The TCS KBS schematic (fig. A2) provides a browser function which allows quick and direct access to various levels of schematic detail as well as other system displays. Pertinent monitoring and control information can be viewed, plotted, and manipulated using only the mouse plotter.

The Space Station Control Center is currently assessing the feasibility of using EPD fault management models for SSF operations and is developing a plan to integrate and evaluate these fault management projects within the control center architecture. The Real Time Data Systems (RTDS) project continues to expand and make significant improvements within Space Shuttle Mission Operations. The RTDS network now distributes real time telemetry data across the JSC local area network, proving that office based mission monitoring is a realistic consideration for control center architectures. RTDS software is now portable across a variety of major UNIX workstation vendors which minimizes control center hardware dependencies.

A prototype KBS advisory experiment protocol manager has been developed at Ames Research Center (ARC) and the Massachusetts Institute of Technology (MIT) for a Spacelab based vestibular physiology experiment, the Rotating Dome. This prototype demonstrated that KBS techniques can significantly improve an astronaut's ability to perform in-flight science and provides protocol flexibility, detection of interesting phenomena, improved user interface for experiment control, real time data acquisition, monitoring, and on-board trouble shooting of experiment equipment. The system, known as the Astronaut Science Advisor (fig. A3), was ground-tested in the Spacelab Baseline Data Collection Facility and was used to support the SLS-1 mission on STS-40. The prototype will be flown and used in-flight on SLS-2 during the STS-63 mission.

Within Space Station Data Systems, the computer and network architectures of Space Station Freedom's Data Management System are being analyzed to provide increased performance and reliability and to determine long-range growth requirements. Additionally, advanced mission planning and scheduling tools are being developed and

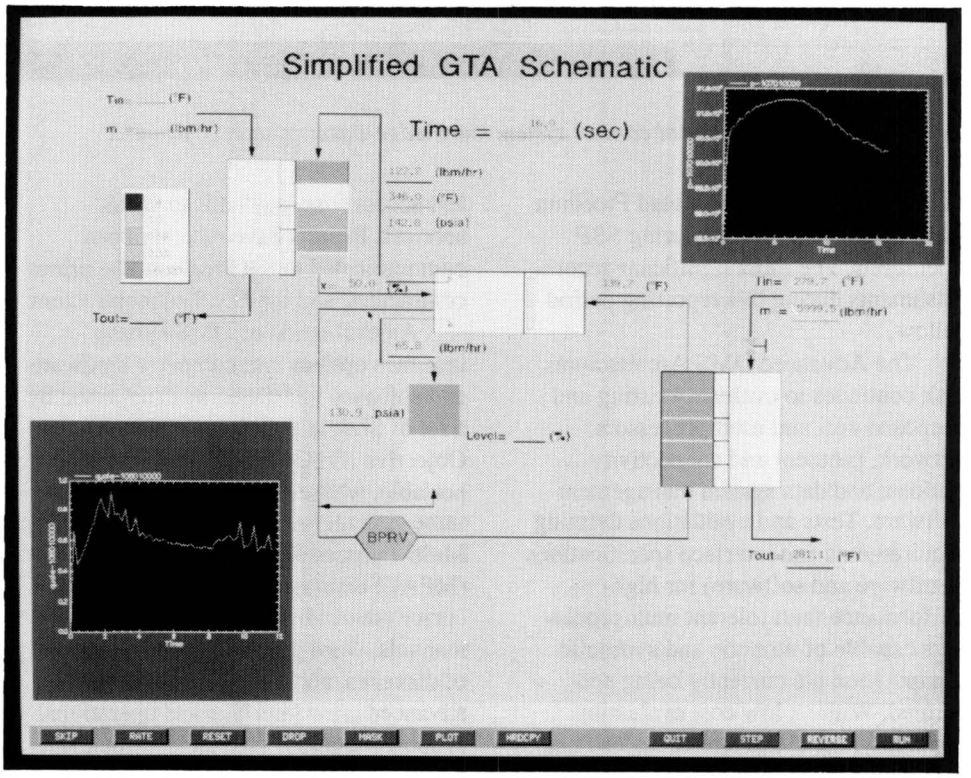


Figure A1. Thermal control system high fidelity simulator simplified schematic.

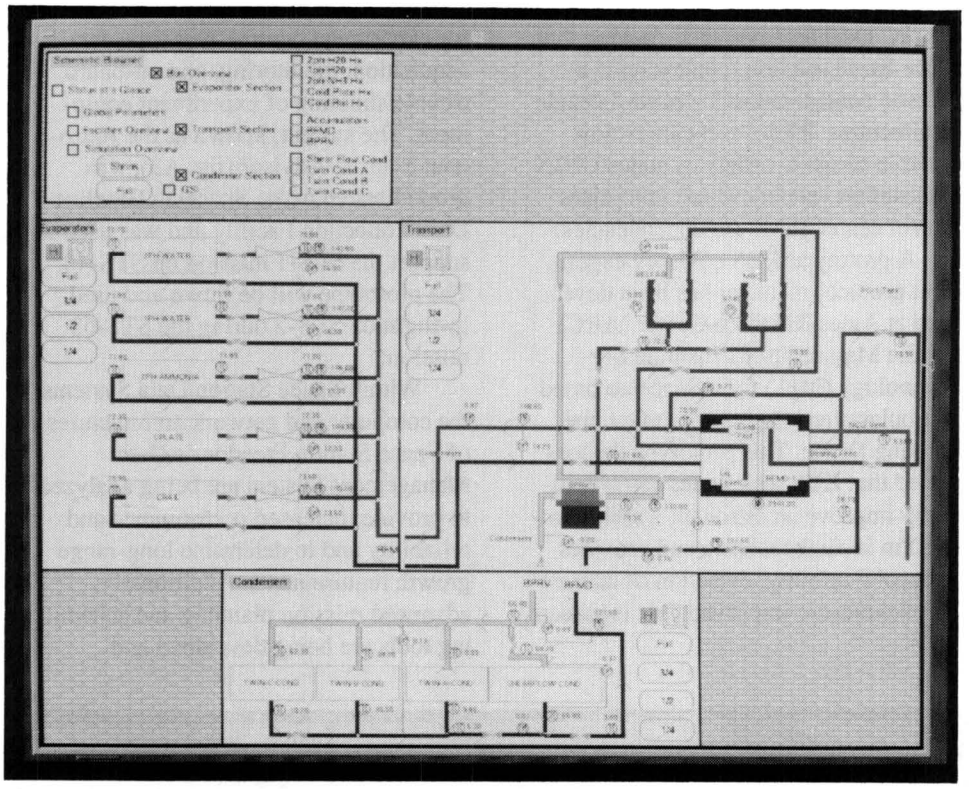


Figure A2. Thermal control system knowledge-based system schematic.

demonstrated for use on-board Freedom as well as on the ground during SSF operations. The most significant accomplishments during this reporting period follow.

The Advanced DMS Architectures task continues to evaluate existing and proposed uni- and multiprocessors; network, protocol and connectivity options; and data system management software. Tests and evaluations defining requirements and interface specifications (hardware and software) for high-performance fault tolerant multiprocessors capable of numeric and symbolic computation are currently being performed. With its low cost evaluation capability, the architectures testbed has provided focus for early verification of baseline and payload interfaces and to test access from payloads to DMS services. Results have recently been communicated to the Program, the prime contractors, and the DMS subcontractors.

An evaluation of DMS system interface options and computer hardware and software interfaces was supported by a set of Shuttle Development Test Objective (DTO) tasks. A Macintosh portable, whose display format has the same general look and feel of the baseline Multi-Purpose Application Console (MPAC) display, was used to evaluate cursor control hardware, use of on line manuals, word processing, management of diskettes, and a number of other advanced crew interface and operational support capabilities. Results of the evaluations were forwarded to the work package contractor responsible for MPAC development and were subsequently used to improve the MPAC design.

The COMputer Aided Scheduling System (COMPASS) continues to improve in functionality and be used in a variety of scheduling applications. It is being used as a backbone for building consensus within the SSF scheduling community. It is currently being evaluated for its ability to schedule facility resources and crew training time. Because of its Space Station relevance, the JSC Shuttle Engineering Simulator (SES) has been targeted to demonstrate facility resources scheduling. This application is nearing completion. The work package prime contractor has already selected it to schedule time within their SSFP facilities.

In Advanced Software Engineering, software tools, methodologies, and environments are being pursued to support the design, development, and maintenance of SSFP advanced software and system engineering applications. The most significant accomplishments during this reporting period follow.

The Failure Environment Analysis Tool (FEAT) is the standard SSFP tool for integrating and documenting system and subsystem Failure Modes Effects Analysis (FMEA) and hazard analysis data. This tool uses directed graphs (DiGraphs) to model cause and effect relationships providing significant benefits over fault trees (fig. A4). Digraphs can be useful and instructive in all program phases. During development, digraphs help engineers understand the strengths and weaknesses of the overall design. In the operational phase, these models can be used by mission controllers to quickly identify and display the possible causes of malfunctions. Mission controllers can use FEAT in the Space

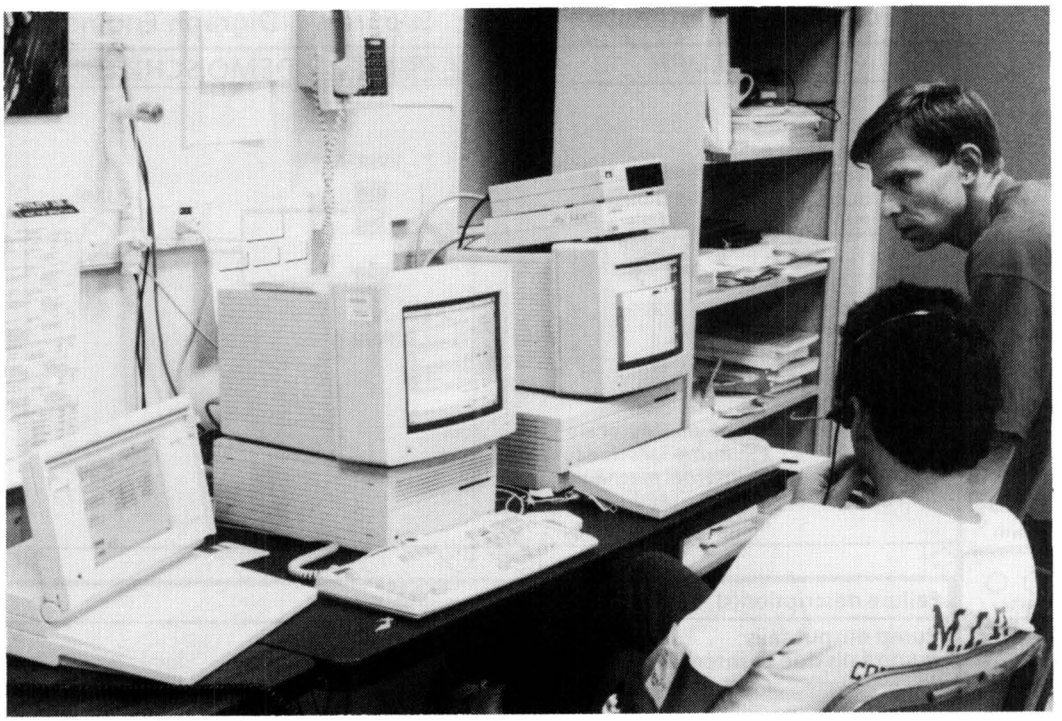


Figure A3. Astronaut Science Advisor system analyzing flight data on STS-40 Shuttle mission.

Station Control Center to monitor operations over the station's entire life. As a training tool, operators can quickly learn the capabilities and vulnerabilities of a system. They will be using digraphs in FEAT, with accompanying schematic drawings and data base information, to speed up and simplify their learning process. During the SSFP MTC Phase Review, FEAT was used to support the Station reboost function. It was also recently selected by the Space Station Control Center to support their Failure Detection Management (FDM) System.

A small proof-of-concept testbed has been established to evaluate alternative techniques for managing and conducting flight software reconfiguration that constrain software lifecycle costs. Currently, the testbed is evaluating the reconfiguration potential of the flight configuration database (MODB) displays and controls datafile using commercial-off-the-shelf hardware and software techniques.

A series of intelligent training systems are scheduled to be prototyped for the Space Station Training Office (SSTO) to demonstrate the value of Intelligent Computer Aided Training (ICAT) architectures and their feasibility for baseline training operations. The first prototype being developed is for training on the SSF Thermal Control System. Additionally, ICAT tools have been provided to the SSTO for further evaluation and support of baseline training requirements. This technology is a strong candidate for commercialization. In fact, tutors to support high school math and science courses and adult literacy classes are already being demonstrated.

Telerobotic Systems focuses on the reduction of intravehicular activity (IVA) teleoperation time for dexterous robotics tasks, even in the presence of significant communications or computation time delays. Advanced telerobotics reduces an operator's workload by allowing the robot to control fine parameters (such as force exerted against a surface) while the operator directs the task. With improved sensing, planning and reasoning, and displays and controls, simple tasks like unobstructed inspections and translations may be accomplished by remote operators in the presence of significant communications time delay. Supervised autonomy can help free the on-orbit crew from routine, repetitive, and time consuming inspection and maintenance tasks whenever possible. The most

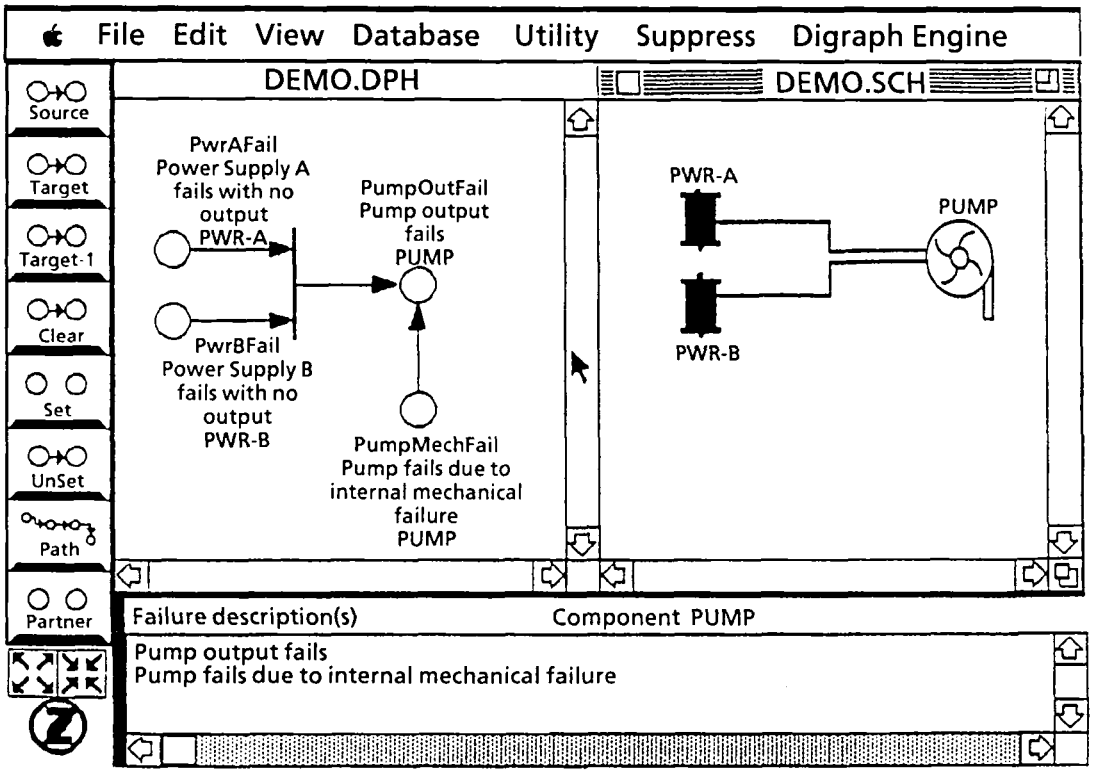


Figure A4. Failure environment analysis tool schematic and its digraph equivalent.

significant accomplishments of this reporting period follow.

Shared control software algorithms that permit simultaneous human and computer-generated control, local/remote control algorithm partitioning to handle time delay, User Macro Interface (UMI) software to build and execute sequence of task steps (macros) under supervised control, and Operator Coached Machine Vision (OCMV) to allow humans to correct and update vision based world models have been developed and extensively tested on the JPL Telerobotics Testbed. These technologies are being transferred to the integrated PIT-segment dual-arm workcell under development at JSC. JPL and JSC are now working cooperatively to link their two telerobotics labs together over an existing Internet network so that robotic simulations can be driven remotely from either of the two sites.

To allow collision prediction and avoidance within a reduced computational environment, work continues on the evaluation of capacitance-based proximity sensors. Four-element capacitive reflector sensor skin arrays have been installed on both Puma 762 and RRC 1607 robot arms. The array is constructed entirely from flight proven materials and coatings. The array's built-in control logic stops the robot up to 12 inches from a sensed object (any dielectric or conductor) and maintains that distance regardless of lighting or humidity. Capaciflectors have been shipped to JSC for integration into their testbed and are currently undergoing further evaluation.

The flat target project has made significant progress. This activity is prototyping a series of robotic targets which offer substantial savings within weight and volumetric constraints. It has received strong endorsements from Level II for its potential savings on SSF ORUs and payloads. Flat target prototypes using microstructures have been designed, fabricated, and environmentally tested. A flight demonstration is currently being planned.

Level II A&R Progress

Level II dedicates two full-time civil servants, several part-time civil servants,

and a number of support contracting personnel to manage the insertion of A&R technology within the baseline program. These individuals are responsible for ensuring integration across Work Packages and International Partners (e.g., Orbital Replacement Unit (ORU) Standards, Direct Current to Direct Current Converter Unit (DDCU) location, Mobile Servicing System (MSS) Delta PDR issues). They also address issues with impact at a programmatic level such as hand controller commonality, SSF/robotic dynamic interactions, and verification. Additionally, overall on-orbit assembly and maintenance responsibility resides at Level II.

Robotics integration is being defined as an SSFP Technical Management Area. It is roughly analogous to an Architectural Control Document (ACD) Agent, except emphasis is placed on integration and verification rather than on hardware development. This allows for the exploitation of the expertise and resources available at NASA field center line organizations, for example the JSC Automation and Robotics Division. Robotics integration is logically divided into Robotic Maintenance/Servicing Task Integration, MSS Integration, and other (e.g., Japanese Experiment Module (JEM) Remote Manipulator System (RMS) Integration, Program-level studies, Change Requests, etc). The robotics integration Technical Area Manager is proposed to become responsible for Robotic Systems Integration Standards (RSIS) Volumes I and II, the Dexterous Task List, the Mobile Servicing Center (MSC) and Special Purpose Dexterous Manipulator (SPDM) System Requirements Documents (this is a joint responsibility with the Canadian Space Agency (CSA)), the robotics section of the Program Master Verification Plan, and chairing the Robotics Working Group. The Technical Area Manager would be made the NASA integrator of the MSS and JEM RMS into the SSFP.

Since ATAC Report 13, RSIS Volume II and PDRD Section 3 Table 3-55 were approved for baselining at the December 4, 1991 Space Station Control Board (SSCB). Table 3-55 is the mechanism for identifying ORUs to be made robot compatible. A total of 359 ORUs which represents 42% of SSFP external ORUs have been identified and represents a 50% offload of EVA to robotics. The RSIS Volume II document is currently being updated to incorporate the modifications agreed to during the SSCB. The RSIS Volume I Robotic Accommodation Requirements is also being updated and will be released as Revision A. Robot-to-ORU and ORU-to SSF interface testing is in progress at JSC and CSA/SPAR. These interfaces include the SPAR micro, SPAR H-Handle, SPAR target, and OSS microconical. The dextrous task list has been further refined through the cooperation of the work package managers, international partners, and Level II.

The End-to-End EVA/EVR Maintenance study has placed heavy emphasis on particular components of EVA/EVR maintenance tasks. Overall end to-end tasks such as Unpressurized Logistics Carrier (ULC) interfaces and operations concepts, ORU transport to/from worksite on MSS or CETA, and EVA worksite setup/teardown by robotics requirements are not as well understood and are significant contributors to EVA maintenance overhead. Further definition of ULC-to-ORU interfaces to include subcarriers for multi-ORU sorties, and incorporation of robot compatible designs for EVA support equipment will continue.

The Robotic Ground Control Splinter to the Robotics Working Group has now met four times. Presentations have been given on available SSF support, candidate control tasks, roundtrip communication latency, and available funding for testing. There are no significant issues concerning the availability of support, however several minor problems need to be resolved. Current issues concerning redundancy management in the Canadian Robotic Systems which preclude robotic ground control are being studied. Candidate ground control tasks include inspection, EVA worksite setup, ORU replacement, and manipulator checkout. A test plan is currently being developed to perform a combined inspection/ORU acquisition and stowage task with a roundtrip video delay of 6 seconds and a roundtrip telemetry delay of 9 seconds in the JSC Robotic Systems Evaluation Lab (RSEL). Actual testing should occur in May, 1992 with a final report and recommendations available by July, 1992.

Work Package 1 A&R Progress

Work Package 1 activities in A&R are limited to the Level I Engineering Prototype Development sponsored projects in Space Station Module Power Management and Distribution and Environmental Control Life Support System fault management. MSFC has conducted in-house experiments with advanced materials processing robotics but such activity has been limited due to funding constraints. Baseline robotic activities have concentrated on support to program-wide robotic interface standards to ensure the compatibility of Work Package 1 ORUs to the ULC and SSF robots.

The Work Package 1 Prime Contractor is independently seeking ways to

increase crew effectiveness and productivity by using automation and robotics. Restructuring has resulted in a longer man tended phase of SSF which presents a golden opportunity for scientific use of the microgravity environment. Advanced automation and IVA robotics can be applied to increase experiment utilization during this phase. Particularly suitable to robotics application are materials transfer and packaging, experiment loading and unloading, limited remote operation of lab equipment, and remote maintenance inspection. After the Permanently Manned milestone is reached, crew time will continue to be in great demand. The man tended phase can be used as a period to prove the capabilities of advanced embedded automation and robotics and verify both the low level of risk and enhanced station operational capabilities expected from robotics application prior to the permanently manned phase.

Work Package 2 A&R Progress

The following sections describe the organization for automation and robotics being developed within Work Package 2 at both JSC and MDSSC under internal funding and the prime contract.

Space Station A&R is centered in the Project Integration Office of the Space Station Projects Office. This office is responsible for defining requirements for A&R; the actual implementation is done by the various system and element organizations. Engineering management support from the institution comes from the A&R Division's Chief Scientist who is also the Functional Area Manager (FAM) for A&R. Support for integration of the Canadian robotics elements with Work Package 2's mobile transporter is provided by both the project office and the institution. To support Work Package 2 A&R activities, JSC has formed an A&R Division with four branches: Intelligent Systems, Flight Robotic Systems, Robotic Systems Technology, and Space Systems Automated Integration and Assembly Facility (SSAIAF). The requirements tracking, integration analysis, technical management, and liaison for robotics comes from the Flight Robotic Systems Branch.

The WP2 prime contractor's A&R effort thus far has been to ensure that hardware developed within this work package will be designed as to make effective use of the robotic systems aboard SSF. The WP2 robotics implementation program was developed jointly between JSC and MDSSC. It consists of making a high maintenance group of ORUs robot compatible, developing EVA tools which would interface with the robot handles, and making EVA worksite equipment capable of being set-up and installed by the Special Purpose Dexterous Manipulator (SPDM). The group of ORUs selected (118 total) to be made compatible includes 6-B Avionics ORUs, Thermal Control System Fluid Box ORUs, and Supplemental Reboost System Waste Gas Fluid Box ORUs. Although these ORUs account for only about 25% of the total ORUs within this work package, they represent almost one-half of the total maintenance replacement activity that is projected to occur during operation.

While there is no strong contractual obligation or requirement for advanced automation, the prime contractor has been working to ensure that technology point solutions can influence baseline design. The prime contractor has supported a wide variety of advanced automation efforts in the past, but only the following activities are currently being developed: Thermal Control System Automation Project (TCSAP), Data Management System (DMS) Fault Detection Isolation and Recovery (FDIR) prototype, Integrated Systems Executive Caution and Warning Synthesis, and a medical decision support system.

The TCS automation project is a joint activity with SSF Level I Engineering Prototype Development. The development of this project is on schedule, and is currently meeting very difficult technical milestones. The ultimate success of this project will depend upon its ability to integrate its products effectively into the baseline program.

The DMS FDIR expert system prototype has been completed and its results documented. The group responsible for the development of this application is now responsible for producing the Flight System Software Requirements (FSSR) for the FDIR portion of DMS system management. This will ensure that the knowledge captured in the prototype system will be incorporated onboard the SSF platform.

The application of advanced automation technology in the ISE software has been deferred because of program restructuring. The function that had originally been targeted has not yet reached the design phase. Although the ISE still has the Caution and Warning (C&W) Synthesis function in its PMC baseline, a particular solution has not yet been determined. In order to stay within the allocated budget, consideration is being given to a minimal approach using a simple pattern recognition technique to synthesize a C&W message from other C&W messages.

An evaluation prototype of a medical decision support system has been developed. Since there are not sufficient resources to integrate this system into the

on-board platform, it is planned to install the application, along with other medical decision support systems, onto a portable computer for evaluation by NASA medical personnel in a clinical environment.

Work Package 4 A&R Progress

The automation activity within Work Package 4 has been concentrated on partitioning control decisions for the electric power system into four decision-making entities. The first, the flight support system, is responsible for issuing the commands to the electric power system aboard the space station. It monitors the system's status and prompts the flight controller for appropriate responses. The three other systems are used to aid the command and control activities of the flight support system by performing detailed event analyses and operations planning, and it is these three systems that efforts to introduce automation have been focused.

The Work Package 4 Engineering Support Center will be used to evaluate the impact of these decision support systems in a ground control environment. This facility features a real-time data system with an open, distributed architecture. In this environment, the focus will be on total power system operations and the evolution of automated decision aids that have the same look and feel as the baseline's proposed control products. This provides a common basis for measuring the benefits of automating diagnosis, security analysis, and resource scheduling.

These capabilities have been hosted directly onto the LeRC Space Station Freedom Power Management and Distribution (PMAD) testbed as a preliminary step before introducing them into the Engineering Support Center. This initiative develops the interfaces that are required to build a communication path between the machines running the automation software and the power testbed's prototype flight control computer. Further, this approach defines the communication requirements for integrating the testbed with the Engineering Support Center. Since the last report, a failure detection and diagnosis system (TROUBLE III) was combined with an automatic scheduling algorithm (BID) to restore power after short circuits had been cleared by circuit breakers. This failure demonstration used the LeRC Space Station Freedom PMAD testbed as its source of real-time data. In addition, this activity developed the requirements for communications between the testbed's flight control computer and the automation software. Based on these requirements, communications are currently being established between the PMAD testbed and the Lewis Engineering Support Center. Data will flow from the testbed through the ESC into TROUBLE III for failure detection and diagnosis. A common user interface, built on the ESC's Silicon Graphics machines, will display testbed functional status utilizing information from TROUBLE III. Work continues on incorporating battery operations and load management into this ground operations environment.

Rocketdyne, Inc. is pursuing a baseline design for the on-board automation which has automatic regulation of battery charging according to specified maximum profiles, closed-loop control systems regulating battery temperature, beta gimbal position control, and array voltage regulation. All of these automatic control systems require set-points specified by ground control. High level requirements have been stipulated for the software that aids the operating personnel to issue the appropriate supervisory commands.

Rocketdyne is also pursuing health monitoring, failure diagnosis, and human interfaces in their IR&D program. A power system advisory controller (IPAC) has been integrated with a detailed simulation of the power system. This simulation produces a telemetry stream which is received by the IPAC. Taken together, they emulate the data retrieval process of a ground support system. The IPAC currently detects analog measurement discrepancies resulting from single point failures. Its capabilities will be extended to include multiple failures and trend analysis.

The robotics effort of Work Package 4 has focused on increasing the level of robotic compatibility as the designs of the robotics systems and the WP4 orbital replaceable units continually mature. The goal is to achieve viable telerobotic maintenance scenarios for each ORU with EVA as the backup. Currently over 80% of Work Package 4 ORUs are designed to be robotically compatible. Examples include the Main Bus Switching Unit, battery, DC to DC Converter Unit, Photovoltaic Blanket and Box, and Remote Power Converter Modules. As designs mature, they are continually verified by computer simulation of ORU installation and removal, by zero gravity telerobotic tests at Oceaneering Space Systems, and by zero gravity EVA tests at JSC's Weightless Environment Training Facility (WETF). These investigations check the adequacy of the design for: handling, alignment and visual cues, as well as mechanical and thermal integrity. Also, WP4 researchers have actively participated in interface design reviews, technical interchanges with CSA, and various ad hoc working

groups addressing robotics and EVA. WP4 has implemented the RSIS interfaces and has supported the development of RSIS as a baseline requirements document that provides design standards for implementing robotic solutions to the SSF maintenance needs.

Mission Operations Projects Office A&R Progress

Automation and Robotics technology use within the Mission Operations Projects Office (MOPO) is driven by the needs of operators to monitor, command, and control the various distributed systems and subsystems of Space Station Freedom.

There are currently four activities underway within MOPO that involve or impact A&R technology. The Space Station Control Center (SSCC) Status and Control Subsystem has been targeted as a likely candidate for advanced technology utilization. A commercial-off-the-shelf network manager to provide core functionality within the Subsystem has been baselined. The definition of knowledge base requirements and design accommodations is continuing. The baseline SSCC scheduler Planning and Scheduling System (PSS) is another effort within the control center suitable for advanced technology insertion. The Extended Real-time FEAT (ERF) project leverages off the development program's production of directed graph models. ERF provides a real time fault analysis capability by emulating mission controller interactions with FEAT using real time data. The requirements definition of ERF has been completed. Finally, a Consolidated Communication Facility (CCF) is being established for the SSCC and Shuttle-based Mission Control Center (MCC). This CCF provides a common front end to both the SSCC and MCC and is expected to save 15% in development and 30 to 40 engineering personnel in operations between the two control centers. MSFC and KSC have expressed an interest in this design concept. This common front end will encourage and facilitate technology sharing between NASA Centers and flight programs.

Following the semi-annual meeting of ATAC at the Johnson Space Center (JSC) (August 13-15, 1991), the Mission Operations Directorate, Space Station Ground Systems Division (SSGSD) prepared an integrated in-depth review of the SSCC project schedules and plans relative to automation capabilities for the SSCC. This information was reviewed with ATAC members on December 10, 1991, and progress relative to that plan is discussed below.

The approach proposed by the SSCC development project included four major areas of emphasis:

a. Detailed review and analysis of existing Level I Engineering Prototype Development activities which may provide early expert system models for SSCC evaluation and use.

b. Initiate expert systems environment selection. This will include assessment of specific products of Artificial Intelligence (AI) development and run time environments to establish a most likely candidate for near term and future use within the SSCC test -bed and operational system.

c. Establish SSCC automation test bed capability for early stand alone development and assessment of AI Tools and to determine which existing expert system applications are suited for control center utilization.

d. Expand AI testbed functionality to allow operational flight following, i.e., running expert system applications in parallel with real time flight operations, as a means to verify expert systems for eventual operational use.

The SSGSD has initiated efforts in each of the above areas. Initial assessments of Level I Engineering Prototype Development models for the thermal control system, electrical power system, and environmental control and life support system indicate potential applicability; however, existing models vary significantly in their use of AI environments. The Model Assessment Team (MAT) and the NASA SSCC development project are continuing their analysis and will make recommendations for SSCC rehost of specific Level I prototype models in the coming months. The SSCC development project has established an early testbed activity in the SSCC facility to serve as the initial infrastructure for an AI assessment capability and to achieve compatibility between early prototyping and future operational system environments.

The JSC Information Systems Directorate will conduct an independent assessment to establish the AI environment best suited for control center utilization. The SSCC testbed and expert systems model prototype assessment plan was reviewed with Level I and a tentative schedule and cost for the initial test bed capability was identified. An initial meeting was also held with OAST Artificial Intelligence Intercenter Working Group members and a strawman list of potential research tasks was established. The areas considered most probable included status and control automation and Fault Tree to Digraph conversion automation.

Payload Operations Projects Office A&R Progress

Automation and Robotics technology use within the Payload Operations

Projects Office (POPO) is driven by the need to provide operational communication, computation, and display services for MSFC based SSFP activities. These activities involve the SSF Payload Operations Integration Center (POIC), the SSF Work Package 1 Engineering Support Center (ESC), and the SSF User Support Operations Center (USOC).

Technologies to support POPO activities revolve around a set of development methodologies and design strategies. System modeling and automated software development tools and techniques are central to achieving increased quality and productivity and constrain lifecycle costs. A variety of design strategies are being pursued which should enable the development of an architecture that is open, flexible, and responsive to the vast set of payload operations requirements. These strategies include exploring distributed computing, developing suitable user interfaces, performing system validation, managing data bases, monitoring & controlling system status, following standards, and building a generic core system.

Acronyms

ACD	Architectural Control Document
COMPASS	COMputer Aided Scheduling System
C&W	Caution and Warning
DDCU	Direct Current to Direct Current Converter Unit
ERF	Extended Real-Time (FEAT)
ESC	Engineering Support Center
FAM	Functional Area Manager
FDM	Failure Detection Management
FEAT	Failure Environment Analysis Tool
FSSR	Flight System Software Requirements
ICAT	Intelligent Computer Aided Training
IPAC	Power System Advisory Controller
JEM	Japanese Experiment Module
MAT	Model Assessment Team
MDSSC	McDonnell Douglas Space Systems Company
MODBN	Mission Operations Database
MOPO	Mission Operations Projects Office
MSS	Mobile Servicing System
OCMV	Operator Coached Machine Vision
POPO	Payload Operations Project Office
POST	Predevelopment Operational System Test
RMS	Remote Manipulator System
RSEL	Remote Systems Evaluation Lab
SES	Shuttle Engineering Simulator
SSAIAF	Space Systems Automated Integration and Assembly Facility
SSTO	Space Station Training Office
TCSAP	Thermal Control System Automation Project
USOC	User Support Operations Center
UMI	User Macro Interface

Appendix B

Flight Telerobotic Servicer Lessons Learned and Technology Evolution

Background

The FTS program was initiated by NASA as a result of a request by the Congressional Subcommittee on HUD - Independent Agencies of the Appropriations Committee on June 17, 1986. The letter to the NASA Administrator, the Honorable James Fletcher, discussed concerns that NASA had not honored the committee's belief that an enhanced automation and robotics program would be useful and garner great benefits for the U.S. robotics industry in the coming years. The letter further proclaimed, "it would be a deep loss to this nation to sacrifice these potential gains simply to assure 'international participation' in the Space Station."

The letter from the Congressional Subcommittee laid the framework for a U.S. Flight Telerobotic Servicer (FTS) by stating, "the minimum requirements necessary to ensure that this country benefits from an enhanced automation and robotics Space Station program." The points stipulated were:

"1. The United States shall develop a flight telerobotic system that will incorporate, but not necessarily be limited to, such features as: dual-arm cooperation; multiple light sources; force/torque and position sensors; redundant manipulators where necessary; and multiple stereo cameras. The telerobotic system will be operated via a teleoperated control station featuring man in the loop with a two-arm bilateral force and position control, stereo displays, and off-line interactive planning. In addition, it is directed that the U.S. telerobotic servicer shall evolve to a compatibility by mature operations (approximately 1997) to include tactile sensors; color vision; supervisory and automated planning; stereo displays; voice understanding/synthesis; natural language interface, and on-line task planning.

2. The above system will be developed and be ready for launching by no later than second element launch.

3. Program planning for the flight telerobotic system shall include:

— STS flight testing, by the 1990-92 time-frame, representative of the initial station construction, servicing, and maintenance activities so as to provide early verification of the capabilities being developed for use on the station;

— use of the flight telerobotic system for assisting as required, in EVA construction, and for servicing, and maintenance activities on the Space Station; and,

— capability of the flight telerobotic system to be upgraded for increasingly more autonomous, flexible execution of the varied task required for a full range of applications.

4. For the first requirement of telerobotic dexterous manipulation of an attached payload, the U.S. flight telerobotic system shall be employed. This in no way alters the roles assigned to Canada in the March 1986 agreement. In fact, the Committee notes that no exclusive servicing roles have been allocated to either Canada or the United States.

5. The flight telerobotic system shall have the capability of being used as a smart front end by station IOC on the Shuttle orbital maneuvering vehicle, on the Shuttle remote manipulator system (RMS), with the Space Station mobile servicing center, with the payload

servicing facility, and with the station orbital maneuvering vehicle.

6. The U.S. telerobotic system will be the basis for design standards for future NASA payloads that require space-based servicing or may benefit from it."

The FTS program consequently evolved from Phase A studies focusing on servicing requirements and telerobotic capabilities, through competitive Phase B contracts for system concept definition and technology readiness development to a Phase C/D contract award in May, 1987 for system development, demonstration, and deployment on the Space Station.

In January, 1991, the FTS program was removed from Space Station and transferred to the OAST to emphasize validation of technologies essential to future space robotics. The move resulted from the budget limitations placed on Space Station, but also recognition of the the importance of this technology for future space exploration and the nation's economic competitiveness. The restructured program still contained the Development Test Flight (DTF-1) to validate the technologies. Subsequent to that decision, the FTS program was partially terminated in September, 1991, and directed to capture critical hardware and software components of the technology for future missions.

The decisions made on the termination of the FTS program have been driven by budget considerations and the lack of a clearly defined mission or user. No advocate exists in the development or user community for this technology, although the need exists. The perception remains that robotics are expensive and not cost effective. However, DTF-1 was over 71% complete at the time of termination and posed to bridge the gap between laboratory development and operational flight system usage. A review of the DTF-1 system and status puts this decision in perspective.

Program Overview and Status

The Flight Telerobotic Servicer (FTS) was developed to enhance and provide a safe alternative to human presence in space. In order to mitigate risks associated with the operational system, the FTS program was originally structured for three missions: Development Test Flight (DTF-1) was to characterize and validate technologies required for telerobotic missions; Demonstration Test Flight (DTF-2) was to validate operations of a telerobotic servicer for the Space Station; and Space Station FTS (SSFTS) was the operational servicer to be deployed on the SSF at First Element Launch (FEL).

The first step for this system was a precursor Development Test Flight (DTF-1) on the Space Shuttle, as shown in figure 1. DTF-1 was to be a pathfinder for manned flight safety of robotic systems. The broad objectives of this mission were three-fold: flight validation of telerobotic manipulator (design, control algorithms, man/machine interfaces, safety), demonstration of dexterous manipulator capabilities on specific building block tasks, and correlation of manipulator performance in space with ground predictions.

The DTF-1 system, depicted in figure 2, comprises a Payload Bay Element (7-DOF manipulator with controllers, end-of-arm gripper and camera, telerobot body with head cameras and electronics module, task panel and MPESS truss) and an Aft Flight Deck Element (force-reflecting hand controller, crew restraint, command and display panel and monitors). The basic building blocks required to perform servicing, maintenance and inspection tasks on Space Station are imbedded in this configuration.

DTF-1 was to be the first on-orbit use of a dexterous manipulator and, as such, was establishing the criteria and design necessary for manned flight robotic safety. These safety criteria would be equally applicable to any electro-mechanical device which is computer-intensive in its control architecture. DTF-1 employed advanced control techniques such as impedance control, inertia decoupling and augmented damping to achieve precise manipulation (e.g., incremental motion of 0.001 inch) while operating over a wide range of payload inertias and masses with variable stiffnesses. Force feedback provided the operator with a "feel" to aid in performing highly dexterous tasks. The robotic device is controlled from a workstation in the Aft Flight Deck of the Shuttle. The workstation was designed to evolve into a configuration capable of supporting Space Station assembly and maintenance prior to man-tended configuration.

The approach used to develop the DTF-1 hardware, software and operations involved flight qualification of components from commercial, military, space, and R&D sectors (actuators, cameras, control algorithms, hand controller, end-of-arm tooling, and force/torque transducer) and the development of the telerobotic system for space applications. The system is capable of both teleoperation and autonomous control (advances state of the art), reliable (two-fault tolerance), and safe (man-rated).

Benefits from the development flight included space validation of critical telerobotic technologies and resolution of significant safety issues relating to telerobotic operations in the Shuttle bay or in the vicinity of other space hardware.

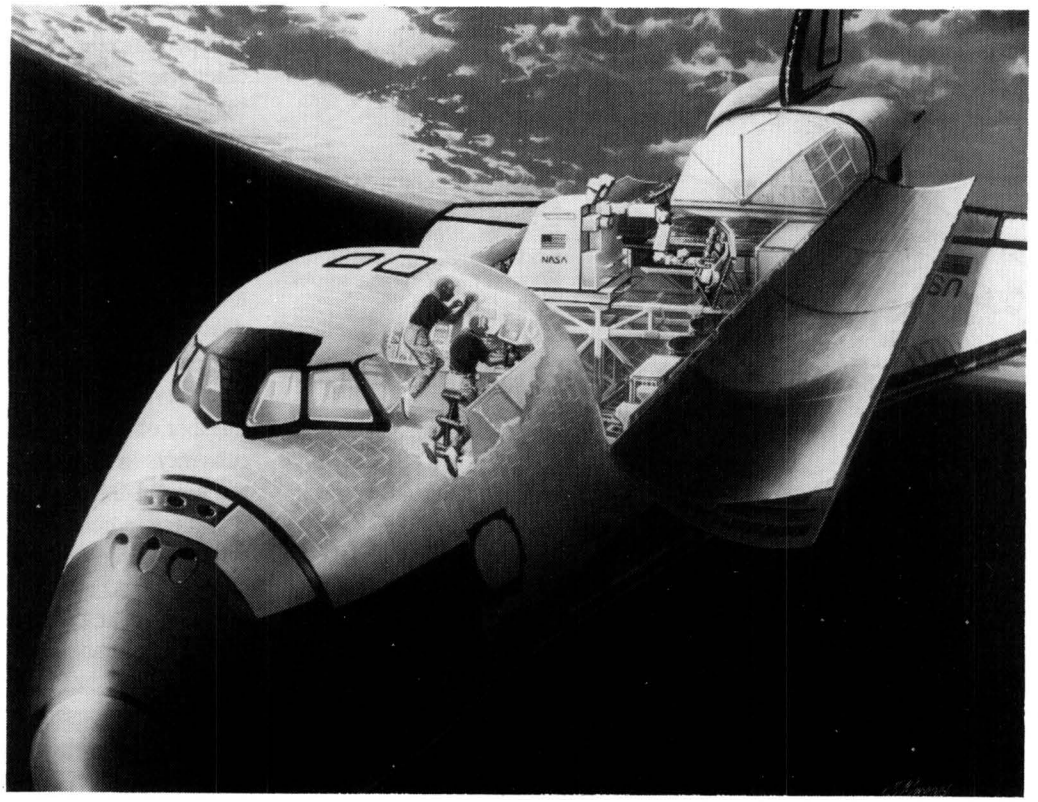


Figure B1. FTS development test flight (DTF-1).

The DTF-1 legacy provides a foundation for future robotic application requirements and development and, in addition, provides a target system for ongoing robotic R&D efforts and operational familiarity.

The status of DTF-1 prior to termination reflected progress toward the goal of validating Automation and Robotics technologies critical for manned space flight. The program was over 71% complete according to the earned value criteria. All system and subsystem requirements had been established and fixed. The formal design process was 95% complete, with the majority of outstanding tasks being assembly drawings required for integration. The DTF-1 subcontractor activity was 85% complete, with the major outstanding deliveries being flight actuators, flight cameras, and the flight computer. As of March, 1992, all subcontractor components had been delivered with the exception of the actuator flat conductor cables. Software design was complete and 40% of the code had been developed. The Software Test Bed was complete and operational for controls development in conjunction with the Hydraulic Manipulator Test Bed. Delivery of flight hardware was scheduled for June, 1993, and 80 working days of margin were available prior to this milestone. The Payload Integration Plan and Interface Control Document had been approved to allow Shuttle integration activities to begin on delivery. In addition, the Phase 1 Safety Review had been completed and documentation to support the Phase 2 review was complete and being reviewed by the appropriate parties.

The question now remains—what are the benefits that can be derived from the FTS program, and what will be its legacy?

FTS Legacy

The FTS program provided a focus for the evolution and integration of Automation and Robotic technologies. The legacy of FTS is multi-faceted: 1) systems lessons learned; 2) industrial base enhancement and qualification;

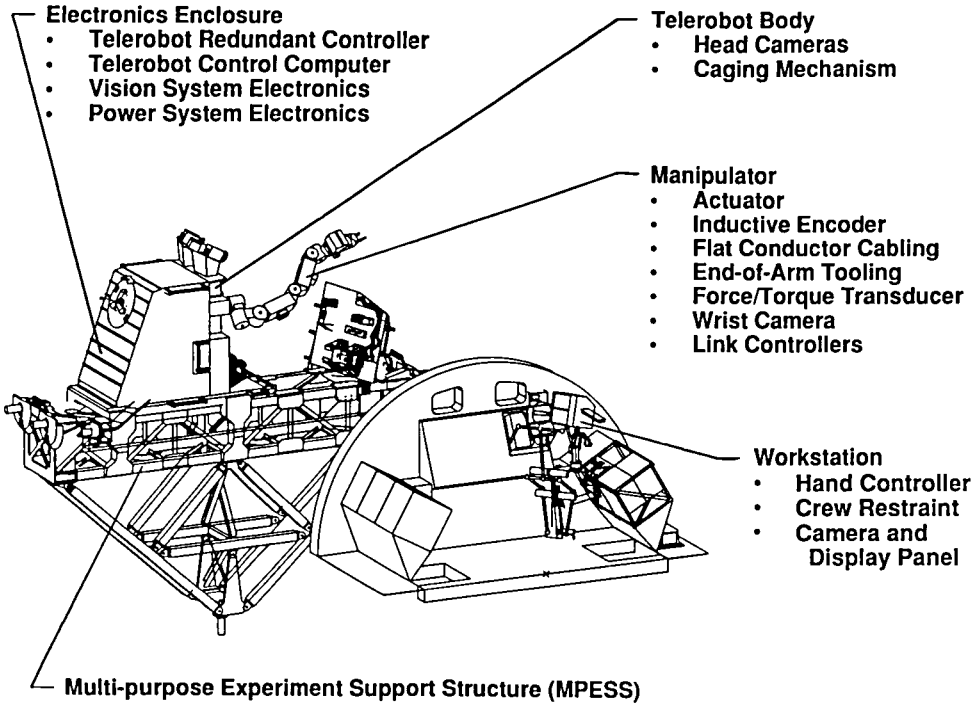


Figure B2. DTF-1 Flight System Elements.

3) technology maturation, and 4) technologies transferred to the commercial sector.

What were the roots of the FTS program?

FTS "pulled" technologies that had origins in academia, industry, and prior NASA R&D efforts, as well as task and interface requirements from Space Station. Work in the R&D community provided a broad base of controls expertise, teleoperations experience, and operator interface architectures. Examples of the technology origins are listed in table 1.

What were the significant drivers and "firsts" which emerged from FTS?

During the design phase of DTF-1, several factors were found to drive the system from a complexity, cost and schedule standpoint. These factors can be grouped into the following broad categories: safety, packaging, performance, and distributed processor architecture. In each of these categories, several notable program "firsts" were achieved during the development effort.

The single largest factor driving the system design was safety. Two-fault tolerance against inadvertent release drove the complexity and size of the gripper by providing two fail-safe brakes. Excessive force prevention increased the number of checks performed on joint runaways in the critical path and hence the around-the-loop timing. Fault tolerance in general drove the number of wires required inside the arm (for cross-strapping and hardware control) and hence the Flat Conductor Cable layering.

Design changes were developed that provided two-fault tolerance against exertion of excessive force on the worksite (i.e., the "runaway manipulator") and inadvertent release of workpieces and tools. To accomplish

Table 1. Technology origins

Technology	Origin	Contract source
Impedance control	CMU, MIT, Univ. of Mass.	GSFC/FTS Phase B, DARPA/ITA
Torque control	CMU	GSFC/FTS Phase B
Inertial decoupling	Stanford University	OAST
Force reflection	JPL, Langley Research Center	OAST
Hierarchical architecture	NIST	GSFC
Distributed controls architecture	JPL/MSFC/ORNL	OAST/OAST/DOE
Sensory feedback	University of Hawaii	GSFC/FTS Phase B
Mini-master hand controller	ORNL	Langley Research Center
Simulator	Martin Marietta	LaRC/Robsim
Manipulator configuration	MSFC	OAST/IOSS, PFMA

those requirements an extensive emergency shutdown system was developed utilizing combinations of hardware and software limit checks. The fail safe emergency shutdown system would shut off power to the manipulator motors and actuate brakes without impacting any other system. In addition, a first was achieved with the JSC Safety Board that has major ramifications for future electromechanical systems that are computer intensive. A deviation to the safety requirements was granted that allowed the use of multiple computer systems, where a quick response was necessary for safety, rather than separate redundant paths. This was implemented with a "smart heartbeat" to monitor execution of safety-critical portions of the flight software. This technique has helped the Shuttle program develop a new general policy for control of payload hazards from multiple computer systems.

Some of the additional unique features of the safety system included the Boundary Management System, a very simplified world model formed by establishing planes in regions where the manipulator must be prevented from entering, and then by monitoring Cartesian and joint parameters in a redundant manner and stopping the arm if it looks like the manipulator could enter one of these areas; a dedicated interface for "releasable" hardware, which did not depend on friction alone to maintain a grip on workpieces; and a hardwire control system, which provided a totally separate means of operating the manipulator, end effector and caging mechanisms from the normal computer system.

Packaging of the controllers within the arm was chosen to reduce the cabling across joints, to reduce the response time and signal noise, and provide self-contained safety checks. This drove the link size for passive thermal dissipation. The harmonic drive actuators provided the cable passageway, two windings (primary and hardwire), precision encoders, and a Hall effects sensor in a compact package.

Advances in packaging were achieved using internally routed flat conductor cables and densely packed Surface Mount Technology (SMT) boards. The internally routed cables greatly reduced the cross-sectional area and eliminates the binding, snagging, and loss of dexterity associated with conventional external cabling. The SMT cards mounted within the manipulator links provided three benefits: a self-contained safety monitoring and shutdown system, reduced EMI/EMC problems, and increased response time during closed-loop operations.

Incremental motion and repeatability specifications required precise joint position knowledge (20-22 bits). Considerable effort was expended to design an encoder to meet this requirement. The major problem was thermal stability of the encoder material. These specifications also had a bearing on the decision to package controllers in the manipulator links.

From a controls standpoint, contact stability and force reflection drove the design. Contact stability was assured by the addition of augmented damping to the control loop. A new controls architecture (pipelining) was being evaluated to provide crisp operator feel. This was required because of the amount of processing required in the critical path and the failure to meet the 20 millisecond around-the-loop time. Again, this system driver stemmed from safety requirements combined with limitations in the distributed processing architecture; i.e., bus traffic, computer throughput.

Real-world controls problems were solved for the space environment by the FTS control system. The inertia decoupling algorithm allows the system to handle a wide range of payload sizes, masses, and inertias. Stability of the system is guaranteed over variations in temperature experienced in space by the addition of a servo torque loop. Algorithms were also developed to accommodate a wide range of worksite stiffnesses, which are anticipated for Space Station robotic maintenance.

Are there lessons learned that are relevant to space robotics as a whole?

Significant lessons were learned during the development of FTS that could be applied to integration of any robotic servicer into a human-rated system. Particular attention should be paid to the formation of performance and safety requirements, as these tend to drive the technology development and complexity of the system. These lessons are very relevant to the integration of robotics on Space Station.

A task-driven methodology should be used to develop the requirements for a robotic system. The optimal definition of a robotic system (manipulator kinematics, mobility, operator interface, etc) stems from a task analysis to avoid specification of unneeded capabilities or features. An understanding of the task requirements (worksite constraints, task element characteristics, sequence of operations) leads to kinematic and dynamic simulations that develop the manipulator configuration, vision system requirements, and collision avoidance requirements. Additionally, the robotic system duty cycles, which drive the host platform resource requirements, are directly related to the task sequence of events.

It is critical to establish a complete set of detailed system and lower-level

specifications early in the program, well before hardware design is initiated. Realistic margins must be established in the requirements to allow for unplanned contingencies as the design progresses. Of equal importance at this time in the program is to plan ahead for verification of the requirements - all requirements should be established in the form of quantifiable, verifiable specifics. The appropriate level of requirements traceability must be clearly established, with customer concurrence.

For a robot, the manipulator and its required performance are the key to ensuring mission success. Realistic force/torque requirements at the interface between the manipulator and the workpiece need to be set to enable the manipulator to perform all its assigned tasks. The kinematics of the manipulator and the relationship with the worksite must be considered with respect to force/torque and also to power. Realistic margins on both minimum and maximum performance should be set up that will allow the manipulator to perform its assigned tasks, but yet consider power and safety implications. While minimum requirements ensure that the manipulator can perform its tasks, maximum requirements help limit loads on the manipulator and the end effector, and on all workpieces with which it comes in contact. In addition to placing requirements on static forces and torques, considerations should also be given to specifying joint and Cartesian velocities and accelerations.

One of the key drivers of the DTF-1 mission was to establish and meet the unique safety requirements for a dexterous robot to be flown on a manned spacecraft. Emphasis was given to meeting the updated Shuttle safety requirements that were established following the Challenger accident. While the Shuttle Remote Manipulator System (SRMS) is the first robot arm to operate on a manned spacecraft, it currently has many waivers and deviations, and is operated in a very slow, preplanned mode - not the desired mode of operation for a dexterous manipulator. This needs to be addressed early in the program as it has major impacts on the hardware and software designs. These are among the first set of requirements that must be established and finalized. The formal safety review process for the Shuttle should be performed in consonance with the system design activities (i.e., Phase 0 Safety Review prior to PDS, Phase 1 prior to CDR, etc).

Critical to the design and acceptance of space robots (as well as all space hardware) is the early involvement of the Astronaut office. This allows lessons learned by the flight crew from previous space flight experience to be input early in the design, gives the system designers and the system users the chance to interact, and ensures vital support from the people that will use the hardware in flight.

What issues in component technology development arose resulting from space environment qualification?

A critical hurdle that must be cleared in the transition of robotics technology to space applications is improved reliability in a harsh environment. Today's laboratory efforts utilize commercial components that, to a large degree, have not been designed from an integrated systems perspective and operate in ambient conditions. Moreover, reliability is not a major concern in these systems because failed components can be readily exchanged. This is not true of a flight system where a failure can potentially condemn the entire mission. The key areas that must be addressed are the selection of parts, materials, and processes; the use of redundancy and cross-strapping to avoid single point failures; analysis of electronics and electromechanical devices to assure performance over the environmental ranges; and a clear understanding of failure modes, their effects, and operational contingencies.

The FTS program encountered and overcame significant parts, materials, and processes development issues with many of the robotic devices used in the ground test beds. These are the kinds of problems typically encountered by any new development program. The most frequent problems encountered were incompatible thermal coefficient of expansion across bonded components such as the 22-bit encoder; non-linear characteristics of devices over temperature; and inconsistent process control at component vendors resulting in failures during development. The program encountered these problems even though all vendor materials were screened for flight compatibility, and processes were reviewed and approved. The program overcame these component development problems and successfully completed life tests in qualification environments.

Another significant issue was the need to develop electronic piece parts for flight environments. Many of the electronic piece parts required for robotic control systems had never flown before. Analysis and testing revealed that these parts would not reliably survive the launch vibration, thermal cycling, and vacuum environments. Specifications must be developed to improve bonding, denote trapped particles, and eliminate non-flight-compatible materials. Parts were then screened to ensure compliance with these specifications. In particular, destructive physical analysis was performed on a single part from each

manufacturing lot for all hybrids to test wire bond strengths, die bonds, and proper clearances. In addition, 100% of all EEE parts received PIND testing to verify that there were no trapped particulates. Although this process is expensive, some parts were found to be defective and could have jeopardized the entire mission had they not been corrected. In an environment where launch opportunities are sparse and launch costs are high, this level of part qualification is justified.

Redundancy and cross-strapping were essential for proving the overall safety design and assuring mission success. Manipulator cabling has always been an issue for terrestrial arms and these redundancy requirements compound the problem. In fact, the actuator cabling requirements drove a new technology for a low friction and stiffness cable capable of passing over 500 conductors.

The FTS program encountered these and other qualification issues, which are summarized in table 2.

These flight qualification issues have not previously been anticipated within the R&D community. NASA's Automation and Robotics program has not typically performed system-level concept definition and design. As a result, the R&D focus may or may not be addressing the critical technology risks associated with future applications. NASA should establish a mechanism for cooperation between the application programs and Code R to develop system-level concept definition at a sufficient level to identify and drive ongoing R&D efforts. Moreover, a portion of the R&D efforts should be focused at resolving these issues. This will require a higher degree of focus on flight qualification issues.

What was the impact of the FTS program on the industrial base, and how is the technology transferred?

Before the start of the FTS program, the technology base for field servicing robotics was largely limited to small entrepreneurial firms with little or no production experience. Those having experience with space flight hardware were even more rare. A major thrust of the FTS program was to provide technical support to these small companies and prepare them for producing and

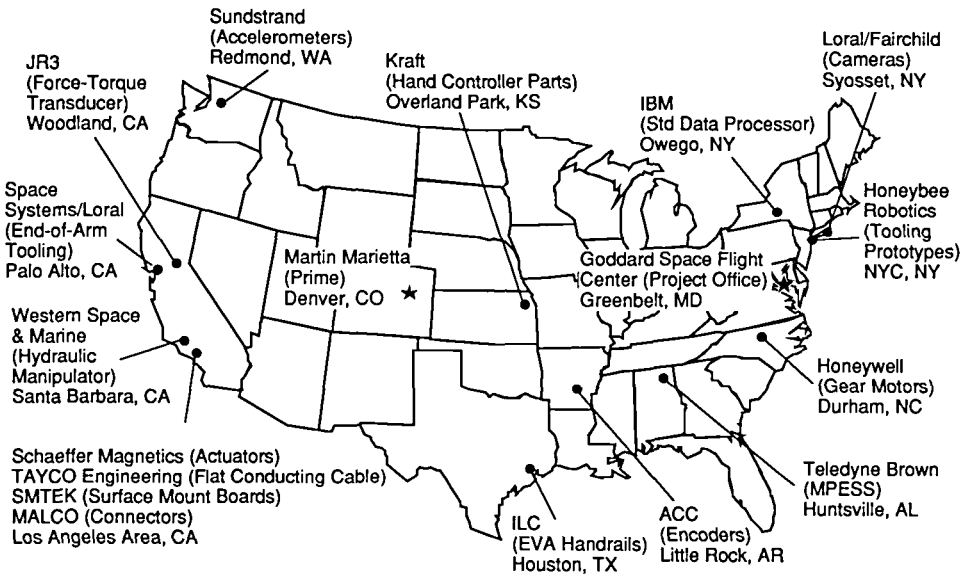
Table 2. Qualification issues

Element	Issues	Solutions
Force torque transducer	Strain gauge drift over temp. EMI susceptibility	Trim and prescreen strain gauges Calibrate and tune electronics EMI shield
22-bit encoder	Sensitivity to gap variations Sensitivity of electronics to thermal variations	Match thermal coefficient of expansion, control lamination process Worst case analysis drives high precision components
Actuator transmission	Friction variation with temperature	Provide torque loop to compensate for friction variations
Flat conductor cable	Signal cross-talk	Delamination High density conductor with low stiffness requirement 10,000Å shielding Lot peel tests Stringent cleanliness standards Multi-layer flex cable designed to route internal to actuator
Controls	Contact stability with large variations in stiffness Large variations in friction Large variations in inertia	Augmented damping with velocity feed forward to improve response Programmable torque loop Inertia decoupling loop
Software	Real-time Ada	Run time environment compiles to bare machine

qualifying space hardware. This experience has temporarily created a pool of talent that industry and government could use to continue our national development and expansion of robotics. These companies and their products are shown in figure 3.

A major by-product of the technology developed by the FTS program has been a better understanding of the components, how they work, and the processes associated with manufacturing. JR3, developer of the force-torque transducer, now has a product that exhibits over four orders of magnitude better performance than their previous commercial products. In addition, the experience gained in packaging the FTS force-torque transducer electronics within the housing has allowed them to offer a superior transducer that is roughly the size of a tuna can with lower susceptibility to noise and electromagnetic interference, is now being incorporated into their commercial line. Another example of better understanding of the product is ACC, manufacturer of the position sensing encoder. Their product represents the most accurate encoder available, given the size constraints of the manipulator joint. The encoder has improved signal-to-noise characteristics, less solder interconnects, and higher reliability than its predecessor.

Schaeffer Magnetics developed the electro-mechanical actuators for FTS. Based on the design effort for FTS, the U.S. now is positioned to reaffirm a leadership role in the space-based applications of harmonic drives. Technology developments in actuators and cabling could lead to lighter, more compact, self-contained mechanisms for other applications. Schaeffer Magnetics is currently applying for a patent on the cable passage through the actuator, which they believe is a preemptive capability.



Note: Electronic and mechanical parts also located in Arizona, California, Colorado, Michigan, Minnesota, New Hampshire, New Jersey, New York, and Texas.

Figure B3. FTS program team.

The flat conductor cable (manufactured by Tayco Engineering) was developed because the hostile space environment can damage plastic and other material used in cables exposed to open space. This cable may also be used for robots in corrosive environments, such as cleaning hazardous waste sites or servicing nuclear power plants. In addition, the size and weight of the FTS cables can provide immediate improvements to aerospace and mechanical devices.

As mentioned previously, significant "firsts" were achieved in the packaging area. To package the controllers within the links, "surface mount" technology was used. This permitted higher density components that required less power, volume, and weight than other available means. The surface mount cards were developed by SMTEK. SMTEK is using this same technology to produce electronic card key locks, the next generation of the card keys now being used in the hotel industry and for security applications.

As required by Congress, a key objective of the FTS program is to enhance the United States' expertise in automation and robotics and, thereby, contribute to this nation's competitive advantage. To capitalize on the emerging FTS technologies that are relevant to ground and space applications, Martin Marietta Civil Space and Communications Company and the Goddard Space Flight Center established a Commercial Applications program to disseminate these technologies to U.S. industry. This effort was involved in an outreach activity to directly contact companies and organizations with a potential interest in FTS technologies. These included industries, small businesses, entrepreneurs, the Centers for the Commercial Development of Space, NASA's Industrial Applications Centers, various U.S. government

organizations, universities, and NASA-sponsored centers. Information was propagated into databases via conference proceedings and publications, supplementing the outreach effort by "advertising" the existence and capabilities of these technologies to the user community.

An industry briefing on the FTS technologies was held in early December, 1990. The 78 attendees at the FTS-sponsored Outreach Symposia represented the U.S. automobile, electronics and undersea industries; the Centers for Commercial Development of Space (University of Wisconsin—WSCAR, ERIM—SAR Center); industrial applications centers (Indianapolis, Research Triangle Institute); university space engineering research centers (University of Colorado, Rensselaer Poly-technic Institute); and the National Institute of Standards and Technology.

Examples of technology that were transferred to industry include NASREM architecture to the Next-Generation Controller Program and to the Robotics Laboratory at MSFC; hand controller commonality software to LaRC; FTS simulation models to the Center for Space Construction at the University of Colorado; actuators and control system technology to robotics companies, including Redzone; and software architecture (NASREM), teleoperations and the human/machine interface (force-reflecting hand controllers) to the U.S. Bureau of Mines, Joy Manufacturing Co., Strictly Business, West Virginia High Tech Consortium. The U.S. Bureau of Mines is also interested in the human/machine interface prototyping tool developed by FTS. They want to use it to develop designs for remotely controlling and automating continuous mining machines. They believe this is necessary to remain competitive with the third world coal mining industry.

Are other countries interested in these technologies?

Several of the FTS subcontractors have had discussions with other nations, who are in the process of developing dexterous manipulators for space servicing. Loral Fairchild, developer of the FTS cameras, has provided data to Spar Aerospace of Canada relative to their Special Purpose Dexterous Manipulator (SPDM) for the Space Station. It is interesting to note that each FTS camera is a space-qualified version of a camera developed for the U.S. fighters such as the F-15 and F-16. The SPDMs are the only qualified system available to date that accommodates the size restrictions associated with dexterous manipulator wrists. The Japanese have also made several inquiries regarding the cameras for use on their Small Fine Arm on the Japanese Exposed Facility (JEM) of the Space Station.

JR3, maker of the force-torque transducer, has supplied procurement data to Spar with respect to incorporating their sensor into the SPDM. The SPDM development laboratory in Canada is currently using commercially available JR3 transducers on their ground-equivalent SPDM.

IBM, developer of the FTS Telerobot Control Computer, has a prototype single processor page on order from Spar. Perkin-Elmer also has two prototype pages on order. The FTS computer is a modified Space Station Standard Data Processor (SDP). This computer contains three CPUs and is qualified for the external space environment. It could very well become the Space Station baseline SDP. If this occurs, FTS will have paid for the non-recurring development cost and provided the pathfinder unit.

The Japanese have formally requested use of FTS components for their JEM Flight Demonstration, a Shuttle flight planned for 1996. The request was for the FTS flight computer and flight software. The fact that the FTS software was developed in Ada makes it highly transportable for other uses. In the past the Japanese have inquired about the legality of using the MPESS structure in the Shuttle bay and the Aft Flight Deck workstation developed for DTF-1. The Japanese are actively pursuing the hardware, software and data produced by FTS to lower their non-recurring effort and reduce the risk.

All of this interest points out the value of the technologies developed by the FTS program. However, the benefits are of transitory nature if no one capitalizes on the knowledge gained. The repository of knowledge for the design and lessons learned is with people who are migrating to other projects. The industrial base developed for space robotics consists largely of small businesses that were relying on the FTS program to help develop their base. Their future viability considering the state of U.S. robotics is questionable. This knowledge gained by FTS should be captured and applied to mitigate risks on upcoming programs such as the Space Station.

Technology Capture

The single most critical issue for U.S. space robotics is the lack of a strong advocacy from the end user community. Many of the users have recognized the value and need of on-orbit servicing but have insufficient funds to pay for the development costs. As with any new technology, the non-recurring development costs far outweigh the recurring fabrication, assembly, and test costs. The FTS program was initiated to provide for

this development. Unfortunately, it was terminated prior to realizing this objective and has left behind a legacy that robotics are too expensive. In actuality, once the DTF-1 system integration was complete, the recurring system costs for additional applications would be low. For example, the recurring cost of a single arm servicing system has been estimated to be between $10M and $15M once the development costs have been borne.

Conversely, NASA's technology branch (Code R) is unable to assume the liabilities and risks associated with a major development program because of their constrained budget and potential conflicts with flight projects. This dilemma doomed not only the FTS program but application of other technologies, such as the Aero Assist Flight Experiment developed within Code R. This debate can be clearly seen in the congressional activities during 1991. The House Committee on Science, Space and Technology, in its authorization report, reduced the FTS request by $40M stating that "the Committee believes that since the original mission of the Flight Telerobotic Servicer has been eliminated from Space Station, the program is no longer needed." Whereas the Senate Committee on Commerce, Science, and Transportation stated in its authorization report: "In the report by the Augustine Committee, great emphasis was placed on the importance of developing space-related technology, as it concluded that 'NASA bears part of the responsibility to assure the viability of the technology base upon which to build the missions of the future.' The committee further believes that one of those key 'enabling technologies' is telerobotics. The reported bill fully funds continued development of the Flight Telerobotic Servicer." The final compromise as described in the Joint House and Senate Authorization Conference Report "... provides $15M for telerobotics research in order to capitalize on the investment made in the Flight Telerobotics Servicer Program." The House and Senate Appropriations Conference went on to appropriate "... $10M of the $55M requested for FTS shall be applied to advanced competitive robotics designs," with the Chairman of the Science Subcommittee on Space stating that "... I certainly encourage NASA to ensure that the significant investment of over $200M made by the U.S. government in FTS over the last five years is not in vain."

Langley Research Center (LaRC) and Johnson Space Center (JSC) have capitalized on the Congressional authorization by structuring a joint program whereby LaRC receives a fully integrated Hydraulic Manipulator Test Bed (HMTB) and JSC receives the integrated flight manipulator arm and residual flight hardware. This relationship, formalized by an MOA, provides for a natural tie between the R&D community and the user community and may provide a mechanism of technology transfer that has eluded the agency in the past. The hydraulic manipulator test bed will serve as a focal point for the demonstration of new technologies and feasibility demonstrations. The system shares the same hardware and software architecture as the flight manipulator and has identical kinematics. These features will assist in the efficient transfer of control algorithms, planning algorithms, and sensors to the JSC user community. The test bed will also serve to evaluate the feasibility and efficiency of performing a wide variety of servicing tasks and is seen as a focal point for building a user constituency. The Flight Manipulator activity complements the HMTB effort by bringing together the advanced technology components developed under the FTS program into an integrated system capable of being carried forward to flight qualification. This manipulator will be used to demonstrate proof of concept, evaluate zero-gravity control strategies, provide risk mitigation for the SPDM, and retain a potential for a flight experiment.

The HMTB, shown in figure 4, consists of a seven-degree-of-freedom hydraulic manipulator with a lift capacity of 60 lb and a tip velocity greater than 24 in./sec. The hydraulic manipulator is controlled from a processing architecture that functionally duplicates the FTS distributed processing architecture. The HMTB incorporates a workstation with a 6-DOF bilateral force-reflecting hand controller and an operator interface that accommodates the hierarchical control consistent with the NASREM architecture. The software hosted on the processing architecture is written in Ada and provides all control, monitoring, and safety features. The HMTB shares the same software as the flight system and will serve as a proof of concept for the overall processing architecture. The major control loops provide for a position, velocity, and programmable analog torque loop at the individual joint level. Major advances have been achieved within these loops to compensate for non-linear actuator effects and contact stability over a wide range of task environments. These have been stumbling blocks in the robotics community since the inception of the manipulator. Moreover, the program is pursuing the development of compensation techniques that will enable the control system to approximate the dynamics of a zero-gravity manipulator. This feature will enable the evaluation of zero gravity effects on the ability to perform tasks.

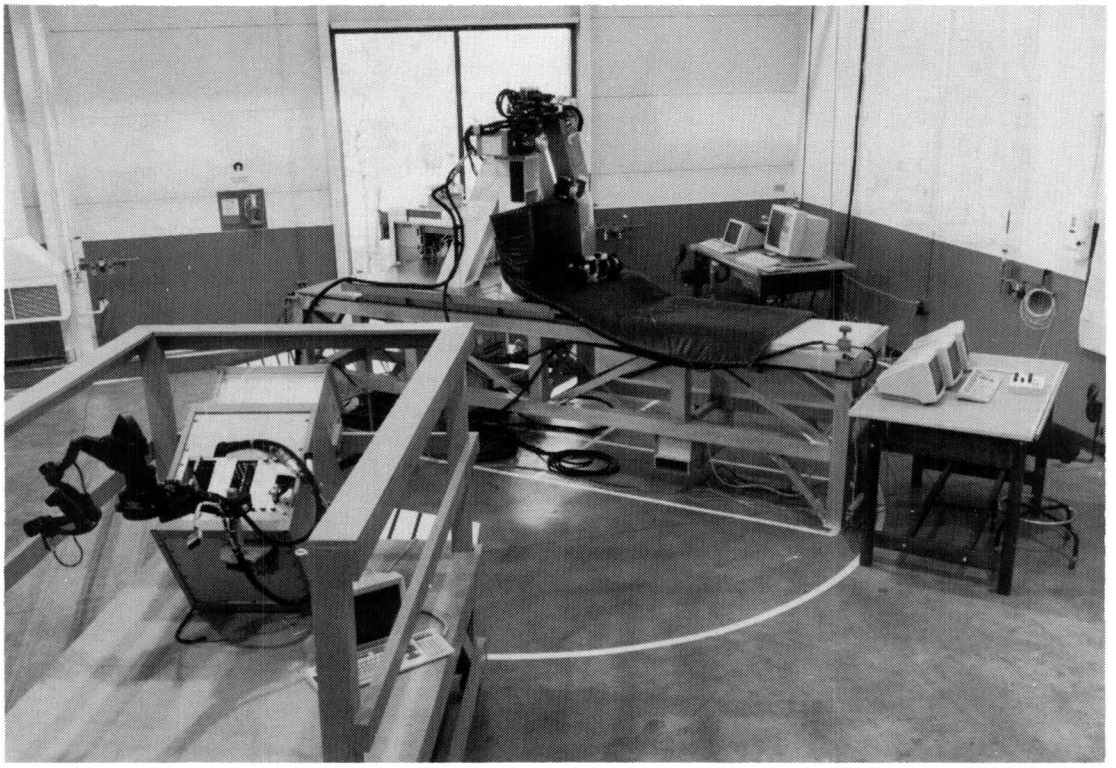


Figure B4. Hydraulic manipulator test bed (HMTB).

The Cartesian control loop that coordinates overall manipulator motion incorporates impedance control techniques that enable automatic control of applied forces and manipulator stiffness in six degrees of freedom.

These control techniques have been the outgrowth of research funded within the robotics community over the last ten years. The FTS program has brought these to full maturity. The Cartesian control loops also incorporate a newly innovated inertia decoupling loop that enables the arm to maintain stability over a much broader range of loads at the tip. Key safety features within the software/hardware architecture include real-time limit checking and automatic shutdown when critical parameters indicate a runaway manipulator. The software also provides for automatic boundary checking to ensure that the manipulator is always controlled within a selected safety envelope. These safety features have been reviewed with the NASA safety board and are consistent with those required for the operation of a dexterous manipulator in a man-rated environment.

The Flight Manipulator will integrate the component technology developed under the FTS program into a fully functional manipulator that can be carried forward into flight qualification. Development efforts associated with the major elements have been completed, and the resulting hardware is shown in figure 5. The FTS program required that laboratory robotics elements be brought to a full level of maturity with capability to operate in a space environment with high reliability. As an example, this required that the signal-to-noise ratio of force/torque transducers be improved by four orders of magnitude and incorporate strain gauge technology that could operate with a linear response from –65 deg to +85 deg. Similarly, the flight electronics packaging required extensive use of surface mount electronics and high-density, low-power packaging. Each manipulator link, for example, contains an embedded processor with analog interfaces and a full complement of motor drive electronics. These electronics typically comprise a standard 5-ft rack of equipment for commercial manipulators. The flight manipulator integration effort will complete the integration of a

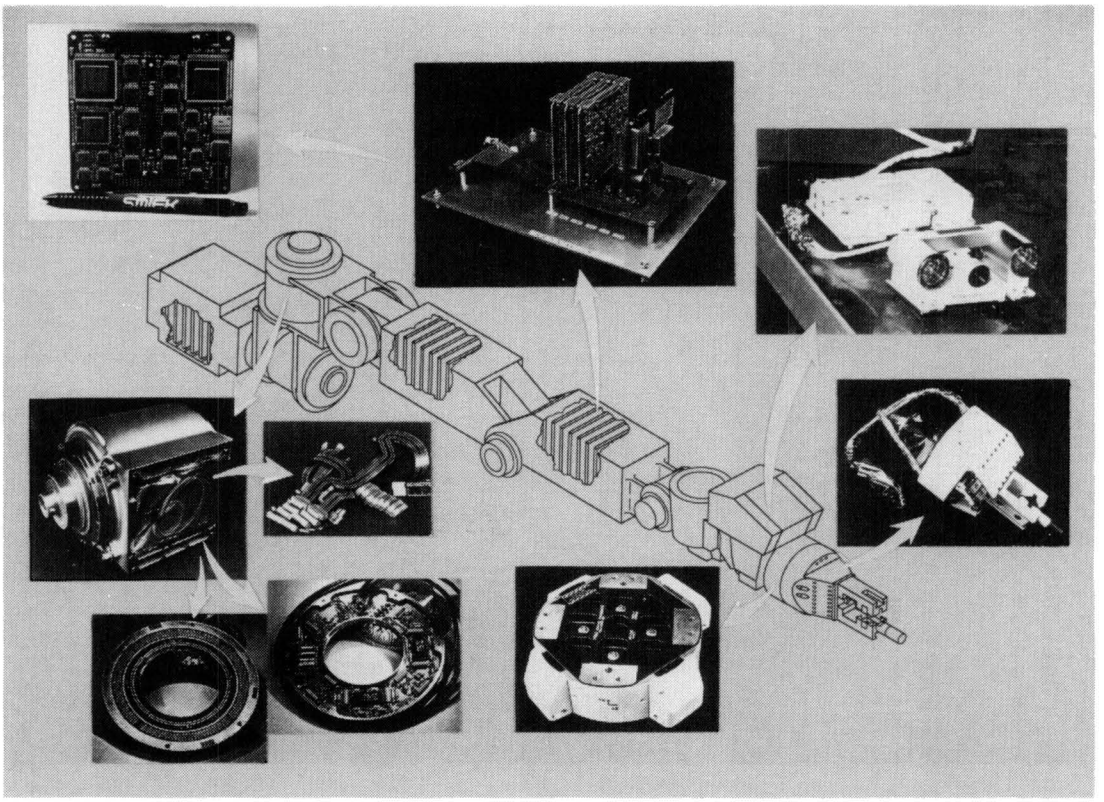


Figure B5. FTS flight manipulator component development collage.

development joint controller with a development actuator and provide testing to verify the adequacy of the design. Following this step, the flight components, shown in figure 6, will be fabricated, assembled, and tested. These actuators, controllers, force/torque transducer, gripper, and camera elements will then be integrated into the final manipulator assembly and tested to characterize overall performance.

The joint program will provide several benefits for both NASA and the country at large. First, the technology development that resides in the flight manipulator is the culmination of over ten years of research and development by OAST. The HMTB and flight manipulator integration will provide a clear focal point for capturing this extended research and packaging it for transfer to the user community. This may prove to be a good framework for focusing and transferring other technology developments within Code R in the future. Second, the manipulator design, which represents the most advanced manipulator development in this country, will enable NASA to understand any potential pitfalls so the next generation system can be improved. Third, the research community has long held the belief that a flight experiment is essential to proving the capabilities of the technology prior to adoption by the operational community. The program preserves that feasibility for an early experiment. Moreover, the United States, at the time of termination, enjoyed a several-year lead in space robotics technology. This lead is being eroded by the Japanese, the Canadians, and the Germans. The follow-on would retard this erosion and retain a leadership position for at least another two years. Fourth, as the Canadian program proceeds, there are significant technical risks that must be mitigated such as safety and component qualification. The flight manipulator provides a risk mitigator for the Space Station program while addressing the needs of the research community.

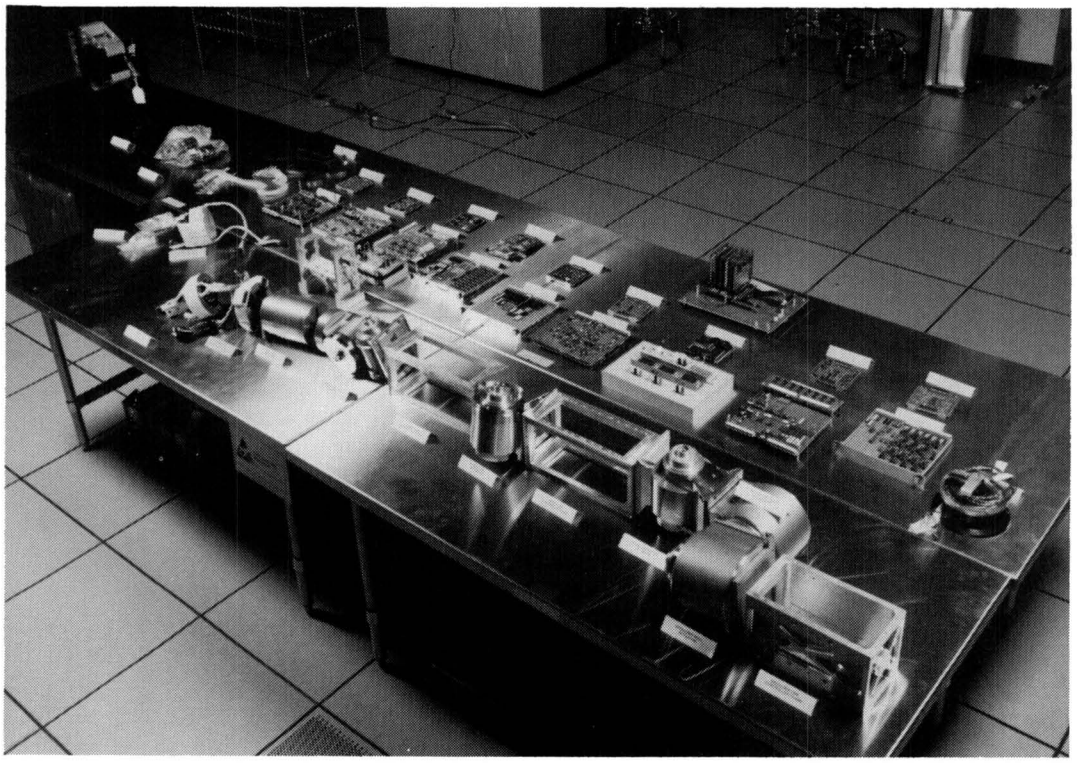


Figure B6. FTS flight manipulator exploded view.

Conclusion

The FTS program was proceeding into final manufacturing, assembly, and test, and had completed the major component development activities for the flight system at the point of termination. This component development brought many OAST technologies to a level of full maturity and represented 75% of the total program cost for qualifying space robotic technologies. NASA should capitalize on this investment in component development and work to allay the perspective that space robotics are too expensive. Cost analyses have been performed that demonstrate that recurring costs are, in fact, quite reasonable ($10-15M).

The ATAC has seen a resurgence of interest in space robotics within Space Station, selective repair missions such as HST, and free-flying micro-gravity experiments. NASA should provide a mechanism to transfer the component technologies to the user communities. The FTS Technology Capture Program being pursued jointly with NASA Langley Research Center and NASA Johnson Space Center is a natural candidate for filling this void and should, in fact, serve as a focal point for the A&R program thrust in onorbit servicing. As such, a flight experiment funded jointly by the R&D community and the operations community would be a clear demonstration of the technology transfer mechanism advocated by the Advisory Committee on the Future of the U.S. Space Program.

Acronyms

FTS	Flight Telerobotic Servicer
NIST	
MPESS	Multi-Purpose Experimental Support Structure
NASREM	National Standard Reference Model
RMS	Remote Manipulator System
SDP	Standard Data Processor
SMT	Surface Mount Technology
SPDM	Special Purpose Dexterous Manipulator
SRMS	Shuttle Remote Manipulator System

Appendix C

Acronyms

A&R	Automation and Robotics
AC	Assembly Complete
ARC	Ames Research Center
ATAC	Advanced Technology Advisory Committee
AWP	Assembly Work Platform
C&T	Communications and Tracking
CDR	Critical Design Review
CETA	Crew and Equipment Translation Aid
Code D	NASA HQ Code for the Office of Space Systems Development
Code M	NASA HQ Code for the Office of Space Flight
Code MT	NASA HQ Code for the Office of Space Flight, Space Station Engineering
Code R	NASA HQ Code for the Office of Aeronautics and Space Technology
Code S	NASA HQ Code for the Office of Space Science and Applications
CR	Change Request
CSA	Canadian Space Agency
CSP	Canadian Space Program
DARPA	Defense Advanced Research Projects Agency
DKC	Design Knowledge Capture
DMS	Data Management System
DTF-1	Development Test Flight (first FTS test flight)
DTLCC	Design to Life-Cycle Costs
ECLSS	Environmental Control Life-Support System
EMI	Electric-Magnetic Interference
EMST	External Maintenance Solutions Team
EPD	Engineering Prototype Development
EPS	Electrical Power System
ESA	European Space Agency
EVA	Extravehicular Crew Activity
EVR	Extravehicular Robot Activity
FDIR	Fault Detection, Isolation, and Recovery
FEL	First Element Launch
FSE	Flight Support Equipment
FTS	Flight Telerobotic Servicer
GN&C	Guidance, Navigation, and Control
GSFC	Goddard Space Flight Center
HOSC	Huntsville Operations Support Complex
ISE	Integrated Station Executive
IDR	Integrated Design Review
IROP	Integration Requirements on Payloads
IR&D	Inhouse Research and Development
IVA	Intravehicular Activity
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KBS	Knowledge-Based Systems

KSC	Kennedy Space Center
LaRC	Langley Research Center
LCC	Life-Cycle Cost
LeRC	Lewis Research Center
MCC	Mission Control Center
MSAD	HQ Microgravity Science and Applications Division
MSC	Mobile Servicing Center
MSFC	Marshall Space Flight Center
MT	Mobile Transporter
MTC	Man-Tended Capability
MUT	Mission Utilization Team
NASA	National Aeronautics and Space Administration
OAST	Office of Aeronautics and Space Technology
OMS	Operations Management System
ORU	Operational Replacement Unit
OSSA	Office of Space Science and Applications
PDR	Preliminary Design Review
PDRD	PDR Document
PI	Principal Investigator
PIT	Pre-Integrated Truss
PMAD	Power Management and Distribution
PMC	Permanently Manned Capability
POIC	Payload Operations Integration Center
POP	Program Operating Plan
RSIS	Robotic Systems Integration Standards
RTDS	Real-Time Data System
SPAR	Spar Aerospace Limited
SSFPAH	Space Station Freedom Payload and Accommodations Handbook
SSSAAS	Space Station Science and Applications Advisory Subcommittee
SDP	Standard Data Processor
SDTM	Station Design Tradeoff Model
SPDM	Special Purpose Dexterous Manipulator
SSCC	Space Station Control Center
SSE	Software Support Environment
SSF	Space Station Freedom
SSFP	Space Station Freedom Program
SSRMS	Space Station Remote Manipulator System
TCS	Thermal Control System
TEXSYS	Thermal Expert System
WETF	Weightless Environmental Test Facility
WP	Work Package

Appendix D

NASA Advanced Technology Advisory Committee

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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 Space Station Freedom. 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 fourteenth in a series of progress updates and covers the period between August 15, 1991-February 27, 1992. The report describes the progress made by Levels I, II, and III of the Space Station Freedom in developing and applying advanced automation and robotics technology. Emphasis has been placed upon the Space Station Freedom program responses to specific recommendations made in ATAC Progress Report 13, and issues of A&R implementation into the Payload Operations Integration Center at Marshall Space Flight Center. Assessments are presented for these and other areas as they apply to the advancement of automation and robotics technology for Space Station Freedom.

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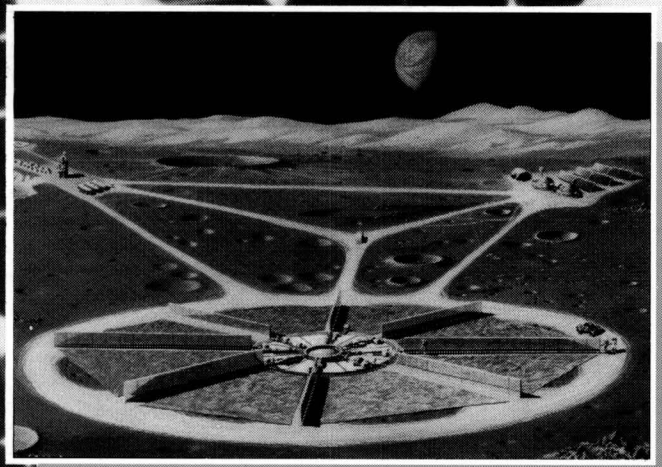

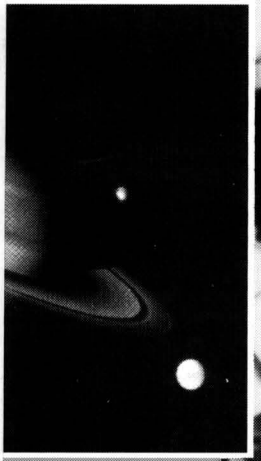

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