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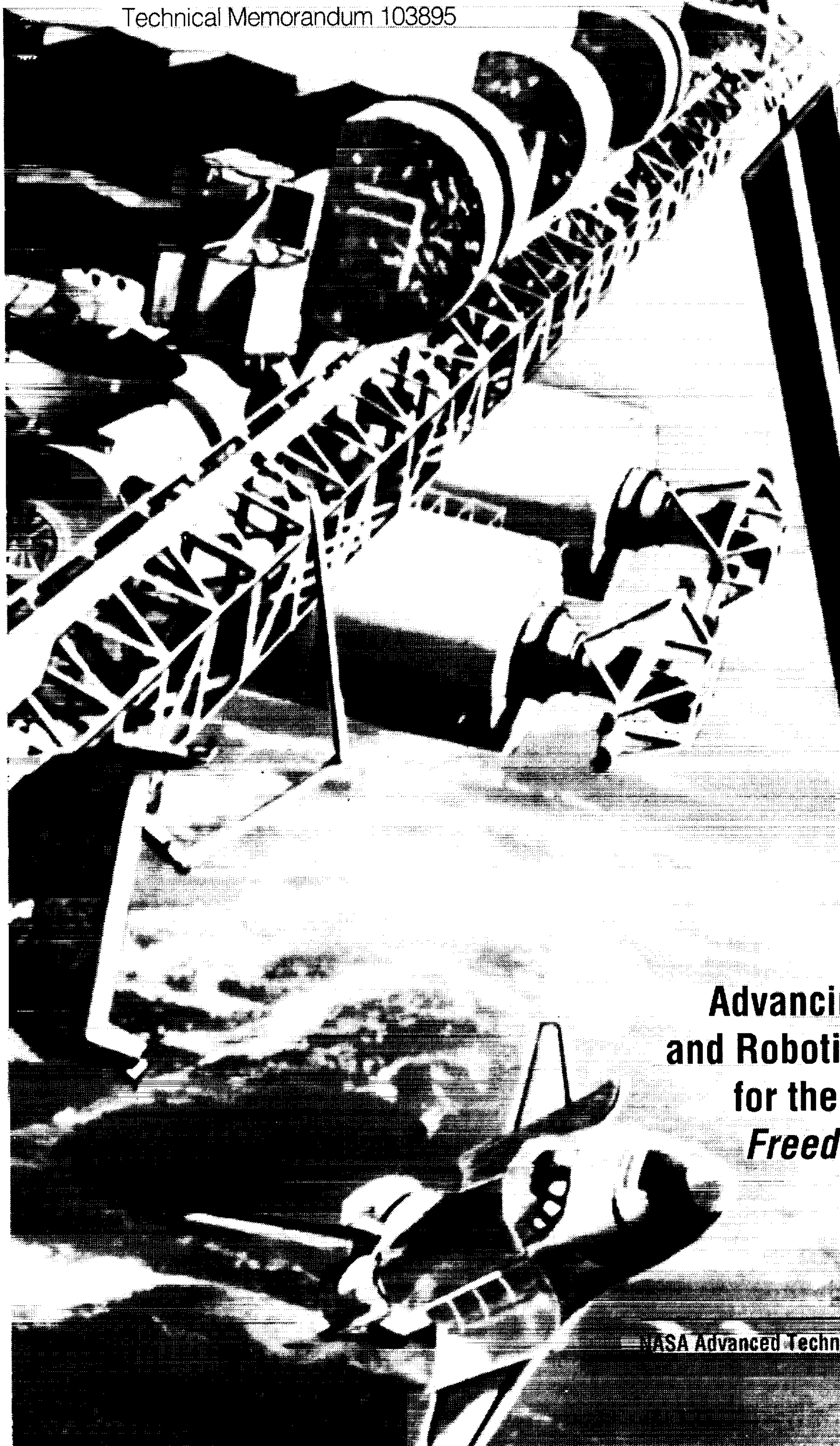

Advancing Automation and Robotics Technology for the Space Station *Freedom* and for the U.S. Economy

NASA Advanced Technology Advisory Committee

Technical Memorandum 103895

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

Progress Report 13
February 15, 1991 through August 15, 1991

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Advanced Technology Advisory Committee
National Aeronautics and Space Administration

NASA

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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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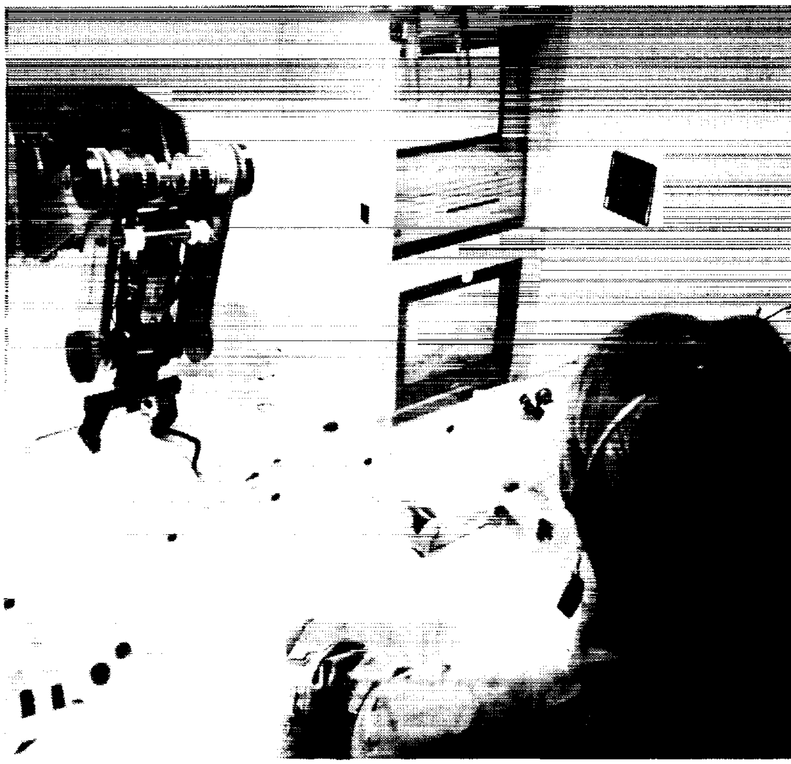
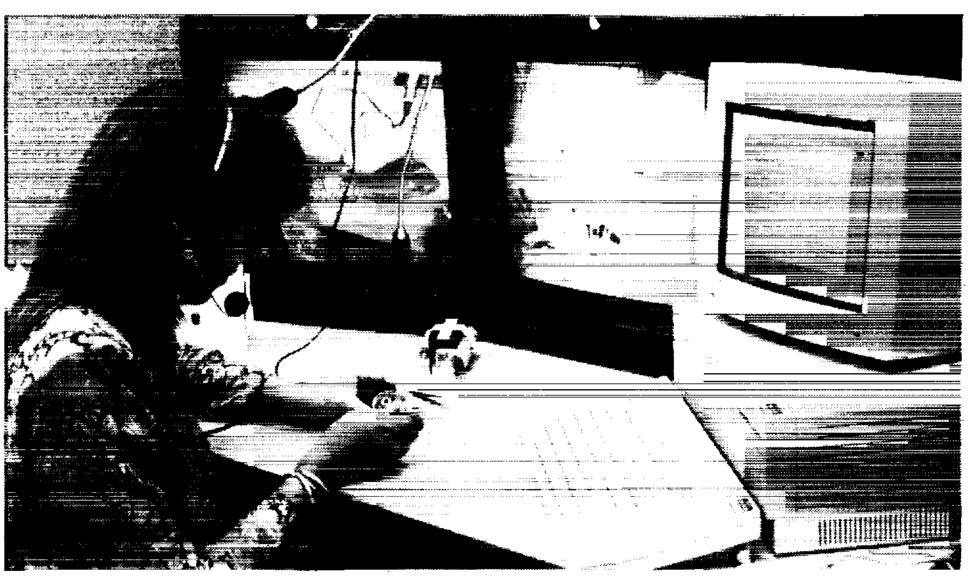


Astronaut performing plant dissection under microgravity environment

Life Science Plant Dissection Utilizing Telescience

Telescience provides for effective interaction of the experiment Principal Investigator (PI) with the onboard crew and experiment through audio and video communications, and networked computer workstations. The PI is able to see a camera view of the onboard laboratory operations inside the onboard glovebox through video downlink. The onboard crew member is able to see a camera view of the PI's ground laboratory work area through video uplink, and receive coaching or assistance. Operational experiment procedures are displayed on both the PI's and crew's computer screens.



Principal investigator assisting astronaut from ground laboratory

Introduction

Background

In response to the mandate of Congress, NASA established, in 1984, the Advanced Technology Advisory Committee (ATAC) to prepare a report identifying specific Space Station Freedom (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 A&R applications for the initial and evolutionary space station. Additionally, ATAC provided recommendations to guide the implementation of A&R 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

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 A&R in achieving this goal. The reports are documented in the ATAC Progress Reports 1 through 12 (refs. 2-13). 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 12 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 12, like previous ATAC reports, received wide dissemination. ATAC Progress Report 12 was distributed in the following categories:

Congress:	25 Copies
NASA:	240 Copies
Industry:	110 Copies
Universities:	50 Copies
Total:	425 Copies

This report is the thirteenth in the series of progress updates and covers the period of February 15, 1991 through August 15, 1991. 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 12. 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 Japanese A&R Space Station Program and the Canadian Space

Station Mobile Servicing System. 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 August 13-15, 1991, for the purposes of reviewing the SSFP A&R activities and formulating the points of this report.

Climate

A preliminary assessment of the SSF restructuring, made in response to the Congressional budget reduction, was completed at the August 1991 ATAC meeting. A summary of the major system impacts are as follows:

(1) All space robotic systems/ technologies for Space Station Freedom will be provided by the Canadians and Japanese. Robotic interface standards are being developed by the SSF Project Office to ensure compatibility with the SSF infrastructure and will provide an opportunity for the integration of U.S.-developed space robotics, e.g., the Flight Telerobotic Servicer (FTS), should that technology development be continued and validated by NASA's Office of Aeronautics and Space Technology (OAST). Provisions have not yet been included for operating the robots from the ground, and hence SSF's robots are highly dependent on the crew's presence.

(2) The Data Management System's (DMS) capabilities have been severely constrained and there may be limited performance margin, if any, left for incorporation of software to support unforeseen contingencies and projected requirements.

(3) All non-time-critical onboard automation functions have been migrated to the ground and provisions have not been included for migration back into the SSF onboard systems at some future date.

(4) The Space Station Control Center (SSCC) proposed design for Mission Operations has not taken full advantage of rule-based expert systems as utilized in the Real-Time Data Systems (RTDS) for onboard systems failure detection. As a result, flight controller productivity will be limited until expert system capabilities are available in the SSCC during the Permanently Manned Capability (PMC) operations phase of the program.

(5) SSF's capability to support the proposed life and material sciences experiments during the Man-Tended Capability (MTC) period may be marginal and could be enhanced with the addition of A&R technologies.

In summary, the Congressional-mandated reduction has resulted in (1) a deletion of all U.S.-developed space robotics capability, (2) has removed all onboard advanced automation from the U.S. portion of SSF, and (3) may preclude advanced automation technology evolution from implementation in SSF onboard and ground operations.

ATAC Concerns

Space Station Control Center

The design of the SSCC originally included a distributed processing environment allowing applications to be executed on flight controller workstations. However, the restructuring process significantly reduced and rephased the funds available for SSCC development, which necessitated a major redesign effort to provide a minimum cost architecture that meets requirements for safe operations with potential for future growth.

The restructuring process resulted in a more centralized design concept for command/control, systems failure detection, and systems failure analysis with distributed processing for the planning and flight design elements of the SSCC. The SSCC design allows for future distribution of systems failure detection and failure analysis processing to the realtime flight controllers' workstations. **It is ATAC's opinion that a distributed computational environment for SSCC systems failure detection and failure analysis, including expert systems, should be implemented to enhance flight controller productivity in the management and control of SSF's mission operations. This configuration would offer a better environment for the eventual migration of advanced automation technologies back into the SSF's onboard system.**

The presently baselined SSCC data distribution design incorporates a Fiber Distributed Data Interface (FDDI) network employing Open Systems Interconnection (OSI) protocols. The OSI protocols have not been developed specifically for robotics control and would likely require augmentation with other Local Area Network (LAN) applications such as the Manufacturing Message Specification (MMS), which is tuned for robotics control, should ground control of the manned-base robots become an SSFP requirement.

Within the SSFP budget constraints, the SSCC has established a design which reduces the initial development costs through the use of a more centralized architecture and use of existing software. In taking this more conservative approach, the use of expert system applications will not be implemented during the MTC operations time phase.

ATAC is concerned that the SSCC has not taken full advantage of the technology work being done in support of shuttle ground mission operations such as the RTDS expert system efforts. In addition, the evolution of advanced automation technologies into the SSCC are not clearly provided for, which could result in flight controller productivity that is lower, during the initial SSF operations phases, than is presently achievable with shuttle ground mission operations systems.

SSF Science, Operations, and Maintenance

Proposed SSF life sciences research facilities include a Centrifuge Facility, a Gravitational Biology Facility, an EVA/Space Physiology Facility, a Gas-Grain Simulation Facility, and a Controlled Ecological Life Support System Test Facility. Since the life sciences experiments are highly dependent upon support from the crew, there is a significant interest in utilizing technologies which would maximize the crew time efficiency. Two of the identified technologies are advanced automation and telescience. However, lack of funding has prevented any serious consideration and/or evaluation of these technologies for onboard utilization. Therefore, minimum life sciences experiments are being planned during the MTC period, due to lack of capabilities to operate the experiments during the absence of the crew.

Proposed material science experiments include protein crystal growth, solidification systems, fluid physics and dynamics, combustion, containerless processing, and biotechnology. Science operations during the presence of the crew will be similar to the Spacelab flights. Unmanned control and management of the experiments should be within the SSF's basic capability since most command sequences will be preprogrammed events and utilize conventional automation techniques.

Realtime video uplink capabilities to support onboard science experiments have been deferred to post-MTC due to the budget restructuring requirements, and there appears to be little SSF planning being implemented to support proposed science experiments. In addition, there appears to be a lack of understanding by experimenters of advanced A&R benefits, and unfamiliarity with which SSFP organization has been established to coordinate A&R requirements.

ATAC is concerned that there appears to be a lack of an SSFP focal point for the advocacy, coordination, and implementation of A&R into the life and material sciences experiments to ensure optimum utilization of the SSF facility and resources, both onboard and on the ground during the MTC period.

A&R Evolution

Due to the Congressional budget constraints, there are no advanced automation and robotics planned for the SSF. **With the exception of Work Package 4 (WP4) Electrical Power System (EPS), there is no commitment on the part of the WP contractors to seriously consider the use of robot-friendly designs, where applicable, to reduce the overall mission operations costs.** The WP4 contractor has done an outstanding effort in their aggressive pursuit of the use of advanced automation and robotics to reduce costs and EVA activities.

The SSF, Level I, advanced A&R development effort represents the only focused in-house effort to aggressively develop and prototype potential cost-effective uses for automation and robotics.

Potential Impact on U.S. Leadership in A&R

As indicated earlier, there is little hope for the implementation of advanced automation and robotics in the SSF design, both onboard and on the ground. **The implementation of Congressional budget constraints has virtually precluded the further development and implementation of U.S.-developed robotics technologies for SSF. With the deletion of the FTS development, world leadership in space robotics technology will be relegated to the Canadians and Japanese. The intent of Congress to have SSF serve as the focus for advanced U.S.-developed A&R technologies, which in turn would stimulate the transfer of these technologies into the U.S. industrial sector for international competitiveness, has not been met. ATAC believes that an integrated NASA A&R program would provide stimulus for increasing the international competitiveness of the U.S. industrial community.**

Focus of Next ATAC Meeting

The next ATAC meeting and report, Progress Report 14, will focus on:

(a) SSF's plans for the development and implementation of the Payload Operations Integration Centers (POIC) for the management of the scientific payloads, and (b) in-depth review of the SSCC's restructured computational environment including the plans for incorporation and migration of advanced automation technologies.

The SSCC review will take place at Johnson Space Center (JSC) in December 1991.

The current proposal is to have the POIC meeting hosted by Marshall Space Flight Center (MSFC) in February 1992.

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 to the extent possible in the midst of restructuring impacts. A review of the progress toward the recommendations from ATAC's most recent report, Progress Report 12, will be discussed first, followed by a review of topics explicitly addressed during the August 13-15, 1991 ATAC meeting, and then a discussion of new A&R issues. Progress appraisal is primarily based upon briefings given to ATAC during the August 13-15 meeting at JSC, but also is based on information obtained by attendance at relevant SSFP review meetings.

Before addressing the Progress on ATAC Report 12 recommendations, however, it is important to note that the program restructuring has entirely changed the context which existed at the time of previous ATAC recommendations. Namely, it was assumed that the United States would be involved in dextrous robotics in the form of the Flight Telerobotic Servicer (FTS). Therefore, making recommendations which integrated FTS into the SSFP in effective ways was natural. Now, with the transfer of the FTS out of the SSFP into OAST as a research experiment, the Station's baseline requirements for robotics will be provided by the Canadian Special Purpose Dexterous Manipulator (SPDM). **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 this intent.**

Assessment of Progress on ATAC Report 12 Recommendations

ATAC Progress Report 12, Recommendation I: Space Station Control Center and Payload Center Automation

"Develop and implement a plan prior to Critical Design Review (CDR) to include advanced automation functions in the Space Station Control Center (SSCC) and the Space Station Payload Center (SSPC) and their supporting facilities with eventual migration to onboard applications to ensure increased productivity and reduced overall operations costs."

SSFP Response to ATAC:

"It is expected that this recommendation will be addressed prior to CDR. The SSCC is the primary ground center for monitoring and controlling core systems of the Space Station Manned Base (SSMB). It is the focal point of operations planning for the Space Station and associated ground system and manages the uplink for core and payload system ensuring the safety of the crew and the integrity of the Manned Base."

"Following SSFP restructure, the major SSCC development challenge has been to provide a minimum cost architecture that provides the command and control capability required for safe manned base operation while allowing the flexibility for future program evolution. Further, the SSCC will incorporate technology and automation advances throughout the life of the program for productivity enhancements when life cycle operations cost reductions can be quantified. To achieve these goals, the SSCC baseline design is a hybrid processing approach incorporating centralized processing for command/ control (data calibration, limit sensing, command processing, data storage, TLM processing) as well as integrated fault detection/ management. All core system calibrated data, as well as products from critical application/ computations, are distributed via a high speed fiber optic network, to intelligent color graphic workstations for processing and presentation to the flight controller. This architecture represents a minimum cost and risk approach to ensure consistency and control of the SSMB operational processes; it also provides growth potential for evolution to a more distributed processing approach including rule-based run-time environments, where appropriate. In developing this hybrid SSCC architecture, the system design reflects a significant degree of leveraging off the Shuttle ground mission operations systems; Mission Control Center Upgrades (MCCU) and RTDS. This has been accomplished both from a lessons learned viewpoint as well as through direct reuse of MCCU and RTDS designs and software."

"Within SSFP budget constraints, the SSCC has established a design which provides a significant level of integration and automation in several key operations areas including Planning and Scheduling, Fault Detection and Management (FDM), and Status and Control. The design also offers improvements in display and computation generation capabilities significantly above that available for present Shuttle mission operation systems. The SSCC architecture is well proven and accommodates the insertion of new technology, such as ruled-based expert systems, while providing continuous stable operations support."

"Presently, the Real-Time Data Systems (RTDS) managed by JSC/MOD is demonstrating and validating the feasibility of advanced automation in the mission control and engineering support center environments. This project showcases the advantages of distributed computing, advanced displays, and console automation. While this approach is still being evaluated by the Space Station Program, it has been selected as a major component of the Mission Control Center Upgrade activity. RTDS is jointly funded by Level I Engineering Prototype Development, Code MD Advanced Programs, and the OAST AI Program. Additionally, DARPA has, at the request of Code MT, provided an advanced graphics workstation for use by the RTDS team."

"Related activities within Space Station Engineering Prototype Development (EPD) include advanced automation applications for monitoring and diagnosis of Power, Thermal and ECLSS subsystems. These applications are implemented on a distributed workstation environment and are intended to become an integral part of the Engineering Support Center environment and possibly migrate to the SSCC after evaluation. It is expected that, as these applications mature and supporting Space Station computer resources are made available, applications will be developed for on-orbit use."

"Automation of applications in a Space Station Payload Center will be the responsibility of the individual payload projects. The EPD activity has sponsored efforts to characterize the type of automation applications which would aid Space Station Payloads. An example is the Astronaut Scientific Advisor supporting a Spacelab Vestibular Physiology experiment. On SLS-1, ground-based support was provided to the science team at the Science Managers Area within the Payload Ops facility. During SLS-2 this capability will be provided on-orbit as well as on the ground. The Advisor increases astronaut productivity and enhances the return of scientific data by improving experiment monitoring, control, and diagnosis of results."

ATAC Assessment:

SSFP does not provide implementation of advanced automation functions such as rule based expert systems as early as desired by ATAC. SSCC has stated that a plan is being developed for migrating the advanced automation technologies to onboard applications sometime in the future. However, ATAC does not have knowledge of this plan. A detailed assessment of the SSCC plan will be conducted by ATAC during December 1991 and reported on in ATAC Progess Report 14.

The Level I sponsored Real-Time Data Systems for ground monitoring and diagnosis of spacecraft systems, provide benefits in improved safety and productivity, and is being developed and tested in the Shuttle Mission Control Center environment but is not included in current plans for the SSCC (until post-MTC) or the Payload Center.

ATAC does recognize some areas of SSCC conventional automation outside the areas of onboard systems monitoring. These include facility status and control, flight planning, and flight scheduling. Further, onboard system failure analysis is supported with the Failure Effects Analysis Tool (FEAT) at First Element Launch (FEL).

ATAC Progress Report 12 Recommendation II: Ground-based SSF Robotic Teleoperation

"Develop and implement a plan prior to CDR for testbed demonstrations and flight experiments to determine the feasibility for operation of the SSF robotic systems from the ground to perform station maintenance."

SSFP Response to ATAC:

"A Space Station 'Untended Operations Study' is being led at Level II to quantify the nature and scope of untended operations that can be supported within the boundaries of the restructured design. The study will identify limiting factors and prepare recommendations for an untended operations concept consistent with projected Station capabilities. The activity is divided into two areas, with MSFC responsible for Untended Payload Operations, and JSC responsible for Untended System Operations."

"In a related activity, the Level II-led Robotics Working Group has established a Splinter Group to determine the feasibility and extent of ground-based SSF robotics teleoperation. This study activity is being led by JSC/MOD with support from telerobotics experts at various centers."

"A Level I Engineering Prototype Development-sponsored task at JPL, which demonstrated robotic inspection with time delay, is currently developing a joint plan with the JSC Automation and Robotics Division to implement this capability on the SSF Robotic Integration Testbed. This activity is being coordinated with Level II Robotics Working Group and splinter group."

ATAC Assessment:

SSFP did not give ATAC a briefing on the status of current planning and progress by the ground control splinter group of the Level II Robotics Working Group. Therefore, an adequate assessment of the SSFP progress on this recommendation could not be accomplished. **The SSCC design does not incorporate network protocols or other applications specifically tuned for robotics control. The baseline design will have to be modified to support implementation of ground control for the Manned-base robots if this becomes a program requirement.**

ATAC Progress Report 12, Recommendation III: Science Productivity

"Prior to CDR, evaluate onboard automation and robotics specifically needed to permit operation of desired science experiments during the unmanned periods of the Man-Tended Configuration phase, and implement an advanced A&R plan as appropriate, to enhance MTC science productivity and utilization."

SSFP Response to ATAC:

"A Space Station 'Untended Operations Study' is being led at Space Station Level II to quantify the nature and scope of untended operations that can be supported within the boundaries of the restructured design, identify limiting factors, and prepare recommendations for an untended operations concept consistent with projected Space Station capabilities. The activity is divided into two areas, with MSFC responsible for Untended Payload Operations, and JSC responsible for Untended System Operations. This is the first step in defining the onboard untended science operations environment for the restructured station. Any advanced automation required to support a specific science experiment will be the responsibility of that experiment."

ATAC Assessment:

The Level II Untended Operations Study was not presented to ATAC. ATAC is not able to assess if this study will address the onboard automation and robotics specifically needed. The Life Sciences and Material Sciences experiments programs as briefed to ATAC did not include use of advanced A&R, except for an Intelligent Microscope which showed major benefits.

ATAC Progress Report 12, Recommendation IV: SSF Dexterous Robots

"Develop and implement a plan prior to CDR for integration of dextrous robots into the onboard SSF science, operations, and maintenance activities."

SSFP Response to ATAC:

"The Space Station Freedom Program is committed to integrating dextrous robots into external post-Man Tended Capability assembly, maintenance, and servicing operations. Crew EVA time is a highly limited resource, and the program relies on the Canadian Special Purpose Dextrous Manipulator (SPDM) and the Japanese Small Fine Arm (SFA) to assemble and maintain the Station core infrastructure and user payloads. The integration of the SPDM and the SFA is a major aspect of the Robotics Integration Technical Area Management Plan that is being developed jointly by Level II and the JSC Automation and Robotics Division. This Technical Area Management Plan defines the objectives, responsibilities, activities and products associated with robotics integration, and serves to document the SSF robotics architecture. Robotic system-to-SSF integration, interface definition, and system and task verification are addressed at a high level in the plan and in greater detail in program documentation such as the SPDM System Requirements Document (SRD), Robotic Systems Integration Standards (RSIS), and Program Master Verification Plan (PMVP). The plan will be baselined and implemented prior to CDR and updated periodically as required. Dextrous robotic systems are a vital part of SSF operations, and are being addressed as a Technical Management Area to ensure that their capabilities are effectively and efficiently applied."

ATAC Assessment:

Level II is making good progress on the organizational management and integration of dextrous robots into the onboard operations and maintenance activities. IVA crew timeline analysis studies have begun which should include dextrous robot monitoring and control. However, there are potential cost increases of imposing the robot friendly Robotic Systems Integration Standards (RSIS) on EVA compatible baselined designs at this stage of development. The SSFP must be able to negotiate and accommodate these potential cost increases or only very limited use of dextrous robots will result. No onboard SSF science support with dextrous robots is currently planned by either science or the SSFP due to lack of budget priority.

ATAC Progress Report 12, Recommendation V: Technology Transfer and Implementation

"Strengthen cooperation between the technology and programmatic (user) sides of the Agency, and provide the SSF Advanced Development Program with funding levels commensurate with that required to transfer and implement advanced A&R technologies into SSF operational environments."

SSFP Response to ATAC:

"The Level I Engineering Prototype Development activity has aggressively pursued cooperation between Flight and Research Centers by building teams of technologists and users for many of the funded tasks. These collaborations have been further facilitated by jointly funding advanced technology applications with the Office of Aeronautics and Space Technology (OAST) and other government and industrial technology-oriented organizations, such as DARPA. Also, the Level I Advanced Studies Program has identified long-range technology requirements necessary for SSF growth and evolution and provided these to OAST in numerous forums."

"During early FY91, OSF developed an integrated technology assessment document entitled 'Office of Space Flight Technology Requirements - Definition and Planning for Coordinated Programs.' On April 26, 1991 this document was transmitted under cover letter from the Associate Administrator for Space Flight to the Associate Administrator for Aeronautics, Exploration and Technology. The assessment reflects the consolidated technology needs of Space Station, Space Shuttle, and Flight Systems/ Advanced Vehicles Programs. Over 250 separate application areas in a range of disciplines were narrowed to a list of top 21 major technology areas. Of these 21 areas, 16 were identified as being program unique and 5 identified as being industry driven. A number of the top 21 requirements support advancements in, and delivery of, automation and robotics technology. For example, functional improvements in vehicle health maintenance, crew training, and robotics are required. It is expected that technologists will use these requirements to formulate the basis of their technology investment. Inherent in this process is the necessity for both sides to continually meet and update each other on their strategic plans and to jointly select technology transition opportunities consistent with the major areas prioritized in the assessment. The Level I Engineering Prototype Development activity recognizes this responsibility and has attempted to establish productive relationships with a number of technology program managers in the automation and robotics areas."

ATAC Assessment:

A greatly improved process of identifying and prioritizing technology requirements by the programmatic (user) side for use by the technology development side of the Agency has been developed. This process, primarily as a result of advocacy by Level I, has placed high priority on advanced A&R. Also, the SSFP Level I Engineering Prototype Development (EPD) (previously the Advanced Development Program) has been productive in transferring and validating advanced A&R technologies into operational organizations (but not yet SSF Program baseline operations systems and plans) despite budget reductions. Further budget reductions will make operational use very unlikely; instead, expansion of EPD in A&R should be supported. In addition, ATAC is concerned that OAST has not yet responded to the technology requirements defined by SSFP in the technology assessment document "Office of Space Flight Technology Requirements - Definition and Planning for Coordinated Programs," thereby resulting in an overall NASA A&R Program that is not coordinated and integrated with SSF programmatic requirements.

ATAC Progress Report 12, Recommendation VI: Flight Telerobotic Servicer (FTS)

"Encourage OAST to implement an intelligent telerobotic flight development project like FTS and to conduct FTS flight experiments on SSF and/or STS which will permit evolution of U.S. dextrous robots onto Space Station Freedom."

SSFP Response to ATAC:

"During early FY91, OSF developed an integrated technology assessment document entitled 'Office of Space Flight Technology Requirements - Definition and Planning for Coordinated Programs.' On April 26, 1991 this document was transmitted under cover letter from the Associate Administrator for Space Flight to the Associate Administrator for Aeronautics and Space Technology and reflects the technology needs of Space Station, Space Shuttle, and Flight Systems/Advanced Vehicles. Robotics was added as a high priority item subsequent to the transfer of the FTS to OAST/RX. Section 4.13 of the document lists seven specific technology areas that support SSF telerobotics technology needs. Discussions have been held with OAST/RX and GSFC pertaining to FTS DTF-1 and potential follow-on flights and with OAST/RC pertaining to robotics technology development. The discussions between OAST/RX and GSFC are on target with Section 4.13 recommendations. The OAST robotics technology program linkages to the identified OSF requirements are expected to improve in FY92."

ATAC Assessment:

The OAST FTS plans were not reviewed by ATAC. ATAC recommendations II, IV, and V above, if aggressively carried out, would create an SSF which uses dextrous robots and thus would encourage OAST to develop a U.S. space dextrous robotics capability. However, a strong and productive OAST program for space dextrous robotics is not possible without adequate funding from the U.S. Congress, and without OAST responsiveness to SSF identified requirements.

ATAC Progress Report 12, Recommendation VII: Life-Cycle Costs

"Utilize a standardized procedure to assess the life-cycle costs across the Space Station Freedom Program resulting from the current restructuring activity and the reduction of onboard advanced A&R technologies."

SSFP Response to ATAC:

"Prior to and during Restructuring, the Program has utilized a variety of tools and techniques to analyze the costs of various design trades and operational approaches. While these individual trade studies may appear unstructured and nonstandard, the approaches used follow traditional aerospace industry practices. It should also be pointed out that solid, well tested, life-cycle cost models do not account for the impacts of automation. This validates the approach of testbedding technology on baseline facilities in order to gain experience with as much engineering fidelity as possible."

"Currently, the Program is culminating its analysis of the impacts of Restructuring with a series of Work Package Delta Preliminary Design Reviews in preparation for the MTC Phase Review. The Program will continue to use available life-cycle cost analysis tools and techniques in support of the development process."

ATAC Assessment:

The SSF Program has not applied a standardized procedure to access life-cycle costs resulting from the current restructuring activity and the reduction of onboard advanced A&R technologies, nor is the SSFP collecting any meaningful metrics in addition to Design, Development, Test, and Evaluation (DDT&E) cost aggregates to support future development of life-cycle cost models. The SSFP has been forced by Congressional budget reductions to take reduced DDT&E measures with regard to advanced A&R, which will probably have implications for reduced productivity and increased operations costs over the life of the program.

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

Assessment of Level I

The Advanced Development Program had previously been reported as the primary mechanism for the advanced development of A&R technology for inclusion in the SSFP. This program is now called the Engineering Prototype Development Program and continues on at a very modest level of funding. The objectives of this program are to enhance baseline SSF flight and ground systems capabilities and to provide enabling technology for SSF evolution.

This program leverages considerable joint funding and is accomplishing significant advanced development relative to the limited funds expended. The emphasis is on placing the advanced technology in the testbeds utilized in the SSFP. This may allow some advanced automation to get into the SSFP as the engineers see its value in high fidelity testbed applications.

Level I is commended for keeping this program alive during the current period of very constrained and limited budgets, and continuing to produce and make available advanced technology. However, the reality of the fiscal constraints precludes SSFP project managers from taking full advantage of the advanced technology being developed by Level I programs.

The Level I A&R program received high visibility through the recent SSF Evolution Symposium held at JSC. ATAC feels that the Engineering Prototype Development Program will not have the impact on the baseline SSFP that it could have because of budget constraints. However, it continues to demonstrate valuable technology that is directly applicable to Space Station Evolution.

Assessment of Level II

ATAC received an excellent presentation from Level II on their robotics activities. In robotics, there was a major shift of attention from interfaces and capabilities of the Flight Telerobotic Servicer to interfaces and requirements for the Canadian Special Purpose Dextrous Manipulator (SPDM). The robotics issues concerning requirements, standards, and interfaces with the SPDM and Japanese robots are being worked. The presentation by Level II directly addressed progress and completion of previous ATAC recommendations in robotics. Effort and progress were evident in establishing standards and interfaces in robotics.

Specific ATAC recommendations were addressed by Level II since the last report. The first response was to ATAC Report 11 Recommendation I to implement a formal design standard which is robot-friendly. Orbital Replacement Unit (ORU) standards are being developed and are included in Robotic Systems Integration Standards (RSIS) Volume I (Robotic Accommodation Requirements) which is baselined in the program and RSIS Volume II (Robotic Interface Standards) which is in Change Request status and has been issued for program-wide review via CR BB003065. This effort specifically addresses the ATAC Report 12 recommendation to baseline the RSIS. However, the Change Request still needs to be approved and resulting impacts absorbed by the program. The standard H-Handle Standard Robotic Interface, Micro Standard Robotic Interface, and Standard Visual Target were tested and evaluated at GSFC, JSC, and CSA/Spar.

Progress was made on the Dextrous Task List by the Work Packages and Level II in the Robotics Working Group. This is responsive to ATAC Report 12 issue to identify specific dextrous robotic tasks in program documentation. This Dextrous Task List is to be incorporated into the PDRD Section 3 as Table 3-55 (CR BB003065). A list of robot-compatible ORUs was compiled representing 413 ORUs or 48% of the Space Station Freedom Program external ORUs. This could represent an offload of 70% of EVA maintenance man-hours from EVA to robotics if the change request to make the ORUs robot-compatible is approved.

Other progress on ATAC recommendations include: 1) integration of models and simulations (ATAC Report 11 Recommendation II)—splinter working group formed to address the issue; 2) operate telerobotic systems from the ground (ATAC Report 11 Recommendation V and ATAC Report 12 Recommendation II)—Robotic Working Group Splinter Group being formed to address the issue; 3) perform an IVA timeline study (ATAC Report 11 Recommendation IV)—study being conducted by Work Package 1 with decision package recommendations due in April 1992.

In contrast to the progress in robotics, no one is assigned to advanced automation in the Level II organization. There has been no effort directed by Level II to incorporate advanced automation. As a result, there are no provisions to review and support hardware scars, software hooks, or other provisions for evolution of the system. The approach appears to be very shortsighted and may increase life cycle operations costs. Advanced automation has been deleted by the restructured Space Station. Advanced Automation Prototypes developed by Space Station Level I may still have an impact on the baseline program, but this is very difficult in the current environment.

A sanctioned Robotics Working Group managed by Level II is now very active sponsoring meetings of the work packages and the international partners. Progress is being made on the integration of telerobotics on space station. The development of Robotic System Integration Standards (RSIS) is crucial to the implementation of robotic interfaces and standards on Space Station enabling telerobotic operations. JSC in their contract baselined EVA for external maintenance with robotics being used where practical and cost-effective. Presently, most JSC Work Package 2 ORUs are not serviceable by robots. Currently, there are no interfaces for grasping by telerobots on the ORUs. If these units are not redesigned to be robot-compatible, the full burden of maintenance of the WP2 ORUs will be through EVA.

In conclusion, the ATAC assessment is that the Space Station program is moving toward the capability to have ORUs replaced by either EVA astronauts or telerobots. This step is absolutely crucial to having adequate servicing capability on the Space Station. Without the capability of interfacing for servicing by the Canadian Special Purpose Dextrous Manipulator system, the Space Station maintenance program would be seriously jeopardized. The U.S. is no longer providing telerobotic hardware for the Space Station, which will seriously degrade the U.S. competitive position in space robotics. ATAC is concerned that the SPDM may not have the full range of capabilities to support desired servicing on the Space Station. ATAC is also concerned that little progress has been made in evaluating Telerobotic Ground Remote Operations for use in the baseline operator control station.

Level II has been very active with its Robotics Working Group trying to establish standards for robotic interfaces and other critical issues. ATAC commends this effort and visible progress, but is concerned that the planned shift of responsibility of the Level II Robotics Working Group from Level II to Work Package 2 will reduce its influence in establishing standards across all work packages.

ATAC is also concerned that there is little or no provision in the Space Station Freedom Program for evolution of the robotic systems and no provision for advanced automation or the evolution to advanced automation. Provisions need to be made in the overall program for advanced A&R evolution; this lack of attention to advanced technology and evolution planning will increase life cycle costs.

Assessment of Work Package 1

Work Package 1 did not send a representative to support the ATAC meeting or report on their A&R activities. There is currently no WP1 plan to implement IVA automation or robotics. This approach will certainly cut front-end costs but will increase the Life Cycle cost for operation of the Environmental Control and Life Support System and Power Management and Distribution system. However, Work Package 1 is supporting the Level II Robotics Working Group and is supporting the work to establish robotic interface standards for its external systems. Although progress is being made, considerable work needs to be done to define, design, and test robotic interfaces for the Unpressurized Logistics Carriers with their Cryogenic Nitrogen Carriers, Cryogenic Oxygen Carriers, and Dry Cargo Carriers, so that cryogenic supplies, dry supplies, and replacement ORUs can be unloaded and handled by the robotic systems.

Assessment of Work Package 2

The WP2 contractor reported a continuation of the decline in A&R staffing that was evident at the time of ATAC Report Number 12. And, at this time, all WP2 ORUs are baselined for EVA maintenance. However, the baseline designs generally do not preclude robotics. And WP2 contract requirements have been modified to state that "SSMB design shall baseline SPDM and/or SSRMS manipulation for external ORUs selected on the basis of hazard to EVA crew members, crew member capability limitations, the potential for reducing EVA maintenance time requirements, reliability, and criticality." The WP2 contractor is maintaining a "Robotic Candidate List" to identify ORUs that could subsequently be baselined for robotic manipulation. Currently the WP2 Robotic Candidate List contains 193 ORUs which represent over 60 per cent of WP2 ORU maintenance man-hours required per year.

In its planning for implementation of automation and robotics, as in other areas, work package 2 is still adapting to the recent program restructuring. The PIT exercise may have provided improved opportunities for robotic accommodation, but the deletion of the FTS would appear to have had the opposite effect, at least initially. Plans to make WP2 ORUs robot-compatible, and to rely on robotics to significantly offload EVA requirements, are hampered by the facts that the remaining (non-US) robots are less well defined than was the FTS and the WP2/Canadian working relationship is not as well established as was the relationship between WP2 and WP3.

Work Package 2 has no reluctance to work the problems associated with establishing a role for non-US robotics in station assembly and maintenance. However, due to the uncertainties and unknowns about the robotics to be provided by the international partners, WP2 seems to believe that responsible project management requires them to plan on EVA for all maintenance. The SPDM is not planned to be available to the program until 1997 (MB-7). This is a little late for robotics to play a big role in assembly.

In report 12 ATAC indicated that all of the advanced automation functions planned for WP2 had been deleted from SSF. The hope was expressed that much of this advanced automation would be moved to the ground. The advanced automation has been removed from onboard SSF, but there appears to be no current plans for implementation of advanced automation on the ground.

Assessment of Work Package 4

The Electrical Power System (EPS) consists of a flight support system on board 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 annunciated. The ground controller's 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 in the planning and decision-making associated with power management control. They plan to test the program on the Space Station Freedom Power Test-Bed. The advisory system consists of three elements: failure diagnosis, security analysis, and operations planning and scheduling. The diagnosis expert system uses available telemetry data to determine the most likely cause of a failure. The security analysis system conducts "what if" contingency analysis to determine the risk of continued operation. The results of this event analysis alter the operating constraints and mission objectives which in turn require a revised operating plan. The scheduling system provides assistance in developing this plan by allocating resources according to the constraints identified by the event analysis system. The output of these programs acts as an expert advisor to the ground controller.

ATAC commends WP4 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 are due to be robot-compatible. They conducted a comprehensive test program with GSFC on the use of FTS for ORU removal and replacement and are currently examining the interfacing between the Canadian SPDM and the EPS modules. They have been an active participant in the Robotics Working Group to establish the Robotic Systems Integration Standards (RSIS) and are actively participating in RSIS revisions with a goal of minimizing cost impacts to SSF.

Assessment of Space Station Control Center

The last report of the ATAC identified an initial impact of program restructuring on the use of A&R in SSF operations. The reduction in number of Standard Data Processors (SDP) and the limitation of systems software in the Data Management System (DMS) to 1 Mbyte will require the transfer of all but Category 1 and time-critical Fault Detection, Isolation, and Recovery (FDIR) functions to the ground, i.e., the SSCC. In order to assess the application of A&R technology in this context, the ATAC received a very comprehensive set of briefings on the SSCC architecture, current R&D work and application plans in fault management, and on related A&R applications in the Shuttle program.

Very successful Shuttle A&R applications have been developed under the OAST, STS, and SSF advanced development programs, and have been transitioned to operational environments. The Real-Time Data System (RTDS) has provided a workstation-based environment for the development of expert systems, and has been used by STS flight controllers to develop automated fault detection capabilities for their individual console positions, including Communications, Main Engine Monitoring, Guidance, Navigation and Control, Mechanical Systems, the RMS, and the Emergency Mission Control Center. This represents an excellent and significant step in the application of A&R technology to control center operations, and should provide an initial target for SSCC.

SSCC advanced development work is planned as follows: At FEL, the flight controllers monitoring onboard systems will have the Failure Environmental Analysis Tool (FEAT) for systems failure analysis. For failure detection, the SSCC utilizes advanced algorithms and special computations developed in conjunction with the FEAT. Both failure analysis and detection information is presented on workstation monitors using displays developed with the "SAMMI" display builder tool. This tool provides flexible support for computation and display of failure detection and analysis at FEL.

The post restructure SSCC development plan shows the full integration of the fault detection and fault analysis capabilities at the MTC delivery. Work on AI/expert systems (such as failure detection with rule-based expert systems) does not start until post MTC. The SSCC architecture has centralized processing of the command/control, fault detection, and fault analysis functions while distributing the planning and flight design functions. It does, however, retain the option to distribute the system failure detection and analysis processing. ATAC believes that the introduction of rule-based expert systems for onboard systems failure detection and analysis should be accelerated. Secondly, ATAC understands the rationale for a centralized command/ control function, but believes all or most of the failure detection and analysis should be decentralized. It is felt this will provide a more flexible environment for the development of advanced automated systems.

The SSCC will provide distributed automation of the complex Space Station planning system. The planning and scheduling subsystem will provide the tools for generation of tactical and short-term plans and schedules with automatic assessment and resource conflict resolution.

In summary, while the SSCC does provide automation of facility operations and flight planning functions at FEL, ATAC believes the additional up-front investment in flight systems monitoring will be far outweighed by the future cost savings to NASA.

The capability to accomplish modeling of the Space Station Remote Manipulator System (SSRMS) is being developed for use in a console within the SSCC. This capability will allow the ground controllers to model onboard SSFP robotic operations prior to actual astronaut operations, which will assure that functions will be accomplished in the most reliable, efficient, and safe manner. Since most robotic operations on SSF will include the use of the Special Purpose Dextrous Manipulator (SPDM) on the end of the SSRMS, modeling of the entire SSRMS/SPDM coordinated system will be required within the SSCC robotics console to assure that all onboard operations are evaluated prior to onboard use by the astronauts.

The present plan for the SSCC, as well as Space Station Training Facility (SSTF), is to take full advantage of the robotics modeling being accomplished within the JSC/Engineering Directorate and/or the Canadian Space Agency (CSA). The JSC Mission Operations Directorate has an active Model Assessment Team (MAT) which is continually assessing and reviewing available models for reuse in the SSCC and SSTF. The assessment of the JSC Engineering Directorate Model, Manipulator Analysis Graphical Interactive Kinematic (MAGIK), and the CSA "MIKE" kinematic model is ongoing at this time. Both models are Shuttle RMS based and include general requirements for modeling of integrated operations of the SSRMS and SPDM along with the capability to model hands-off with the SRMS for joint Shuttle/Space Station freelance robotic operations. The SSCC will rehost one of these models after appropriate review and analysis to ensure that all SSCC planning and real-time robotic operations requirements can be met. The present models may not include SPDM since the design information is not yet mature enough. In addition, due to the issue of CSA/USA roles and responsibilities which is still being worked by the SSFP at Level II, neither the SSCC design team nor the MAT has been able to obtain detailed technical data regarding the specifics of the planned CSA MIKE models.

Assessment of Payload Operations Integration Center (POIC)

The development of the POIC has as a stated goal the avoidance of future operations costs through the use of expert systems in system monitoring, control, and fault analysis. The only current A&R application described was an AI-based tutoring system to train payload specialists and the supporting operations team. The briefing on the architecture design for the POIC was less detailed than that on the SSCC, but was sufficient to identify potential system elements to support this automation. However, there is a general concern that budget decisions could create similar barriers to automation as described above for the SSCC.

Crew-tended payload operations are planned to be similar to Spacelab operations. Due to budget constraints, the development of a planning and scheduling system has been deferred, and the scheduling system used for the current Spacelab will be used into the late 1990s. Where payload control can be automated from the ground, this will be supported in parallel with crew-controlled operations. Because the primary function of the POIC is to support payload operations, many of the potential applications of A&R will be dependent on the experiments being flown. Consequently, they must be developed along with the experiments and cannot be evaluated at this time.

Assessment of SSF Science Payloads

ATAC received for the first time a briefing from the scientific community on proposed SSF life and material science experiments, and to what extent A&R is being utilized.

Life sciences biological research facilities on SSF include a Centrifuge Facility, a Gravitational Biology Facility, an EVA/Space Physiology Facility, a Gas-Grain Simulation Facility, and a Controlled Ecological Life Support System Test Facility. Because life science experiments are highly dependent upon support from the crew, there is a particular interest in utilizing advanced technology where there can be a significant savings in crew time compared to the costs. Life sciences experiments can benefit significantly from telescience capabilities which would provide improved communications between crew and principal investigators, and which would allow for real-time changes to experiment protocols. However, given the current funding limitations and lack of an SSFP focal point for coordination, there is currently very minimal if any advanced A&R technology planned for use in SSF life science experiments. In addition, real-time video uplink capabilities have been deleted as a result of SSF restructuring. Because of being highly dependent upon interaction with the crew, there are no life science experiments planned on SSF during MTC except for those brief times that the crew is present on STS flights.

Material science SSF experiment areas include protein crystal growth, solidification systems, fluid physics and dynamics, combustion, containerless processing, and biotechnology. Science return from material science experiments will begin in 1997 during MTC and will continue into PMC and beyond. Science operations during times of crew presence will be similar to Spacelab flights except for the added tasks of collecting and securing of samples, experiment setup for unmanned runs, and rack/module equipment changeout. Unmanned operations will require minimal two-way communications between payloads and ground. Payload automation will typically consist of preprogrammed command sequences and automated fault detection for out-of-limits conditions.

There appears to be little SSF planning being implemented to support proposed science experiments. Also, there appears to be a lack of understanding by experimenters of advanced A&R benefits, and which SSFP organization is established to coordinate A&R requirements. **ATAC is concerned that there appears to be no A&R focal point in the SSFP organization to which science payload personnel can come for expertise and advice.**

In summary, SSF life science payloads are highly dependent upon crew support, and rely very little on advanced A&R. Thus, very minimal return from life science experiments is expected until PMC. SSF material science payloads generally do not require the crew other than for experiment setup, and science return is expected to begin during MTC. SSFP should designate a science A&R focal point, and should provide real-time video uplink capabilities to enhance telescience effectiveness.

New A&R Issues: Space Station Control Center

Space Station Control Center Automation

During the ATAC Report 12 review in February 1991, it was indicated that all SSFP automation functions would be migrated to the ground Space Station Control Center (SSCC). Pursuant to this new direction, ATAC recommended in Report 12 that: SSFP develop and implement a plan prior to CDR to include advanced automation functions in the Space Station Control Center (SSCC), the Space Station Payload Center (SSPC), and their supporting facilities with eventual migration to onboard applications to ensure increased productivity and reduce overall operations costs.

At the August 1991 ATAC review, it was reported that the funding would not support a rule-based expert system technology development until post MTC. The Level I Advanced Development Program review indicated that there are many expert system prototypes for power, thermal control, environmental control, etc., that have been developed to the point to justify future implementation within the SSCC.

ATAC recommends that 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.

Onboard SSF Science, Operations, and Maintenance

Science Productivity

Science return from material science experiments will begin in 1997 during MTC after launch of the U.S. Laboratory with minimal, if any, enhancements from utilization of advanced A&R. Material science payload automation will typically consist of preprogrammed command sequences and automated fault detection for out-of-limits conditions. Life science experiments are highly dependent upon support from the crew, and can benefit significantly from telescience capabilities which would provide improved communications between crew and principal investigators, and which would allow for real-time changes to experiment protocols. However, real-time video uplink capabilities have been deleted as a result of SSF restructuring.

A conclusion of a study conducted by the SSFP Level I Engineering Office indicated that there is currently no visible focal point within SSFP for the payload community to come to for expertise and advice on DMS design requirements. It is ATAC's opinion that a focal point within SSFP for advanced A&R expertise and consultation available to the payload community would be very productive for enhanced SSF science return.

ATAC recommends that SSFP increase its 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.

Robotic and EVA SSFP Maintenance

Since the ATAC Progress Report 12 there has been an extensive effort to develop standards for assuring that robotics can be used for SSFP maintenance functions, including ORU changeout. The Robotic Accommodation Requirements document (RSIS Vol. I) has been baselined via directive BB003023, the Robotic Interface Standards and PDRD Section 3 Table 3-55 have been developed and issued for program-wide review via CR BB003065; Robot-to-ORU interface testing is in progress at GSFC, JSC, and CSA/SPAR; and SSFP Level II has defined an IVA maintenance demand study. However, during the ATAC work package reviews of ORUs most of the contractors indicated that modifications of their proposed ORUs to meet robotic capability are not within the baseline program. Also, it was indicated that the SPDM may not be able to support robotic change-out of ORUs even if they were modified to accommodate the operations.

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

SSRMS and SPDM Accommodations

The Canadian A&R Space Program, as represented by SPAR, has demonstrated outstanding performance in space robotics with the Shuttle RMS and other previous robotics applications, and has established a large experience base for space robotics. SPAR's experience lends strong credibility to the anticipated success of SSRMS and SPDM. The SPDM will have considerably more dextrous robotic capabilities than the SRMS and can provide significant capabilities to support ORU maintenance requirements. However, ATAC is concerned that the SSRMS and SPDM robotic capabilities to support SSF needs may be reduced if not fully integrated into SSFP plans.

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

A&R Technology Utilization

Level I Engineering Prototype Development

The Level I Engineering Prototype Development Program is the only significant advanced A&R development being pursued within the SSFP. During the past year, this program has focused on completing demonstrations of advanced automation software on SSFP high fidelity testbeds prior to the Critical Design Review (CDR). These efforts have increased the awareness of the SSFP workpackage contractors of the benefits of advanced A&R technologies, and have initiated an integrated effort for preliminary technology verification and validation.

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

ATAC Progress Report 13 Recommendations

Space Station Control Center

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."

Onboard SSF Science, Operations, and Maintenance

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."

Recommendation III: Robotics and EVA SSFP Maintenance

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

Recommendation IV: SSRMS and SPDM Accommodations

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

A&R Technology Utilization

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."

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Appendix A

Space Station Freedom Program A&R Progress

The Space Station Freedom Program (SSFP) has committed to apply 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. The program recognizes 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 other government, industrial, and academic initiatives.

Progress by the SSFP is described in the following sections.

Level I A&R Progress

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, 11, and 12 Appendices A.

Advanced Programs has recently 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 Space Station flight and ground systems capabilities by prototyping applications of advanced technology. These improvements will lead to increased system productivity and reliability, and help prevent increased operations and life cycle costs due to technological obsolesence. The activity evaluates 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, Exploration and Technology; the Space Shuttle Program; the Office of Space Science and Application; 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.

Currently, the majority of the Engineering Prototype Development FY91 budget of $7.4M is dedicated to A&R applications and technology development. Nineteen tasks are divided between Flight and Ground Systems ($2.6M), Space Station Data Systems ($2.3M), Advanced Software Engineering ($1.4M), and Telerobotic Systems ($1.1M). Thirteen of the tasks are leveraged by joint funding from the Office of Aeronautics and Space Technology (OAST), the Shuttle Program, the United States Air Force (USAF), and the Defense Advanced Research Projects Agency (DARPA). The joint funding adds $7.3M 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 & Development funding to address complementary objectives of Engineering Prototype Development. 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.

During FY91, the continuing resolution process, program restructuring, and FY92 Congressional deliberations forced Engineering Prototype Development to allocate funds in seven increments. The result of this "Just-in Time" financial management exercise has been numerous schedule slips, strained joint funding relationships, and an uncertainty regarding task continuation during the coming fiscal year.

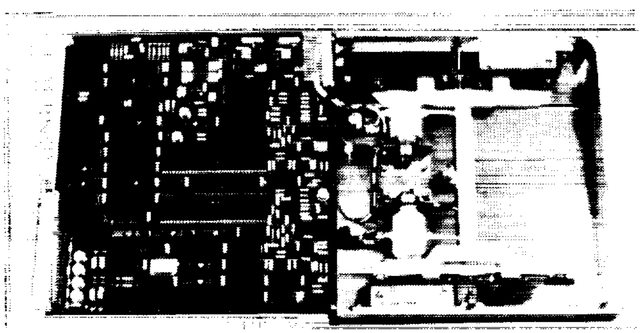
In the Flight and Ground Systems area, advanced automation applications are being developed for Power Management and Distribution (PMAD) and Environmental Control and Life Support System (ECLSS) at Work Package 1, the Thermal Control System (TCS) and applications for the Mission Control Center (MCC) 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 also 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, etc.) and identify KBS implementation 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 during this reporting period follow.

PMAD FDIR application and user interface software on the Marshall Space Flight Center (MSFC) PMAD testbed has been linked with the Lewis Research Center (LeRC) Power Management and Control (PMAC) testbed. The second successful test of this linkage demonstrated the ability for LeRC and MSFC to schedule primary and secondary loads respectively; LeRC then detected a fault, rescheduled its loads, and issued a power reduction warning to MSFC; MSFC then automatically shed all low-priority secondary loads. It is planned to continue linked test-bed demonstrations to further integrate power generation and power distribution automation. PMAD Breadboards are shown in figure A1. The Texas A&M Center for the Commercial Development of Space has expressed interest in applying Electrical Power System autonomy technology derived from SSM/PMAD to their Commercial Expendable Transport program. This may provide an additional flight opportunity.

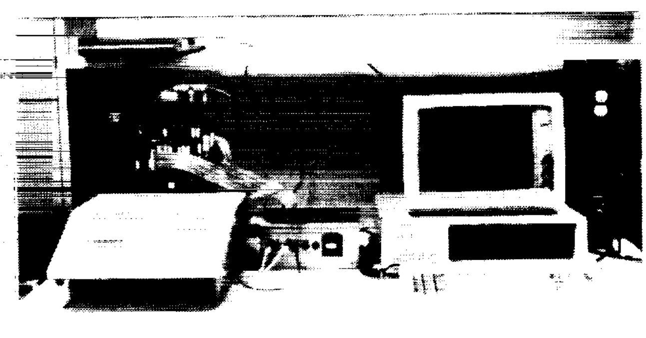
Advanced automation techniques have been selected to support the ECLSS Predevelopment Operational System Test scheduled to begin evaluating the Air Revitalization Subsystem in January 1992. Work continues on a potable water quality monitoring prototype by using inputs from a high-fidelity simulation.

The Thermal Control automation project is being integrated into the SSF Thermal Control System (TCS) test-bed to support the TCS verification process. Communications between the RODB-like software and the thermal test-bed data collection software has been established and will be tested during ambient and thermal vacuum tests this fall. The TCS test-bed at JSC is shown in figure A2.



Digital Dual Channel Dc
Remote Power Controller (50amp)

Dc-Dc Converter (6.25 kw)



Common Controller Card

Figure A1. Power management and distribution breadboards.

The RTDS continues to expand and make dramatic improvements within Space Shuttle Mission Operations. The Flight Director Wind Monitor system flawlessly supported Flight Directors during STS-37, -39, -40, and -43. In addition, new Fuel Cell and Data Processing Expert Systems were placed on-line in the Shuttle MCC. Improved data acquisition software was also used successfully in support of the recent Shuttle missions.

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, 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. Crew members and the experiment's Principal Investigator have been actively involved in the prototype's development and evaluation. 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. Recently, a number of scientific principle investigators have indicated that "intelligent tending" will be crucial to their experiments.

Within Space Station Data Systems, the computer and network architectures of Space Station Freedom's Data Management System are being analyzed to

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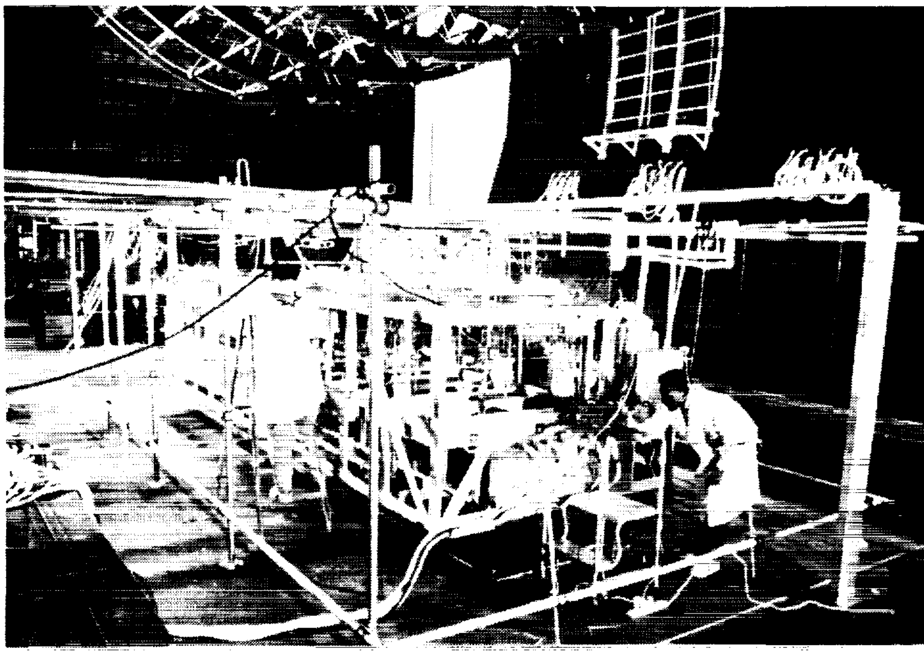

Figure A2. Thermal control system testbed at Johnson Space Center.

provide increased performance and reliability and to determine long-range growth requirements. Additionally, advanced mission planning and scheduling tools are being developed and demonstrated for use on board Freedom as well as on the ground. 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 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. 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 is currently being supported by a set of STS Development Test Objective (DTO) tasks. Recently, an STS DTO on STS-43 using a Macintosh portable evaluated 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. Computer and software was also used to support the Lower Body Negative Pressure Suit Experiment.

The COMputer Aided Scheduling System (COMPASS) continues to improve in functionality and is used in a variety of scheduling applications. It has been used to derive and highlight schedule scenarios within the SSFP Design Reference Mission documents and is currently being evaluated for its ability to schedule facility resources and crew training time. MDSSC 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. Tasks have included developing and evaluating Ada cross-compilers for existing KBS tools and benchmarking their performance using operational advanced automation prototypes, creating tool kits which support the reuse of design information, and developing and demonstrating verification, validation, testing, and maintenance tools and techniques for flight and ground software. Intelligent Computer Aided Training architectures are being developed and demonstrated in operational settings. These architectures offer training improvements by reducing the overhead involved in setting up training environments, scheduling classes, and developing simulations. The most significant accomplishments during this reporting period follow.

The Failure Environment Analysis tool has been selected by Level II as the standard tool for integrating subsystem Failure Modes Effects Analysis (FMEA) data. This tool uses directed graphs (DiGraphs) to model cause-and-effect relationships, providing significant benefits over fault trees. Digraphing facilitates modeling and produces a very-high-fidelity simulation capability as a natural by-product of reliability engineering.

The Software Support Environment (SSE) is currently being evaluated and characterized for potential technology enhancements to support ground software development. A variety of Computer Aided Software Engineering (CASE) environments are being surveyed for their contributions towards improving management of the software lifecycle. The Air Force Software Life Cycle Support Environment (SLCSE) was evaluated in terms of modularity, dependence on VAX/VMS services, amount and clarity of documentation, and its language usage in light of SSF coding standards for possible integration with the SSE to improve the growth and evolution of SSE services.

A series of intelligent training systems are scheduled to be prototyped for the Space Station Training Office to demonstrate the value of ICAT architectures and their feasibility for baseline training operations. The first prototype being developed is for training on the SSF Thermal Control System. Additionally, the ICAT architecture is being evaluated to support Spacelab crew training at MSFC.

Telerobotic Systems focuses on the reduction of 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 boring maintenance tasks whenever possible. The most significant accomplishments during 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 Test-Bed. A full set of satellite assembly and maintenance tasks, including satellite capture, servicing bay access, ORU changeout, satellite refueling, electronics board changeout, and satellite closeout, have been performed under time delay with cooperative, equal status dual-6-dof arms. A narrated videotape explaining the technologies demonstrated has been produced and distributed. JPL is now completing a series of operator performance tests with novice operators to establish the standard learning curve for operator training in these advanced technologies.

These technologies are being transferred to the integrated PIT-segment dual-arm workcell under development at JSC. Current efforts involve rehosting the software in an IRIS graphics workstation in real-time Ada. The control algorithms have been translated into Ada and are being verified with a 7-dof Robotics Research arm and a 6-dof hand controller, while the OCMV software is optimized to run inside the graphics environment. 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.

At GSFC, four-element capacitive reflector sensor skin arrays have installed on both Puma 762 and RRC 1607 robot arms. The Puma's array is constructed entirely from flight-proven materials and coatings, including the appliqué NASA logo. 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. If the object advances, the Puma will back away. If the object retreats, the Puma will attempt to continue its trajectory. Qualification of the capaciflector's sensitivity to various flight proven materials is underway. Capaciflectors are being shipped to both JSC and JPL for integration into their testbeds. Preliminary tests with capacitance sensors mounted on a simulated box-type ORU have detected mounting holes and narrow slots for blind docking/

berthing. This technology has accelerated rapidly to demonstrating totally autonomous ORU berthing, with the ORU mounted sensors detecting an opening, aligning the payload's face parallel and the payload's Z axis normal to it, and inserting the payload into the cavity. This technology holds great promise in successfully completing identified ORU changeout tasks where the SPDM or SSRMS cameras may be blocked from viewing a berthing slot by the grasped ORU.

Level II A&R Progress

Level II devotes 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., ORU Standards, DDCU location, MSS Delta PDRissues). 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. A force-reflective hand controller for control of end-effectors such as the SSRMS and APS is shown in figure A3.

Robotics integration is being defined as an SSFP Technical Management Area. It is roughly analogous to an ACD Agent, except emphasis is placed on integration and verification rather than on hardware development. This allows for the opportunity to exploit the expertise and resources available at NASA field centerline organizations, for example, the JSC Automation & Robotics Division. Robotics integration is logically divided into Robotic Maintenance/Servicing Task Integration, MSS Integration, and other (e.g., JEM RMS Integration, Program-level studies, Change Requests, etc.). The robotics integration Technical Area Manager is proposed to become responsible for RSIS Volumes I and II, the Dextrous Task List, the MSC and SPDM System Requirements Documents (this is a joint responsibility with CSA), the robotics

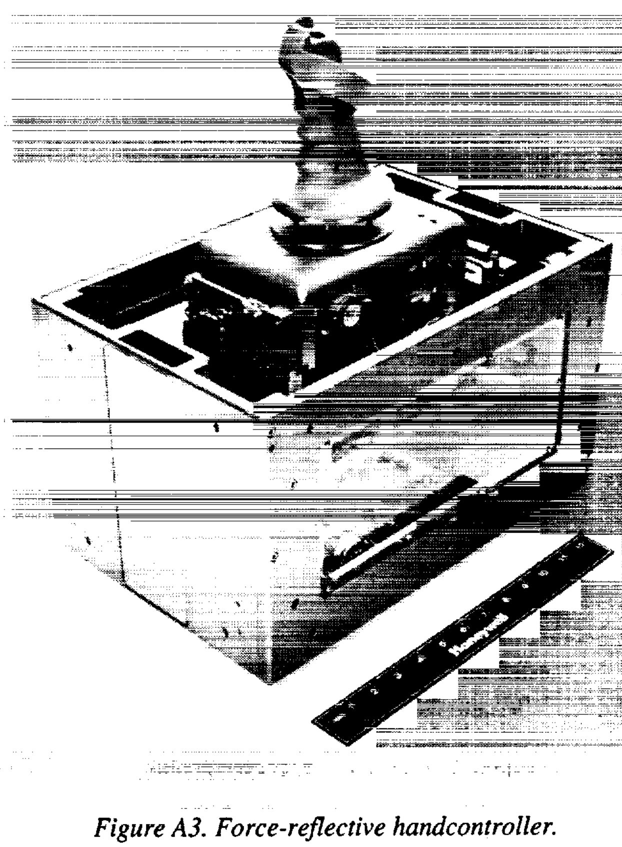

Figure A3. Force-reflective handcontroller.

section of the Program Master Verification Plan, and to chair the Robotics Working Group. The Technical Area Manager is also proposed to be the NASA integrator of the MSS and JEM RMS into the SSFP.

Since ATAC Report 12, the RSIS Volume I Robotic Accommodation Requirements has been baselined and the RSIS Volume II Robotic Interface Standards and PDRD Section 3 Table 3-55 have been developed and issued for program-wide review. Additionally, Robot-to-ORU interface testing was concluded at GSFC and has begun at JSC and CSA/Spar. The Dextrous Task List has been refined and a list of Robot-Compatible ORUs to be incorporated into the PDRD has been generated. A total of 413 ORUs, which represents 48% of SSFP external ORUs, have been identified. This provides a potential of offloading 571 maintenance man-hours from EVA per 8.33 years which represents a 70% offload of EVA to robotics.

There has been an ongoing international program issue concerning the location of the DC-DC Converter Units (DDCUs) for the ESA Attached Pressurized Module and the NASDA Japanese Experiment Module. Level II initiated a study involving ESA, NASDA, and the EVA & Robotics community to determine if external DDCUs could be made robotically compatible. An intensive cooperative effort has resulted in two candidate robot/EVA compatible configurations. This study has demonstrated that cooperation between the external equipment developer and the robotics community is the key to successful implementation of robot-compatible design.

SSF internal and external maintenance responsibility has been formally delegated to the In-flight Maintenance Working Group. IVA, EVA, and Robotic crew time has been established as a program-level resource just like weight and power. Specific allocations to each Work Package and International Partner have been made. Level II has also initiated an IVA maintenance demand study and delegated the study responsibility to WP1.

Level II has initiated a collision prediction and avoidance trade study. This study is expected to determine the number and location of external cameras required to support collision avoidance using only operator cues provided by direct and indirect viewing. It will also evaluate the added value of automated collision prediction. The results of this study are expected by early 1992 and will be used to recommend changes to the PDRD as appropriate.

Level II is also leading an effort to integrate the various robotic simulation activities within the SSFP. A Robotics Simulation Splinter to the Robotics Working Group has been chartered to evaluate, coordinate, and recommend robotic simulation activities.

Work Package 1 A&R Progress

During its long operational lifetime, significantly large amounts of Space Station Freedom design knowledge and experience concerning the different subsystems and components are, and will be, generated. Trade studies, alternative designs, configuration simulations, and prototype systems will be commissioned and conducted producing a flow of knowledge and experience throughout the whole spectrum of engineering and scientific disciplines.

To support WP1, several tools have been developed. These are the Design Alternatives/Rationale Tool (DART), Environmental Control and Life Support System Simulator (ECLSS-Simulator), Module Rack Integration Analysis and Optimization Tool, Packaging Manager (PACKMAN) and Automated Logistics Element Planning System (ALEPS).

The Work Package 1 Prime Contractor independently is 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 paragraphs 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 while 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. In a recent institutional reorganization, JSC 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 WP2 prime contractor's A&R group is organized similarly to the JSC organization. Three main groups are managed within system's engineering and integration: A&R analysis, A&R development, and A&R integration. While there is no strong contractual obligation or requirement for A&R, the prime contractor has been working to ensure that technology point solutions can influence baseline design.

Within Robotics, the contractor has aggresively pursued making the high-maintenance external ORUs robotically compatible. As of August 1991, the WP1 candidate list consisted of 193 ORUs. This represents over 60% of the MMH/YR requirement for MB-1 through MB-7. Furthermore, it has been determined that baseline designs do not preclude robotics. ORU designs currently being evaluated include; the Avionics 6-B Box, the Avionics Box on the radiator door, the Standard Quick Universal Interface Device (SQUID), the Zip Nut, the Fluids Box, and a variety of tools.

Within Automation, the contractor has focused on three fault management applications to improve fault detection, isolation, and recovery (FDIR) of the Integrated Station Executive (ISE), the Data Management System (DMS), and the Thermal Control System (TCS). The ISE FDIR expert system is based on parsimonious set covering and uses failure space models from the Failure Environment Analysis Tool. It is projected to be delivered by the PMC software release. The DMS FDIR expert system now includes an MTC laboratory module model with local bus and MDM models currently being developed. This activity is forming the basis of the DMS System Management FDIR FSSR. Finally, the TCS automation project is a joint activity with SSF Level I Engineering Prototype Development. As described earlier it is well on schedule to support baseline TCS evaluation.

Work Package 4 A&R Progress

One of the strategies used during the latest restructuring of the Space Station Freedom project was to move all but the most essential fuctionality from aboard the space station to the ground control center. WP1 activities have been refocused to address the needs of ground-based operations.

The refocused approach concentrates 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. When addressing failures, this system must detect the failure and isolate affected systems so that the station's integrity is not jeopardized. In addition, the corresponding flight rules must be executed to minimize system degradation. 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 on these three systems that efforts to introduce automation have been focused. The event analyses are conducted by a diagnostic expert system and by a security analysis system. The diagnostic system uses available telemetry data to determine the most likely cause of the failure while the security analysis system conducts contingency (What if...?) analyses to determine the risk of continued operation. The results of these event analyses alter the operating constraints and mission objectives, which in turn require a revised operating plan. The scheduling system provides this plan by allocating resources according to the constraints identified during event analysis. Human operators coordinate the exchange of information among these four systems.

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 products are being connected directly to the LeRC Space StationFreedom PMAD testbed as a preliminary step before introducing them into theEngineering 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 test-bed's prototype flight control computer. Further, this approach defines the communication requirements for integrating the test-bed with the Engineering Support Center.

This activity augments the baseline design in an advisory manner. The baseline design has automatic regulation of battery charging according to specified maximum profiles, along with 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. The decision aids will help operating personnel issue the appropriate supervisory commands to these systems under all circumstances.

Rocketdyne, Inc. is also pursuing health monitoring, failure diagnosis, and human interfaces in their IR&D program. They have successfully integrated a power system advisory controller with their electric power system simulation. To date, they have demonstrated detection and diagnosis of measurement anomalies.

The Robotics effort at Work Package 4 has focused on designing the orbital replacement units so that they accommodate telerobotic manipulation with human EVA as a backup. As this design matures, it is continually being 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 WETF. These investigations check the adequacy of the design for: handling, alignment and visual cues, as well as mechanical and thermal integrity. Also, WP4 has actively participated in interface design reviews, technical interchanges with CSA, and various ad hoc working groups addressing robotics and EVA. In particular, WP4 has implemented the RSIS robot to ORU and ORU to SSF interface requirements, as well as advocated RSIS revisions that would lower the costs of incorporating robotic technology into the SSF design.

Appendix B

Japanese A&R Space Station Program

Overview

Japan is responsible for the development of the Japanese Experiment Module (JEM) and its associated Remote Manipulator System (RMS). The JEMRMS is one of the Japanese Experiment Module elements which Japan is developing in the international collaboration of Space Station Freedom. One-man operation has been baselined for controlling JEMRMS to allow a single crew member to manipulate the robot arms from Pressurized Module (PM) to support the exposed (external) environment tasks as depicted in figure B1. JEMRMS performs these tasks with two manipulator arms, the Main Arm (fig. B2), and the Small Fine Arm (fig. B3). The Main Arm is fixed to the PM and will be used for large payload handling. The Small Fine Arm is attachable/detachable to and from the Main Arm and will be used to handle small, light payloads requiring dextrous manipulations. In order to facilitate the one-man operation, an integrated system consisting of a highly automated control system and a man-in-the-loop control system has been baselined to provide a reduction in crew time and crew fatigue. The basic functional diagram of the JEMRMS is shown in figure B4.

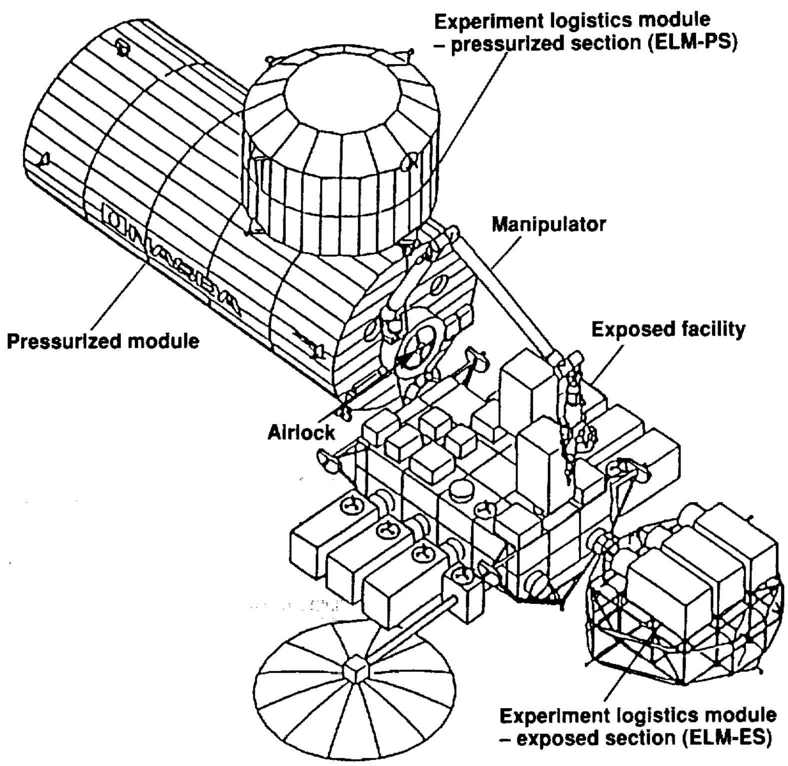

Figure B1. General arrangement—Japanese experiment module.

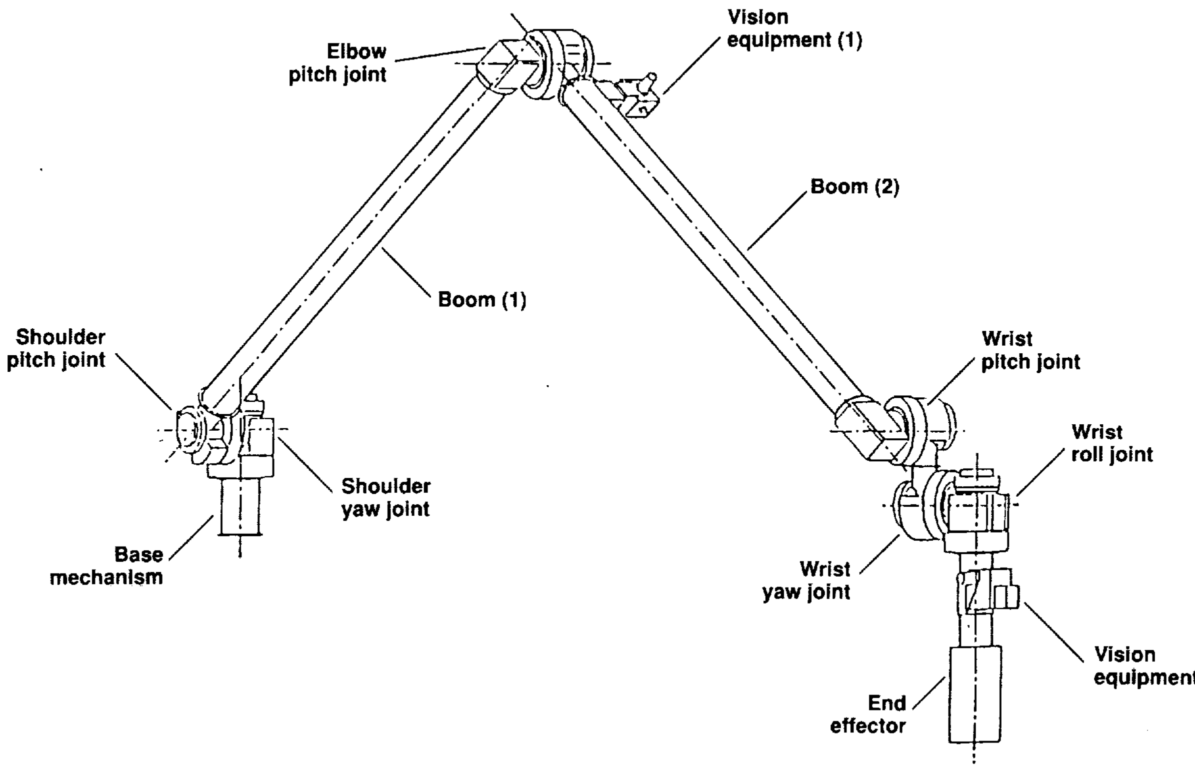

Figure B2. JEMRMS configuration (main arm).

Key Technologies and Components

Key JEMRMS technologies are as follows:

- Collision avoidance
- Space-qualified robotics arm and control system
- Man-machine interface
- Bilateral force feedback control
- Dynamic simulation tools
- Test and validation methodologies

Key JEMRMS components are as follows:

- Highly efficient, long-life joint mechanism
- ORU design for the Main Arm joint mechanism
- 6-DOF hand controller consisting of a single hand controller for the Main Arm and the Small Fine Arm control
- Force/torque sensor
- Long life, replaceable end effector for the Main Arm
- Small, light weight TV camera and pan/tilt mechanism
- Small Fine Arm tool
- Stereo vision (projected)
- Mobility of the Main Arm base mechanism (projected)

Computational Environment

A 16-bit MPU and the co-processor will be used for the robotics control, the MPU being a NASDA QPL part and the co-processor being developed by NASDA. The software environment consists of the C language for the JEMRMS control.

Development Status

The advanced research and development evaluation and test of the key technologies and components were conducted during the Phase B study. These efforts included the joint mechanism of the Main Arm; the Force/moment sensor; the Stereo vision system; the 2-dimensional model; and the 3-dimensional man-machine interface model.

The development tests of the ORU-type Main Arm joint mechanism model, the controllability test of the Main Arm and the Small Fine Arm using single

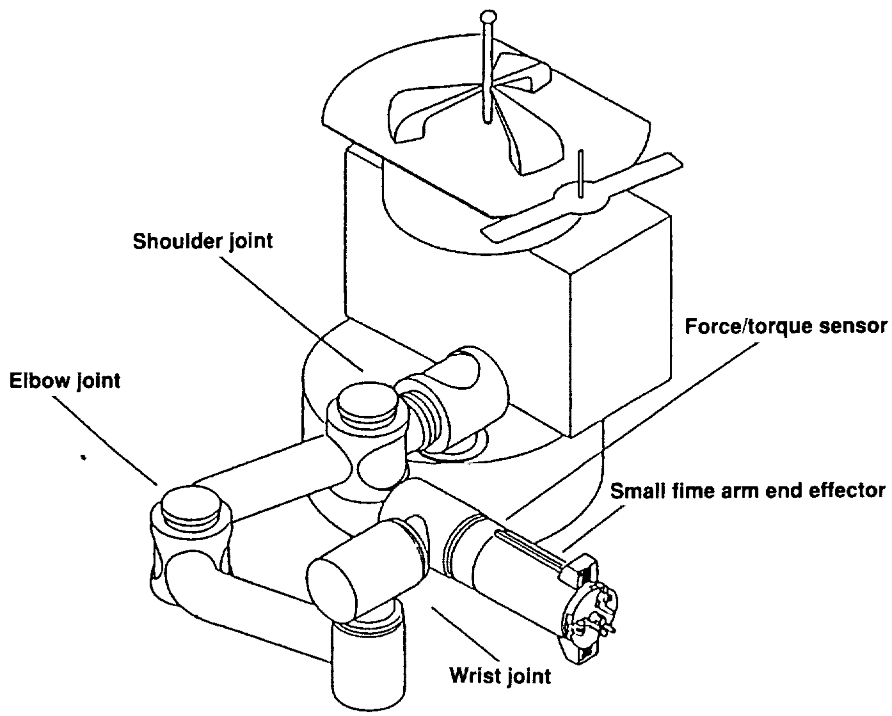

Figure B3. Small fine arm.

6-DOF hand controller, and the Small Fine Arm end effector models (gripper and tool) were completed in September 1990.

The Phase C developmental effort, using the baseline configuration established during Phase B and its associated follow-on study, was initiated during January 1990 and is scheduled to be completed during the latter part of CY-1991.

Experiments Status

Several experiments are being planned for the JEM. Material science and life science experiments are primarily conducted inside the JEM PM, while engineering experiments and other experiments requiring the use of large equipment are planned to be implemented on the JEM External Facility (EF). The First and Second Groups of experiments are shown in figure B5. There are about 20 experiments planned for eventual flight. Figure B6 depicts a concept of a material sciences experiment operated by preprogrammed robotic control.

Projected Evolutionary Growth

Space automation and robotics (A&R) is considered by Japan to be a critical technology for their future space activities and NASDA has implemented a focused and concentrated research and development effort to achieve their overall space A&R objectives. The JEMRMS represents Japan's first attempt to develop a space robot.

Research is now being focused on the second-generation space robot which can be controlled from the ground. The second-generation space robotics efforts consist of research on the telerobotics control technologies and the design of an on-orbit flight demonstration experiment using the Engineering Test Satellite (ETS-VII). The ETS-VII is an experimental satellite to demonstrate the rendezvous/docking technologies and the use of on-orbit space robotics. Objectives of this experiment are as follows:

- Coordinated control of the robot arm and the satellite attitude
- Demonstration and evaluation of the teleoperation capability
- Demonstration and evaluation of on-orbit servicing capability with emphasis on the battery exchange and the fuel resupply operations, both of which will be done by ORU exchanges.

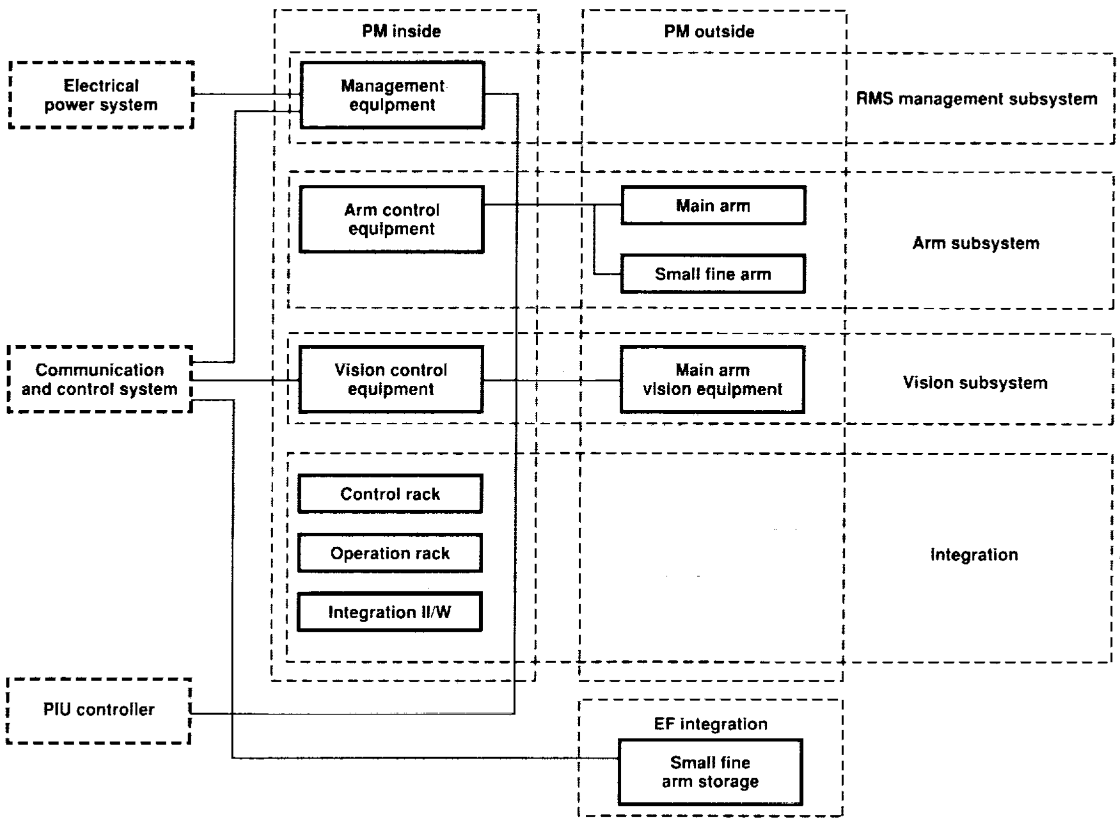

Figure B4. Basic schematic diagram of JEMRMS.

The third-generation space robot will be the autonomous space robot using advanced technologies from the second-generation space robot (described above) as the baseline infrastructure and including AI-based technologies. Basic research has been initiated for this effort with information being exchanged through the Space Artificial Intelligence, Robotics, and Automation Symposium (SAIRAS) and the Space Robotics Forum. The first annual SAIRAS meeting, organized by NASDA, was held in 1987 and has had annual meetings every year since 1987. The six Japanese space agencies and societies sponsoring SAIRAS are NASDA, Institute of Space and Astronautical Science (ISAS), National Aerospace Laboratory (NAL), Japan Society for Astronautical and Space Science (JSASS), Japanese Society for Artifical Intelligence (JSAI), and Robotics Society of Japan (RSJ). The SAIRAS '90 meeting was the first international meeting sponsored by the six Japanese organizations noted above and by three U. S. organizations, the AIAA, AAAI, and NASA. The Space Robotics Forum was also organized by NASDA in 1987 with two major objectives: to provide an opportunity for the robotics and space engineering communities to communicate with each other; and to provide an integrated environment to study and investigate the space robotics issues. The membership of the Forum consists of approximately 100 engineers and scientists from the national labs, universities, and private industry. Several of the technologies resulting from the Forum discussions have been applied to civil applications.

Participants

Major participants in Japan's integrated space A&R program are shown in figure B7. Roles played by each of the participants are shown in figure B8.

1st group	*2nd group
Isothermal furnace	Physical and chemical experiment facility
Gradient heating furnace	Vapor growth facility
Zone melting furnace	Solution growth facility
Levitation furnace	Fluid physics facility
Cell culture equipment	Small animal holding
Protein crystallization equipment	Extravehicular exposure unit
Electrophoresis unit	Space environment measurement
Clean bench	Experiment support equipment for manipulator remote control from ground

* Candidate

Figure B5. List of experiment equipment.

Summary

Japan's space automation and robotics program is a well-focused and integrated program with well-defined goals and objectives. Roles played by each of the major participants are designed to provide maximum leveraging of the expertise resident in each of the participating organizations and there is a very structured program to transition the technology from basic research to space flight applications. In addition, a formal mechanism is in existence to transfer the pace technologies to the industrial sector, thereby providing the Japanese with a unique strength in the application and implementation of industrial robotics to their areas of interest.

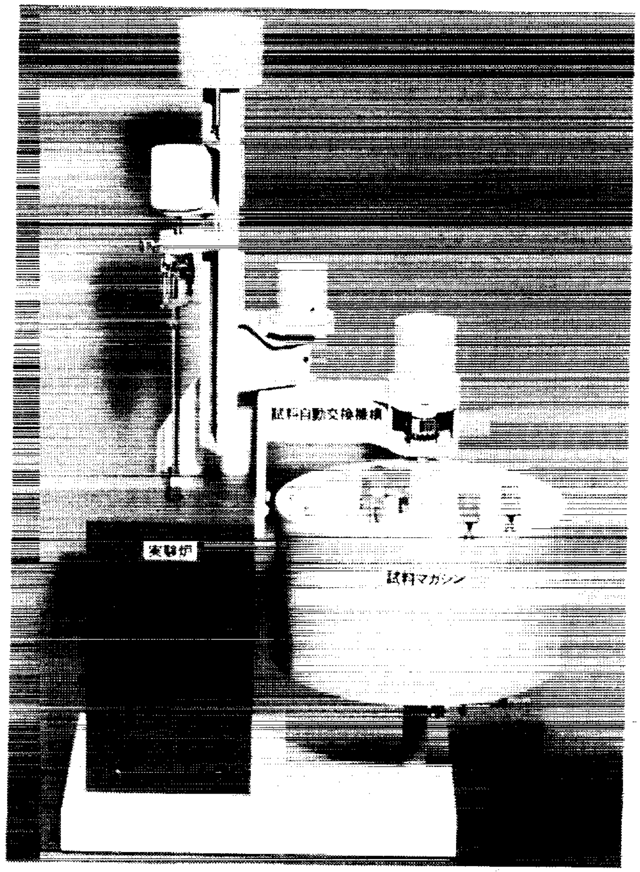

Figure B6. Mockup of material sciences experiment operated by preprogrammed robotic control.

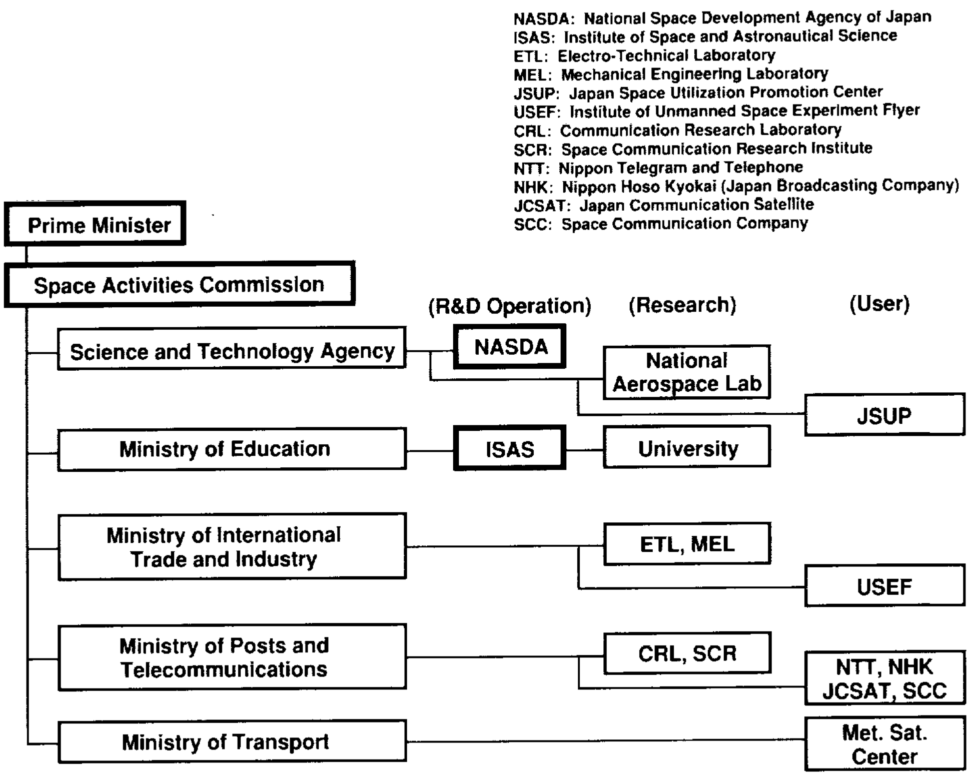

Figure B7. Space-related organizations in Japan.

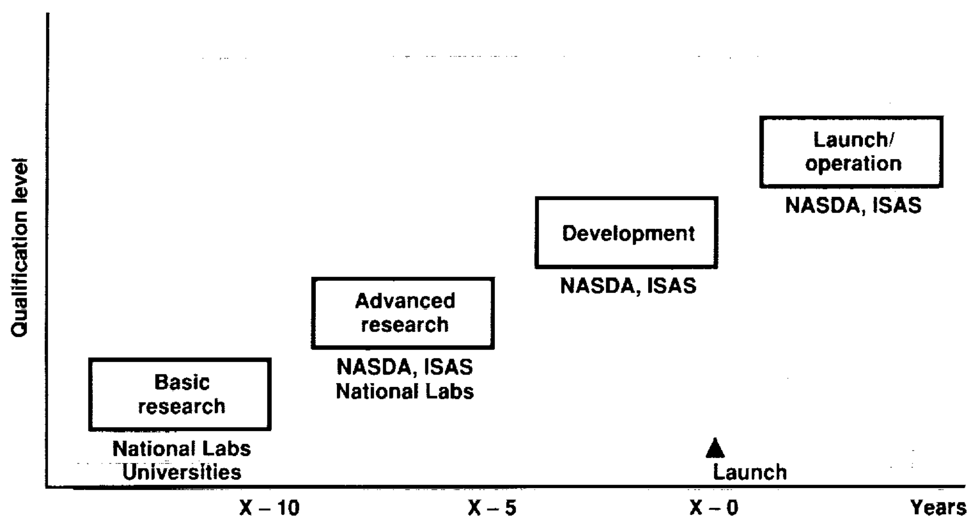

Figure B8. Role sharing for the space projects.

Appendix C

Canadian Space Station Program Mobile Servicing System

Introduction

Canada is responsible for the development and construction of the only currently operational space telerobot, the Shuttle Remote Manipulator System (SRMS). Canada's role under the Space Station International Agreement is the development and operation of the Mobile Servicing System (MSS). Major elements of the MSS are the Mobile Servicing Center which is the responsibility of Canada. The Mobile Servicing Center (MSC) includes the Mobile Transporter (MT) which is United States supplied. The MSS includes two telerobots, the Space Station Remote Manipulator System (SSRMS) and the Special Purpose Dextrous Manipulator (SPDM). The MT allows linear motion along the Station truss. The objectives of the Canadian Space Station Program include the development and operation of the MSS, participation in the operation and utilization of Space Station Freedom, and the generation and spinoff of technology development, primarily in A&R.

The Canadian program is an investment of $1.2B (Canadian) of which $800M is allocated to develop and construct the MSS. The system design, baseline capabilities, and advanced program elements represent significant advancement in A & R technology.

The MSC shown in figure C1 is composed of three major components: the MBS, the SSRMS, and control equipment. Also shown is the SPDM. The MBS is the mechanical interface to the U.S. supplied transporter and also includes the power, data, and video systems for the MSC. The MBS accommodates the SSRMS, SPDM, tools, and attachment fixtures for holding and transporting Orbital Replacement Units (ORUs) and payloads.

The SSRMS is functionally similar to the Shuttle RMS but has increased reach and load capability. The SSRMS is a redundant system with 7 degrees-of-freedom. The most unique feature of the SSRMS is that both ends are identical and either end can act as the base or the tip. Either end therefore can be coupled and operated from any Power Data Grapple Fixture (PDGF) on the MBS or any other location on the Space Station. This allows the system to include self-relocatability by moving from one PDGF to another like an inch worm.

The SPDM can mount and operate from any PDGF on Space Station, the MBS, or the end of the SSRMS as shown in figure C1. The SPDM includes two identical seven-degree-of-freedom arms which are mounted on a body with an additional five degrees-of-freedom. The system includes wrist and body TV cameras, a tool change-out mechanism at each wrist, and tool storage.

The MSS has been assigned a role in a number of Space Station functions including assembly, external maintenance, payload servicing, payload deployment, retrieval, transportation, and handling. The SPDM will provide the dextrous capabilities required to accomplish these functions. SPDM functions include inspection and monitoring, ORU exchange, utility connect and disconnect, mate and demate of connectors, manipulating small payloads, and the positioning of tools and materials to support EVA.

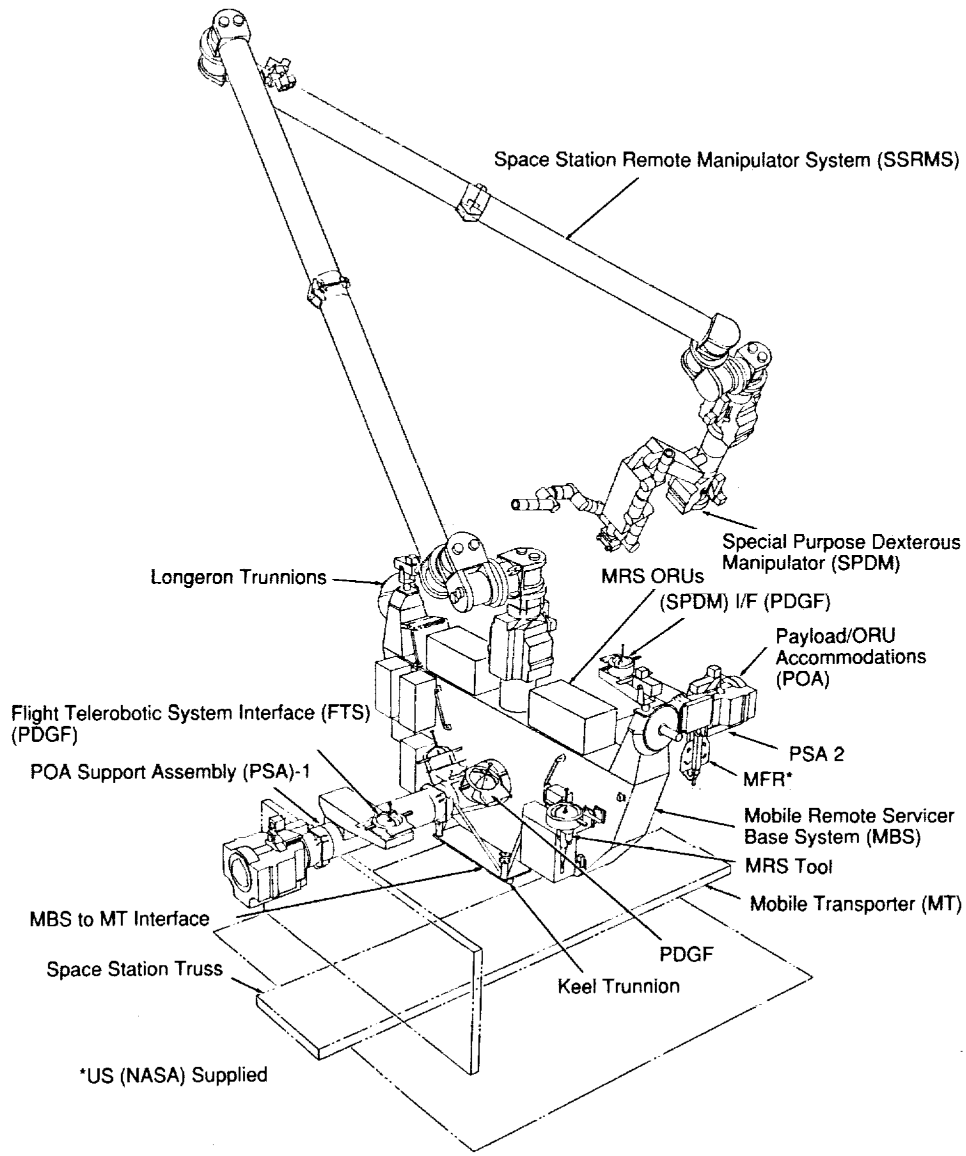

Figure C1. Mobile Servicing Center, including special purpose dextrous manipulator.

To accomplish these Space Station functions, an impressive list of A&R technologies are planned for the MSS. The SSRMS and SPDM will both have force and moment accommodation, which allows limiting and the controlled application of tip forces and moments. This force/torque information is also displayed to the operator. All manipulators will have closed-loop control using an artificial vision function allowing automatic tracking and capture of marked targets. Automatic task primitives for manipulator motion, tool positioning and activation, and ORU removal and installation are planned as part of the baseline system. A number of routine functions for system operation will also be automated, such as system startup and shut down, deployment and storage, and tool acquisition.

ATAC Assessment of SPAR Space Station Program Robotics Activities

The Canadian Space Agency hosted a visit for ATAC members in October 1991 to the Advanced Technology Systems Group of SPAR Aerospace Limited located in Toronto, Canada. The following assessment is based upon the review provided to ATAC by SPAR of its robotics capabilities and, in particular, its SSRMS and SPDM programs. The SPAR visit specifically included briefings on SPDM ORU handling and on SPAR research for control of robots for future applications, and included tours of the SRMS laboratory, robotics analytical and experimental laboratories, and SPDM Ground Test-Bed Facility.

The SPAR developed target, micro interface, and H interface have been incorporated into the SSFP RSIS document as standard robotic handling features. The target provides coarse and fine alignment for the SPDM to the ORU. The micro interface provides SPDM interface to smaller ORUs (0-250 lbs) while the H interface provides interface to larger ORUs (100-1200 lbs). ORUs have V guides or alignment levers for rotational and translational misalignment, and are compatible to both crew and robotic changeout. The alignment capabilities of the target, micro interface, and H interface are shown in table C1.

The SPDM ORU Tool Changeout Mechanism (OTCM) is compatible to both the H and micro interfaces. It has an opening range of travel of 0 to 5.5 inches, a grasp force of 200 lbs, a 25 ft-lb clockwise torque and a 50 ft-lb counterclockwise torque capability.

SPAR briefed ATAC on its research program for control of robots for future applications. The thrust of the research is in the application of advanced control methods enabling greater precision, higher speed, improved payload handling and, in general, improved performance through higher bandwidth control. One area of this research having immediate near-term application for the SPDM is force-moment accommodation. The approach is to establish torque output as a joint control objective. The benefit for the SPDM will be stability of the manipulator in contact with a wide class of SSF equipment without significant mechanical or operational constraints. The strategy is that improved control leads to relaxation of mechanical design constraints.

ATAC toured the SPAR SRMS laboratory which is outfitted to investigate "planar motion" of the SRMS in a one-g environment and to conduct analysis of instrumented RMS arms which have flown on previous Shuttle flights. This has provided SPAR with a substantial database of robotic flight performance under one-g and zero-g conditions with which to validate engineering models for future space robotic developments. SPAR's space robotics engineering experience and flight performance database lends strong credibility to its SSRMS and SPDM development activities.

ATAC toured the SPAR analytic robotic path planning laboratory in which simulation models of the SSRMS and SPDM are utilized to investigate robot trajectory planning and to optimize various geometric configurations. ATAC also toured the SPAR robotic experimental laboratory which houses a large industrial robot and associated support equipment to investigate and evaluate advanced robotic control techniques. An advanced control technique demonstrated was torque output control at the joints of a robot. A single joint of the industrial robot was implemented with such control and demonstrated stability in contact over a range of surfaces.

ATAC toured the SPAR SPDM Ground Testbed facility which has a full-scale hardware model of the SPDM manipulators in place and fully operational, including R&D engineering workstation controls and displays (figs. C2 and C3). SPAR demonstrated the SPDM functional capabilities for ORU replacement, including both operator control and automated vision control. Several graphical displays for aid in ORU replacement were demonstrated, including force-torque feedback displays and virtual target displays. SPDM collision avoidance capability which utilizes geometric modeling was also demonstrated, including a laser scanner capability for updating geometric models.

SPAR indicated that the current SSF SSF Standard Data Processor (SDP) capacities are adequate for SSRMS and SPDM. Growth beyond the baseline MSS capabilities will require additional SDPs.

CSA indicated that there is no known technical reason to prevent implementation of ground control of the SSRMS and SPDM, and the planned HW and SW should not preclude the future use of ground control operations. It is ATAC's opinion that a flight experiment would validate the feasibility for such an approach.

The SSRMS CDR and the SPDM PDR are scheduled for August 1992.

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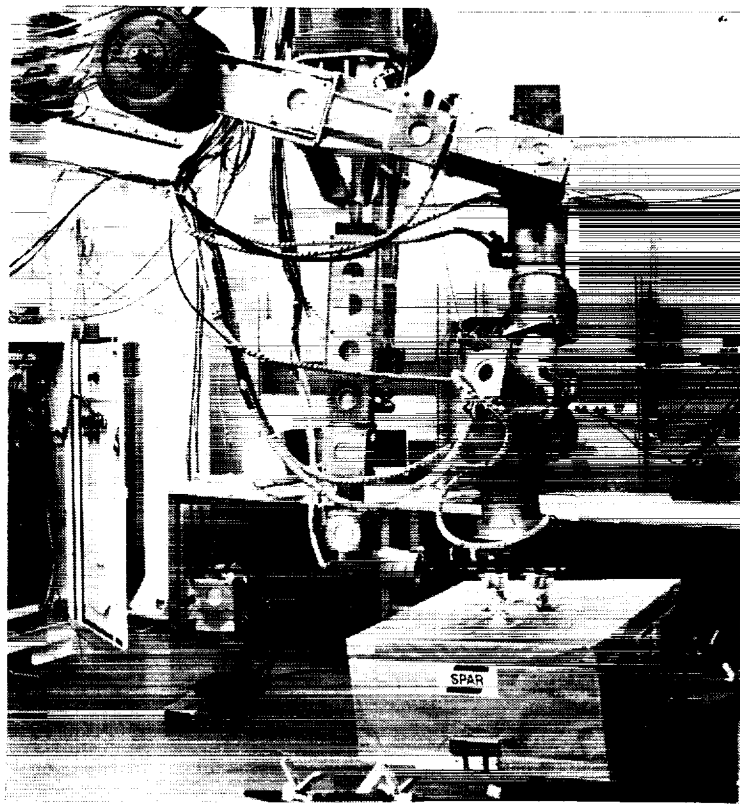

Figure C2. SPAR SPDM ground test-bed model replacing ORU.

Summary

The Canadian A&R Space Program, as represented by SPAR, has demonstrated outstanding performance in space robotics with the Shuttle RMS and other previous robotics applications, and has established a large experience base for space robotics. Their SPDM plans are not far advanced beyond what they have already accomplished, although the SPDM will be more dextrous than the SRMS. SPAR's experience lends strong credibility to the anticipated success of SSRMS and SPDM. ATAC was highly impressed with the robotics experience and capabilities of SPAR, and fully anticipates that the SSRMS and SPDM will successfully meet SSF needs and requirements.

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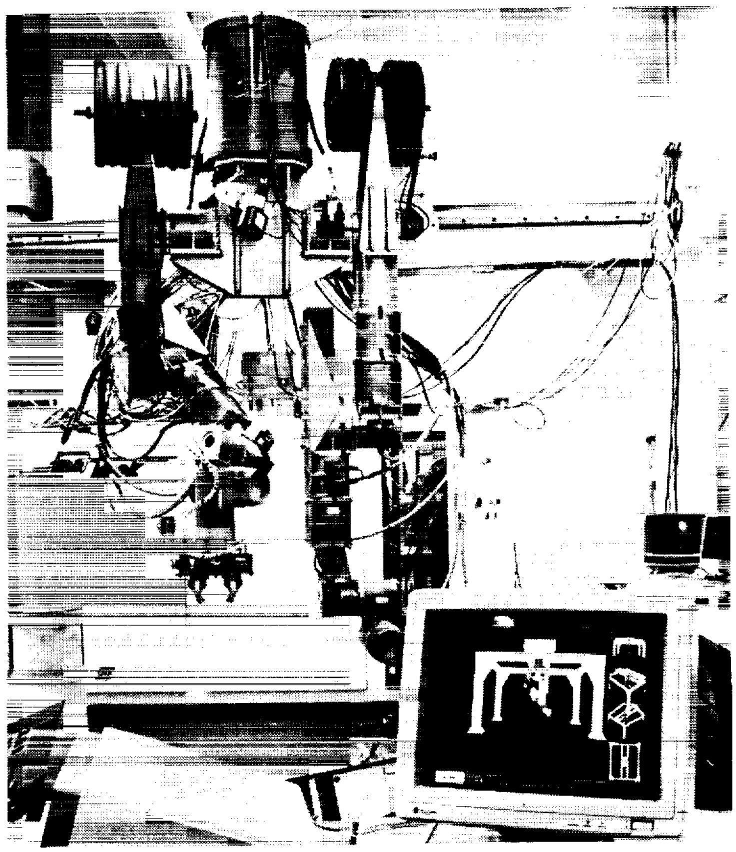

Figure C3. SPAR SPDM ground test-bed workstation collision avoidance display.

Table C1. ORU INTERFACE ALIGNMENT CAPABILITIES.

	X Axis	Y Axis	Z Axis
Target	±0.05 inches	±0.05 inches	±0.20 inches
	±1 degree	±1 degree	±0.5 degrees
Micro	±0.50 inches	±0.50 inches	±0.25 inches
	±35 degrees	±11 degrees	±30 degrees
H	±0.50 inches	±0.70 inches	±0.55 inches
	±26 degrees	±15 degrees	±20 degrees

Appendix D

Acronyms

A&R	Automation and Robotics
AC	Assembly Complete
ALEPS	Automated Logistics Element Planning System
ARC	Ames Research Center
ATAC	Advanced Technology Advisory Committee
AWP	Assembly Work Platform
C&T	Communications and Tracking
CASE	Computer Aided Software Engineering
CDR	Critical Design Review
CETA	Crew and Equipment Translation Aid
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, Exploration and Technology
Code S	NASA HQ Code for the Office of Space Science and Applications
COMPASS	Computer Aided Scheduling System
CR	Change Request
CSP	Canadian Space Program
DARPA	Defense Advanced Research Projects Agency
DART	Design Alternatives/Rationale Tool
DDCU	DC-DC Converter Units
DKC	Design Knowledge Capture
DMS	Data Management System
DTF-1	Development Test Flight (first FTS test flight)
DTLCC	Design to Life-Cycle Costs
DTO	Development Test Objective
ECLSS	Environmental Control Life Support System
EMI	Electric-Magnetic Interference
EMST	External Maintenance Solutions Team
EPD	Engineering Prototype Development
EPS	Electrical Power System
EVA	Extravehicular Activity
FAM	Functional Area Manager
FDIR	Fault Detection, Isolation, and Recovery
FDM	Fault Detection and Management
FEAT	Failure Effects Analysis Tool
FEL	First Element Launch
FMEA	Failure Modes Effects Analysis
FSE	Flight Support Equipment
FTS	Flight Telerobotic Servicer
GN&C	Guidance, Navigation, and Control
GSFC	Goddard Space Flight Center

Acronyms—continued

IDR	Integrated Design Review
ISE	Integrated Station Executive
IVA	Intravehicular Activity
JEM	Japanese Experiment Module
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
MBS	Mobile Remote Servicer Base System
MCC	Mission Control Center
MCCU	Mission Control Center Upgrades
MSC	Mobile Servicing Center
MSFC	Marshall Space Flight Center
MSS	Mobile Servicing System
MT	Mobile Transportation
MTC	Man-Tended Capability
MUT	Mission Utilization Team
NASA	National Aeronautics and Space Administration
OAST	Office of Aeronautics and Space Technology
OCMV	Operator Coached Machine Vision
OMS	Operations Management System
ORU	Operational Replacement Unit
PDGF	Power Data Grapple Fixture
PDR	Preliminary Design Review
PDRD	PDR Document
PIT	Pre-Integrated Trusss
PM	Pressurized Module
PMAD	Power Management and Distribution
PMC	Permanently Manned Capability
POIC	Payload Operations Integration Center
POP	Program Operating Plan
RMS	Remote Manipulator System
RSIS	Robotic Systems Integration Standards
RTDS	Real-Time Data System
SDP	Standard Data Processor
SDTM	Station Design Tradeoff Model
SLCSE	Software Life Cycle Support Environment
SPDM	Special Purpose Dextrous Manipulator
SQUID	Standard Quick Universal Interface Device
SRMS	Shuttle Remote Manipulator System

Acronyms—concluded

SSAIAF	Space Systems Automated Integration and Assembly Facility
SSCC	Space Station Control Center
SSE	Software Support Environment
SSF	Space Station Freedom
SSFP	Space Station Freedom Program
SSMB	Space Station Manned Base
SSPC	Space Station Payload Center
SSRMS	Space Station Remote Manipulator System
SSTF	Space Station Training Facility
TCS	Thermal Control System
TEXSYS	Thermal Expert System
UMI	User Macro Interface
WETF	Weightless Environmental Test Facility
WP	Work Package

Appendix E

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13. ABSTRACT *(Maximum 200 words)*

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 thirteenth in a series of progress updates and covers the period between February 14-August 15, 1991. 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 12, and issues of A&R implementation into Ground Mission Operations and A&R enhancement of science productivity. 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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