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

Progress Report 12
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Advanced Technology Advisory Committee
National Aeronautics and Space Administration

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Cover: Space Station Freedom
Permanently Manned Capability

Insets: Lunar Base
Planetary Exploration

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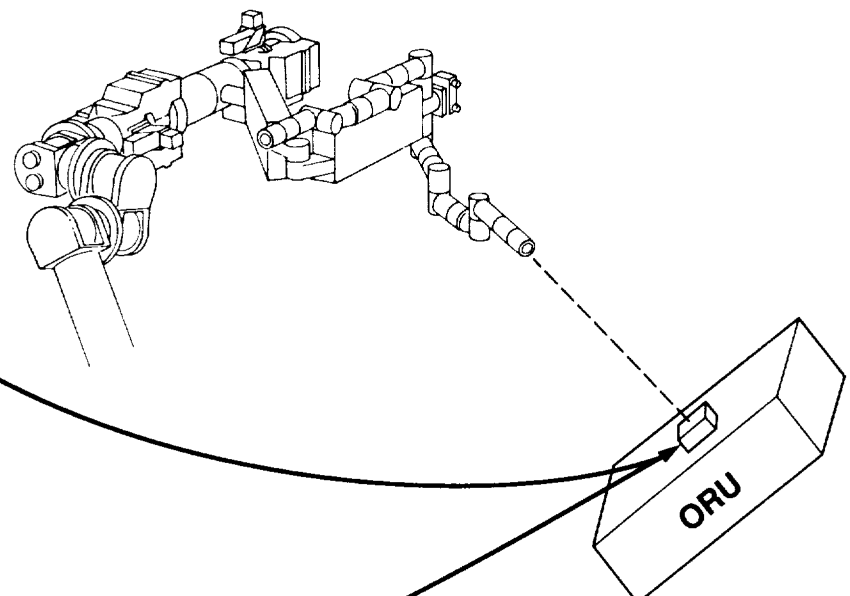

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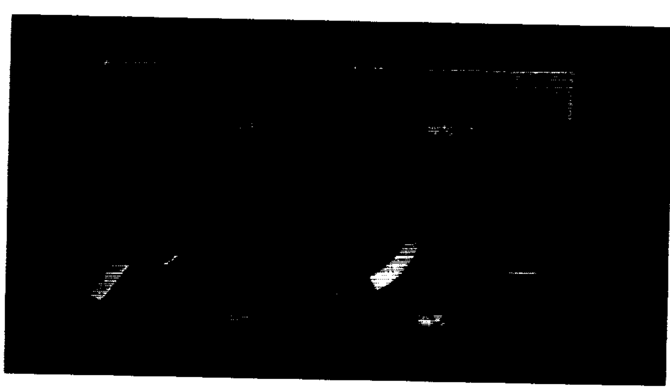
Micro Standard Robotic Interface



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H-Handle Standard Robotic Interface

The Space Station Freedom Program, under the leadership of Level II Automation and Robotics personnel, has developed Robotic Systems Integration Standards to to ensure maximum utilization and effectiveness across all work package systems for the robotics replacement of most Space Station Freedom ORUs. Robotic Systems Integration Standards developed include the Micro standard for ORUs from 0 - 250 lbs. and the H-Handle standard for ORUs from 100 - 1200 lbs. In addition, interfaces have been defined for tool changeout mechanisms and visual cues. These robotics standards are also applicable to the Canadian Special Purpose Dexterous Manipulator which provides Space Station Freedom with dexterous manipulator capabilities.

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 automation and robotics applications for the initial and evolutionary space station. Additionally, ATAC provided recommendations to guide the implementation of automation and robotics in the Space Station Freedom Program (SSFP).

A further requirement of the law was that ATAC follow NASA's progress in this area and report to Congress semiannually. In this context ATAC's mission is considered to be the following.

ATAC Mission

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

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

The ATAC has continued to monitor and prepare semiannual reports on NASA's progress in the use of automation and robotics in achieving this goal. The reports are documented in the ATAC Progress Reports 1 through 11 (refs. 2-12). Progress Reports 1 through 5 covered the definition and preliminary design phase (Phase B) of Space Station Freedom. Progress Reports 6 through 11 covered the startup of the design and development phase (phase C/D) of the SSF. Phase C/D will lead to a completely assembled station to be operational in the late-1990's.

ATAC Progress Report 11, as previous ATAC reports, received wide dissemination. ATAC Progress Report 11 was distributed in the following categories:

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

An additional 400 copies of ATAC Progress Report 11 were distributed with the NASA Aerospace Safety Advisory Panel Annual Report.

This report is the twelfth in the series of progress updates and covers the period of August 23, 1990, through February 14, 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 11. Also, summaries of progress in A & R in the Space Station Freedom Program Office and the Flight Telerobotic Servicer (FTS) as written by those offices, respectively, are provided as appendices. The report draws upon individual ATAC members' understanding and assessments of the application of A&R in the SSFP and upon material presented during an ATAC meeting held February 12-14, 1991, for the purposes of reviewing the SSFP A&R activities and formulating the points of this report.

Climate

In the first half of 1990 the Space Station Freedom Program conducted a descoping of the SSF design in order to meet power and weight limitations. The impact of that descoped design on A&R was addressed in ATAC Progress Report 11.

In the fall of 1990, Congress mandated an $8B budget reduction for the Space Station Freedom Program over the next 5 years, including a reduction in FY91 from $2.6B to $2.0B. This budget reduction of $600M caused the SSFP to initiate a major restructuring activity and a further descoping of the Space Station Freedom design. At the time of the February 1991 ATAC meeting, the extent of the restructuring was not fully defined by SSFP, and ATAC was not able to complete its assessment on the impact of restructuring on advanced automation and robotics.

However, the current restructuring activity will have a major impact on the implementation of U.S.-developed advanced automation and robotics technologies if a plan is not developed and implemented to migrate this technology from the ground to onboard SSF systems.

SSF A&R Programmatic Decisions

The SSFP reported two major A&R programmatic decisions at the recent ATAC meeting:

(1) "to move all automation from onboard SSF to the ground except for time critical functions, and (2) to transfer the FTS to OAET."

These decisions have several potential implications including higher long-term life-cycle operational costs, fewer onboard capabilities for supporting engineering and science experiments, degraded scientific experimental capabilities during the man-tended phase, and sole reliance on a foreign supplied dexterous robotic capability. The full impact of these decisions has not been assessed. In addition it appears that no plans have been specifically defined at this time for implementing the A&R move to the ground nor for migrating the capabilities later to onboard SSF.

ATAC fully understands the SSFP decisions in light of the Congressionally mandated budget reductions. However, ATAC, within its Charter, must also inform Congress that these decisions reflect a loss of U.S. commitment to be a world leader or even a knowledgeable participant in advanced automation and robotics for space applications.

ATAC Concerns

Ground-Based SSF Science, Operations, and Maintenance

For several years the members of the ATAC community have proposed that implementation of ground-based advanced A&R into the Space Station Control Center and the Space Station Payload Center can lead to significantly increased capabilities and reduced cost for SSFP. In that context and as a result of a major reduction in program funds, ATAC agrees with the recent decisions to move many of the functions to the ground for the short-term initial assembly phase of the SSF. However, to realize those savings and increased capabilities, the SSFP must carry forward a comprehensive plan for use of advanced automation in these ground facilities.

ATAC is concerned that plans have not been sufficiently defined for incorporation of ground-based advanced automation technologies that will lead to the achievement of these benefits. There is further concern that no definitive planning effort has been initiated to consider the process for eventual migration of some of the automation techniques developed on the ground back to the flight system. If this function is not addressed, then the long-term cost of ownership of the SSF will significantly outweigh any short-term advantages resulting from the programmatic decisions. There is concern about the viability of keeping the "marching army" on the ground technically competent over the 30-year lifetime of the project. During its next review cycle, the ATAC committee will request a review of ground operations impacts as a result of the recent scrub activity and detailed briefings for the incorporation of advanced automation technologies.

ATAC is also concerned that the feasibility for teleoperation of the SSF robotics systems from the ground is not being adequately addressed. Despite the recommendation of the Fisher-Price study "to implement ground-based remote control of SSF robots for monitoring and control of all robot functions" and "to evaluate the benefits of the use of ground-controlled robots early in the assembly time period between shuttle flights," there is inadequate SSFP planning to determine the feasibility for operation of SSF robots from the ground.

Onboard SSF Science, Operations, and Maintenance

As part of the restructuring process, Space Station Freedom's scientific use is being directed towards Life Sciences and Material Sciences research and experiments. It appears that most, if not all, of these experiments will occur after the man-tended phase is completed. In addition, it appears that the experiments' requirements have not been evaluated against the capabilities afforded by the restructured Space Station infrastructure.

ATAC has two concerns with this approach: Space Station capabilities are not being fully utilized to support the research focus of Space Station during the man-tended phase; and, an IVA study has not been initiated to investigate the role of humans and machines in the conduct of these experiments.

It is the opinion of ATAC that the use of advanced automation during the man-tended phase of the Station assembly can provide additional support of early experiments during this period of station operation. Lack of scientific utilization of the Space Station during the man-tended phase may lead to disinterest in the Science community in use of the Station after the man-tended phase is over.

There is doubt that the SSF EVA activities including maintenance and operations can be conducted without the use of robotics. However, if the use of robotics is required, then the SSF program will become highly dependent on the Canadian-developed Space Station Remote Manipulator System (SSRMS) coupled with the Special Purpose Dexterous Manipulator (SPDM). This dependency on the Canadian SSRMS and SPDM is due to the deletion of the FTS as a Space Station flight element and has been transferred to the NASA Office of Aeronautics, Exploration and Technology (OAET) for integration into their overall A&R research program. The Canadian robotics program presented at the last ATAC meeting in Reston represented a highly focused and integrated technology program leading to the eventual evolution of intelligent robotics. The program addressed near term as well as far term technology requirements and focused the AI and robotics research within the Canadian community to a common space-oriented goal.

ATAC is concerned, however, that a backup robotics system and/or set of validated robotics technologies are not being pursued within the United States for U. S. specific mission requirements.

The Space Station decision to transfer the FTS from the Space Station program to NASA Headquarters OAET has removed the technology focus and emphasis for FTS, and its "end product" functional utility is of concern to ATAC.

A&R Evolution

The latest restructuring activities have drastically reduced the Data Management System's (DMS) Standard Data Processors (SDP) from 14 to 6 with little, if any, performance contingency margin. The number of sensors and onboard sensor processing has also been significantly reduced with minimum capability for onboard Fault Detection, Isolation and Recovery (FDIR) capabilities. From the presentations given to ATAC, the engineering criteria/rationale utilized in the sensor selection process could not be determined.

The capability to implement advanced automation capabilities in the future, e.g., automated fault management and control and system health management, may have been severely compromised by the sensor deletion process and may result in all related functions being permanently relegated to ground control due to prohibitive costs for future onboard implementation.

A procedure for assessing life-cycle costs should be developed and standardized for use in the decision process for the implementation of advanced A&R across all work packages. Industry has already realized a significant return on its investment for advanced automation technologies in specific areas of ground-based applications.

Space Station Freedom, with a research emphasis on life sciences and material sciences, can serve as a forcing function for the development and verification of automation and robotics technologies to monitor, maintain, and repair complex hardware systems in space.

However, before this can become a reality, the technology base developed by OAET must be integrated, coordinated, and focused to Space Station's advanced A&R programmatic requirements.

Without this technology integration and coordination, technology will be developed for technology's sake only. With the technology focused on specific program needs/requirements, the resulting demonstrations will lead to the flight qualification of new A&R technologies to enable future missions, reduce systems costs, and increase the competitiveness of the United States.

Adequate funding must also be ensured and maintained to achieve a realistic SSF advanced technology development program which can meet its program objectives in a timely manner and allow technology transfer between OAET and SSFP. ATAC feels that this technology "transfer gap" cannot be ignored any longer if the United States is to maintain its leadership in space.

In addition, testbeds for support of engineering analysis and tradeoffs are not being maintained; this capability is a valuable and critical resource which the Station should use to fully test, evaluate, and verify integrated systems/subsystems. These testbeds represent a major investment by NASA in previous years and, in most cases, can be maintained with minimum funding and can yield a positive return on NASA's investment.

In summary, the recent SSF restructuring activities have been driven by cost, power, and weight constraints. Due to these requirements, advanced onboard robotics capabilities have been relegated to foreign participation, and advanced onboard automation functions delegated to ground mission control. There is serious concern that these decisions will limit the scientific, operational, and maintenance capabilities of the SSF due to the high long-term costs. In addition, there is a programmatic trend that suggests that the U.S. role in space automation and robotics will not only be severely degraded but will also be highly dependent in the future on foreign-developed A&R technologies for use in U.S. missions. ATAC will require a detailed briefing, during the next review cycle, of the plans to implement advanced A&R technologies in the ground facilities with eventual migration to onboard SSF systems.

Potential Impact to U.S. Leadership in Space Robotics

The reasons for having a long-term national commitment to Automation and Robotics remain relevant (i.e., long-term productivity and financial leverage). These benefits require a long-term national commitment to A&R technology. The U.S. applications of telerobotics to the Space Station Freedom are now on the verge of disintegration and collapse. The requirements for U.S. assembly, servicing, or repair of U.S. assets in space are planned to be satisfied by foreign technology from the Japanese, Canadians, and Europeans. This represents a most dangerous situation for the future of space robotics technology development in the United States.

There is currently a large research and technology base in telerobotics in the United States as a result of the Congressional mandate which established ATAC. The U.S. holds its own in the international forums in A&R technology.

However, the U.S. does not have a commitment to the engineering development and the applications testing and refinement of flight telerobotic systems.

The Japanese and Europeans have established development programs for intelligent robots for terrestrial and space applications, and Canada has established a significant program as part of SSF. With the reduction of funding and emphasis in the nuclear power field, the FTS program was the only major telerobotics activity in the United States. The removal of the FTS from the Space Station Freedom Program could significantly delay this technology in the United States.

ATAC is of the opinion that (1) a long-term U.S. commitment to telerobotics is still required in the national interest; (2) a development project with a deliverable flight system, like FTS, and related to technology programs is a viable way to pursue this interest; (3) with cost/benefit tradeoffs in mind, the currently planned DTF-1 experiment should proceed unchanged; and (4) as a follow on to DTF-1, OAET should be encouraged to implement an intelligent telerobotics flight development project with delivery and application on SSF or another NASA flight program.

Focus of Next ATAC Meeting

Restructuring has shifted the emphasis of SSFP A&R implementation from onboard to the ground. Also, some portions of the science community contend that experiment capability will be degraded by lack of advanced automation technologies. Because of these reasons, it is proposed that the next ATAC meeting be focused as follows:

1. SSFP plans for A&R implementation into the Space Station Control Center and into the Space Station Payload Center.

2. Capability of SSF to support life and material science experiments.

The current SSFP proposal is to have the meeting hosted by Level III at JSC in mid-August 1991.

ATAC Assessments

The ATAC assessments for this reporting period are based upon the committee's appraisals of progress in advanced automation and robotics for Space Station Freedom to the extent possible in the midst of the restructuring activities. A review of the progress toward the recommendations from ATAC's most recent report, Progress Report 11, will be discussed first, followed by a review of topics explicitly addressed during the February 12-14, 1991, ATAC meeting, and then a discussion of new A&R issues.

Before addressing the Progress on ATAC Report 11 recommendations, however, it is important to note that the program restructuring has entirely changed the context which existed at the time these recommendations were made. Namely, it was assumed that the United States would be involved in dexterous robotics in the form of the 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 OAET as a research experiment, the Station's requirements for robotics will be provided by the Canadian Special Purpose Dexterous Manipulator (SPDM).

It is ATAC's understanding that the Congress had provided funding for NASA's 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 contrary to this intent.

In concert with this restructuring decision, ATAC now has a minimal role, if any, in the review and assessment of robotics applicable to SSFP.

Assessment of SSFP Progress on ATAC Report 11 Recommendations

ATAC Progress Report 11, Recommendation I: ORU Standards.

"Define and implement prior to CDR a formal design standard for ORUs that will be both astronaut and robotic friendly in all SSF work packages."

It is the ATAC's assessment that the restructured SSF has incorporated both astronaut and robotic friendly designs for access and reach which enable assembly and maintenance by either humans or robotic systems. This is extremely encouraging. Substantial work (especially by Level II, JSC, GSFC, LeRC, MDSSC, Rocketdyne, and Canada) has been done to draft the Robotic Systems Integration Standards (RSIS) Volumes 1 and 2, and to complete an Interface Design Review (IDR) on standard designs for robot-to-ORU interfaces. However, despite this, no specific dexterous robotic tasks are identified yet in program documentation, and the RSIS has not yet been baselined as planned 6 months ago. There is enough inertia in the design cycle so that little robotic compatibility yet exists. This is true of both the individual ORU designs and the positioning and orientation of the ORUs in the truss segments.

The IDR recommended two integrated attachment mechanism/grasp area interfaces for different mass ORUs, a common tool/end effector design, and a visual cue design. These are standard designs for the robot-to-ORU interfaces. Additional robotic interface classes, the ORU-to-Station, the Robot-to-SSF, and the Robot-to-End

Effector/Tool interfaces are undefined as yet, and are intended to be addressed in future IDRs. The Human-to-Robot interfaces and standards are separated organizationally at Level II from the robotic systems engineering while clearly being a critical element of robotic task accomplishment. A future IDR should also address this area. Viewing has not yet been addressed from the Pre-Integrated Truss (PIT) perspective. For instance, the number of cameras useable for robotic operations has been reduced to four even though the restructured SSF has also removed direct line of sight for most locations. Also, the deletion of the special effects processor reduces the maximum number of simultaneous views possible from five to three which impacts dexterous task performance.

Having the specified Level II interfaces does not ensure that ORUs can be maintained. Maintenance task verification is a requirement that is not addressed or planned. This involves design and verification of robotic capability, design and verification of interfaces and "reach and clearance" envelopes, and maintenance task verification testing.

The summary ATAC assessment is that a reasonable start has been made on this ATAC recommendation; however, many very important aspects remain to be addressed by the delta Preliminary Design Review (PDR) in July.

ATAC Progress Report 11, Recommendation II: A&R Development Tools.

"Develop and implement prior to CDR a common set of robotic primitives, simulation systems, and modeling tools for use by all the robotic systems developers across all work packages."

The ATAC assessment of SSFP progress on this recommendation is that the intent is there but little has actually been implemented. A Robotics Working Group meeting, planned for March 1991, should establish a schedule of accomplishment of needed common design, modeling, simulation, and analysis tools for robotics as well as define roles and responsibilities (including the Canadian Space Agency) for these tools. Criteria for performance assessments using all robotic simulations and all computer models were addressed between GSFC, JSC, Martin Marietta, and MDSSC to support FTS analysis, but this activity has been effectively halted due to restructuring activities.

Only in the simulation models and collision prediction and avoidance areas have there been substantial efforts to standardize and coordinate tools and their use.

ATAC recognizes that in regard to models and simulations, it is difficult to gain commonality. In most cases simulations are developed by different organizations for specific analysis objectives. Rarely are those objectives the same, which is why it often seems that simulations or analyses are redundant or overlapping, when in fact they are tailored for different purposes. Models, both geometric and math, are also hard to transfer readily from one facility to another in software form unless a common software development environment is defined and implemented early in the process.

The Multibody Interactive Dynamics of the Arms and Station (MIDAS) simulation and analysis effort at Level II is focused on integration analyses. Its implementation must take into account the user's needs for easy access and training at the various centers and contractors. This work seems to be in its early stages and the importance of its coordination with the various design and operations organizations is apparently well appreciated. A recognition that the fidelity required by individual subsystems in their own simulations cannot be totally maintained in the integrated simulation would make MIDAS a more practical tool to serve the needs of Level II integration.

ATAC Progress Report 11, Recommendation III: End-to-End Software Integration.

"Develop and implement prior to CDR software standards, Software Support Environment standards, and a plan to provide end-to-end software integration for both flight and ground applications."

Neither software standards nor Software Support Environment (SSE) standards were addressed by Level II in the ATAC briefings.

As part of restructuring, the SSFP is rethinking its software acquisition, development, and integration approach and has targeted late March 1991 as a decision date. Certain functionality has been restructured from onboard to ground capability (e.g., inventory management and fault diagnosis and recovery) which also impacts standards and integration plans. Given these major changes there is no software integration plan as yet, nor a schedule to produce this plan.

There are flight to ground functional partitioning rules (e.g., only time-critical functions will remain automated on the station). What functions are, and what functions are not critical remain to be defined in specific terms. The functional partitioning rules dealing with the "Zone of Exclusion" and TDRSS handover should receive additional attention.

There is currently no testbed for Integrated Station Executive software testing as is needed, due to the termination of the OMS Integration testbed prior to the operational status of the Avionics Integration Environment.

The ATAC assessment is that little progress has been reported in this area as yet, and that essentially no software infrastructure exists (or is planned) for the inclusion of advanced automation approaches. Thus, future inclusion of applications for these technologies does not appear possible.

ATAC Progress Report 11, Recommendation IV: IVA Study.

"Complete a study prior to CDR similar to the Fisher-Price study, to assess and evaluate the IVA resources available to meet SSF onboard assembly, operations, and maintenance requirements."

Progress was made toward recognizing the need to start analysis of IVA resource requirements. During this period, the Space Station Program was occupied with the design review of the previous baseline while simultaneously working on the 90-day redesign of the Space Station based on congressional budget reductions. It is necessary that operational considerations, including the allocation of astronaut time, inside and outside the pressurized volume, be a part of the redesign effort. It has been shown by the Fisher-Price study that waiting for a design to be completely defined before analyzing the IVA and EVA timelines will lead directly to unworkable solutions.

A Level I productivity study was conducted and reviewed by experienced astronauts with recommendations to offload overhead associated with onboard operations. However, ATAC is still concerned that the IVA resources for Space Station are oversubscribed in operating and maintaining the station, leaving little time for science operations. The removal of advanced automation and robotics from the program to reduce upfront costs may result in greater operations costs and a potentially critical oversubscription of astronaut EVA and IVA time. This concern has been expressed by various Space Station and contractor A&R focal points. A study of IVA maintenance requirements is planned to start in the spring of 1991. This study, however, only considers the maintenance issues and not the entire timeline and utilization of the astronaut time. A complete IVA and EVA study is needed as soon as possible. The study should explicitly address all phases of SSF (MTC, post-MTC, PMC, post-PMC, EMCC) to ensure specific configurations and crew sizes are correct.

ATAC Progress Report 11, Recommendation V: Ground-Based SSF Robotics Teleoperation

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

Operator Controlled Machine Vision (OCMV) software has been developed giving the local operator the capability to help a telerobot interpret data from remote vision sensors and plan appropriate collision free motion. However, very little overall progress is evident on this recommendation despite the advocacy of the Fisher-Price study and systems analysis conducted on the problem. Ground-based robotics teleoperation continues to be an important area for future operation and maintenance of the Space Station Freedom. A plan to assess the feasibility of operating Space Station Freedom telerobotic assets from the ground, regardless of the source of those robotic devices, remains a critical need in the program especially in view of the 1) several years of man-tended operations and 2) marginal capability of crew and in-space teleoperated partners' robots to satisfy the maintenance requirements.

ATAC Progress Report 11, Recommendation VI: Hooks and Scars

"At the completion of the Space Station Freedom scrub activity and prior to CDR, determine the extent to which the planned SSF baseline configuration at Assembly Complete will support the implementation of advanced A&R applications, with emphasis on the Data Management System (DMS) architecture and sensor instrumentation."

Since the last ATAC briefing, three Space Station planning exercises have been under way which could have significant impact on "hooks and scars" for advanced A&R: The Resource Scrub, the Pre-Integrated Truss, and the Space Station Restructuring.

The Resource Scrub resulted in most monitoring and automated control capability being moved to the ground. The Restructuring effect on the DMS, still continuing, has resulted in the reduction in the quantity of Standard Data Processors (SDP) from 14 to 6. The goal is to achieve full core station operations in two "hot" computers and one "hot" workstation. The fundamental DMS architecture is unchanged and the system is designed for easy growth, if additional core and payload computers are authorized. SDP racks and network designs should accommodate capability for future expansion.

The DMS software is currently undergoing a scrub. The goal is to reduce all DMS systems software to 1M byte. This has simplified the command and control structure. The Operation Management

System (OMS) functionally has been descoped and absorbed by the Integrated System Executive (ISE) which handles the minimum required top level functions. Other functions are allocated to system software or to the ground. The ISE will accommodate station-wide Fault Detection, Isolation, and Recovery (FDIR) for Category 1 and time-critical functions. All other FDIR is transferred to the ground. The number of sensors and effectors, and the onboard sensor processing were reduced which may compromise the capability to implement advanced A&R capability in the future. ATAC received only limited information on the effect of restructuring on the Space Station Control Center (SSCC) and the capability of SSCC to accommodate the increased ground-based A&R over the lifetime of the program.

The Pre-Integrated Truss (PIT) exercise had little effect on system automation but provided increased emphasis and design accommodation for robotic application. The PIT required the redesign and location of ORUs; and standard interfaces and robotic access were a major influence during the PIT exercise including accommodation of robotic device mobility. This increased accommodation for robotic application continued during the restructuring; however, the FTS was deleted from SSF during this exercise. Therefore, the increased robotic operation will be the responsibility of the international partners.

A comprehensive answer to Recommendation VI is not available since the Restructuring activity is continuing. A complete review of "Hooks and Scars" should be accomplished as soon as the new configuration is defined.

ATAC Progress Report 11, Recommendation VII: Advanced A&R Technology Implementation Funding

"Ensure funding stability for SSF advanced A&R technology development and emphasize funding level commensurate with that required to transfer and implement these technologies into the SSF operational environments."

As reported in the last report of the ATAC, the SSF Advanced Development Program has been the primary mechanism for the introduction of A&R technologies for the Space Station Freedom Program; however, the budget history of this program has not been stable. The Advanced Development Program budget projections, presented in the previous ATAC report, were for a $12M program for 1991 growing to $16M for 1992. The 1991 program has been reduced to $7.7M of which only $1.8M has been distributed. The remaining $5.9M has been requested but budget authority had not been approved at the time of the ATAC briefing.

A&R Status Review of Levels I and II; WP1, WP2, WP3, and WP4; and CSSP

Assessment of Level I

The Advanced Development Program has been a primary mechanism for the advanced development of A&R technology for inclusion in SSF. Budget fluctuation and funding limitations have significantly reduced the technology transfer effectiveness of this program and have continued during this review period. The Space Station restructured program phases, First Element Launch (FEL), Man-Tended Capability (MTC), and Permanently Manned Configuration (PMC) no longer includes Assembly Complete (AC) following PMC. The period between PMC and AC was the period when the A&R technologies from the Advanced Development Program were to be implemented. The longer period of time between MTC and PMC could benefit significantly from A&R for science, remote monitoring, control, and reconfiguration of systems during unmanned periods.

To address the budget reductions and the increased need for A&R due to Restructuring, the Level 1 Advanced Development Program content has been revised to be more responsive to critical baseline Space Station requirements. The program office has implemented a task selection process which emphasizes nearer term developments. Budget reductions and task schedules not consistent with Restructuring have resulted in the termination of 14 tasks.

The Advanced Development Program has established a consistent process to evaluate tasks for inclusion and has emphasized task demonstrations compatible with Space Station Program milestones. The currently proposed Advanced Development Program consists of 19 tasks in a four-element Work Breakdown Structure (WBS). ATAC commends the Advanced Development Program efforts to infuse A&R into the Baseline Space Station Freedom. However, with the nearer term focus requiring earlier development and demonstration, the budget levels are considered inadequate. ATAC feels that for a successful A&R program, not only should the budget be increased for the development but the recipient of the technology at a work package center and its contractor be involved in the demonstrations. This would ensure effective technology transfer and allow rapid implementation for those technologies which demonstrate positive results.

Assessment of Level II

ATAC received generally a very good set of in-depth presentations of Level II activities. Level II also arranged an excellent presentation by the Canadian Space Agency.

There still appears to be a lack of adequate Level II staff to plan, coordinate, implement, and manage an effective A&R program which benefits Space Station Freedom over its entire life. For instance, there is no one assigned, even part-time, to advanced automation applications and design accommodations. Also, there has been no apparent effort to have the Level II Group Directors for Operations and Utilization, and Systems Engineering and Integration provide semiannual reports of progress in the areas of advanced A&R.

The Integrated Systems Preliminary Design Review (ISPDR) did not address any hardware scars, software hooks, or other provisions needed to support advanced automation evolution, nor did it address robotic systems evolution. The restructured SSF design did not add these, of course.

Advanced automation is detrimentally impacted by not having a sufficiently clear user mission statement of objectives for the restructured SSF. To a lesser extent the same is true for robotics. Three examples will be discussed.

For the first example, additional attention should be focused on the reduction in functional redundancy as a result of restructuring to reduce power, weight, sophistication, and cost. The question has to be asked: "To what extent does advanced automation on the station or on the ground need to fill in to maintain the same degree of program technological and safety risks, or how far is the program willing to increase these risks by excluding advanced automation?"

As a second example, the onboard Data Management System is being simplified and much of its original automation is being deleted. This means that many of the formerly onboard core system management functions are being moved to the ground, which conflicts with the down-scaling of the communications and tracking system (C&T). The C&T system now takes on more criticality in the overall command and control of the SSF, yet it is also being made less redundant. The Zone-of-Exclusion of each orbit cuts SSF communications with the ground for about 10 minutes each orbit, effectively leaving SSF on its own. This in turn, tends to raise the criticality of the ground command and control functions with respect to the use of advanced automation. The DMS has been cut back rather drastically; and ATAC urges that additional fiber optic cables, larger card cages, and less power-greedy CPUs (which exist) should be considered for growback before MTC as needed scars for the future.

As a third example, advanced automation might be able to make MTC science more productive during untended periods. Software controlled switches were removed in last fall's scrub activity. Thus, if there is a power transient that causes a circuit breaker to open, it cannot be reset until the crew arrives. Additionally, this impacts investigation as to cause and whether the correct spares are available on the station.

No overall IVA crew time analysis has yet been conducted. It is critical that SSFP conduct such an analysis to identify the problems of crew oversubscription for which advanced automation and/or ground control of robots is needed. It should include analysis of the diagnostic error rate of omissions and commissions due to Built-In-Test and Built-In-Test Equipment (BIT/BITE) reliance and crew need to aid diagnosis conducted on the ground. In Skylab and Shuttle, such contingencies have had major timeline impacts of hours to days.

Turning to robotics, the efforts to achieve ORU interface standards seem to be progressing well. The dexterous task identification study could apparently benefit from efficient task analysis tools as the previously proposed task analysis process is quite time consuming. A preliminary definition of the role of dexterous robots on SSF has been defined by Level II, but the need exists to identify specific dexterous robotic tasks in program documentation and to baseline the RSIS. Work in this regard is ongoing and results are expected by this summer. External maintenance studies continue and even with the reductions due to restructuring, there is expected to be a useful role in maintenance for robotic systems.

The restructured design to a pre-integrated truss that does not require onorbit assembly is a sound step. However, maintenance and repair of truss members must still be provided for.

The collision prediction and avoidance efforts appear to be making progress through the use of robotic simulations.
The summary ATAC assessment is that neither advanced automation nor U.S. robotics is a major part of the restructured program. SSFP has essentially no U.S. advanced automation even on the ground, nor adequate design accommodations for future migration from the ground for those applications where this makes sense. Thus, future evolution to reduce operations costs is most unlikely due to the lack of adequate

design accommodations and program infrastructure. With the transfer of FTS out of the program, no U.S.-furnished robotic systems remain on SSF in contrast to very active Canadian and Japanese onboard space robotics programs.

The United States is in jeopardy of losing its capability to compete with foreign competition in space automation and robotics.

Assessment of Work Package 1

During this and previous reporting periods, Work Package 1 (WP1) continued studying those specific implementations of automation and robotics which promised to result in the greatest benefits to Space Station capability and operational efficiency. The conclusions of these design studies have tended to provide strong support to the arguments for incorporating robotic operations and maintenance, and for using automated expert system monitoring of critical subsystems. However, the various budgetary scrubs and system reconfigurations have now essentially eliminated the possibility of using those technologies in the WP1 baseline program.

Present SSF plans call for a Man-Tended Configuration capability. This could be a period of productive utilization of the Microgravity Laboratory, if the experiments and processes can be run and maintained efficiently in an automated mode between astronaut visits. Using an assumed complement of eight materials processing payloads, the WP1 study showed that a general purpose Laboratory Assistant Robot would improve the facility utilization by more than a factor of 2 over a system in which each experiment was individually automated. This could simultaneously result in significantly lower life-cycle cost. That study has now been terminated, with no plan to implement IVA automation.

Similarly, studies and architecture designs and demonstrations funded by the Level I Advanced Development Program were conducted on systems to perform FDIR monitoring and control of critical subsystems in the Environmental Control and Life Support System. All designs for FDIR monitoring of the Potable Water and Hygiene Water systems were completed and a study was starting on the air revitalization system. Another automation system to monitor and control the Power Management and Distribution (PMAD) system is being developed with participation of WP4. These applications are also funded by the Level I Advanced Development Program and OAET. These applications are in jeopardy of being descoped and phased out, primarily because of reduced and uncertain funding. Reductions in scope to the DMS have made the eventual migration of this software to the flight system challenging, but not entirely impossible.

In summary, the ATAC now sees no advanced automation and robotics flight hardware or software in the WP1 baseline. This situation conflicts with the need for more automation to support science experiments during the Station's longer man-tended period. It also reflects a disregard for minimizing life-cycle cost, in favor of accommodating the immediate need to cut front-end costs.

Assessment of Work Package 2

The current perspective on WP 2 is not dramatically different from that reported in ATAC Progress Report 11. Modest progress, across the work packages and levels, in standardizing accommodations for the limited robotic content remaining in the program has continued. However it is now clear that the scrub and related SSF reconfiguration activities have indeed abolished any short (or medium) term expectation of advanced automation and robotics evolution onto Space Station Freedom. The recent restructuring has resulted in deletion of much of the A&R content of the WP2 program. Fourteen (out of fourteen) Level III funded advanced automation supporting development tasks were cancelled or disconnected from SSFP. The total funding associated with these 14 tasks was about $1 M. It is now conceded that SSF is unlikely to have advanced automation for the man-tended capability phase or even for the permanently manned capability phase. The program infrastructure support will not exist.

The constraints on weight, power, and computation will severely limit the possibilities of a retrofit. The spacecraft design lacks many sensors for anomaly resolution and fault diagnosis. It also lacks accommodations for evolution (hooks and scars). It is, of course, still possible to implement advanced automation in the SSF ground infrastructure. It is clear that this alone could have a major impact on SSFP life-cycle cost. ATAC urges that this area receive a high priority in future SSFP budgets and plans.

The pre-integrated truss exercise may have provided improved opportunities for robotic accommodation. Robotic (and EVA) access to ORUs would appear to be substantially improved as was the provision for robotic device mobility. WP2 progress is apparent in the development of ORU standards, A&R development tools, and end-to-end software integration. Much of this progress reflects program wide activity (as ATAC had recommended). The SSFP progress in implementing ATAC recommendations is described elsewhere.

Assessment of Work Package 3

The deletion of the external experiments attachment capability during the 1989 time frame and removal of the FTS from the SSFP in 1991 has effectively eliminated WP3 from the ATAC review process. However, the following remarks are offered.

ATAC separately reviewed and assessed the FTS program status at the contractor's plant on February 6, 1991, in addition to conducting a review at GSFC at the general ATAC meeting. Though a little late, the contractor is to be commended for initiating and implementing a major management reorganization of the FTS project which has increased the cost effectiveness of the program activities. The program funding was also reviewed and the results indicated that the contractor had not exceeded the allocated budget by more than 25%; the overrun was partially due to a change in the program requirements and a lack of program specifications. The impact of the decision to transfer the FTS program out of the SSFP into OAET could not be assessed at the time of this ATAC review.

The reasons for having a long-term national commitment to Automation and Robotics remain relevant (i.e. long-term productivity and financial leverage). These benefits require a long-term national commitment to A&R technology. The U.S. applications of telerobotics to the Space Station Freedom are now on the verge of disintegration and collapse. The requirements for U.S. assembly, servicing, or repair of U.S. assets in space are planned to be satisfied by foreign technology from the Japanese, Canadians, and Europeans.

The Japanese and Europeans have established development programs for intelligent robots for terrestrial and space applications, and Canada has established a significant program as part of SSF. With the reduction of funding and emphasis in the nuclear power field, the FTS program was the only major telerobotic activity in the United States. The removal of the FTS from the Space Station Freedom Program could significantly delay and/or eliminate this technology in the United States.

ATAC is of the opinion that (1) a long-term U.S. commitment to telerobotics is still required in the national interest; (2) a development project with a deliverable flight system, like FTS, and related to technology programs is a viable way to pursue this interest; (3) with cost/benefit tradeoffs in mind, the currently planned DTF-1 experiment should proceed unchanged; and (4) as a follow on to DTF-1, OAET should be encouraged to implement an intelligent telerobotics flight development project with delivery and application on SSF or another NASA flight program.

Assessment of Work Package 4

There is considerable work going on at the Lewis Research Center with regard to the Electrical Power System Testbed. This testbed is primarily used to evaluate power distribution and control schemes. It also provides a basis for evaluating automation techniques for later use on SSF. However, there did not seem to be a direct link back to SSF for eventual adaptation of these techniques.

With regard to the Electrical Power System Automation on SSF, a four-tiered energy management system had been defined prior to restructuring which involves automation of power system operational control, system protection, and systems status monitoring. This represents a considerable amount of advanced systems automation and will provide SSF with a highly efficient energy management system when implemented. Because this system interacts with the OMS, the effects of the recent SSF restructuring (with respect to reduction of DMS assets and the SSF ability to maintain the integrity of the Electrical Power System) should be studied. Also, the effect of transferring the automated functions to the ground should be examined with regard to resources available to provide this capability.

Several Rocketdyne Inhouse Research and Development (IR&D) expert system projects were described which will be integrated into the advanced development testbed.

WP4 is designing the Electrical Power System ORUs for telerobotic replacement compatibility. To accomplish this, they solicited the Mission Utilization Team (MUT) at GSFC to perform graphic simulations to determine the feasibility of servicing the integrated electrical assembly (IEA). In addition, a comprehensive test program was implemented in the Robotics Lab at GSFC to examine the mechanical and human factors issues associated with IEA-ORU exchange. Such parameters as attachment mechanisms, alignment guides, visual cues, end effectors and tools, operator skill levels, and timelines were examined. The results of these activities should be folded into the ORU flight designs, operational timelines, tools and end effectors, and robot performance requirements. In addition, the data accrued from these tests should be included in the robotic systems integration standards, modified for operation with the currently baselined Canadian SPDM, which replaces the FTS.

Assessment of Canadian Space Station Program A&R

ATAC for the first time received a review of the A&R status of the Canadian Space Station Program. The Canadian Space Station Program has established an A&R program which includes the development of advanced A&R technology, application of advanced A&R in space, and the transfer of the technology to the private sector. Results of this review are presented in Appendix C, "Canadian Space Station Program A&R."

The ATAC perception is that Canada has established a significant A&R program with a high probability of accomplishing all of its objectives.

New A&R Issues

Ground-Based SSF Science, Operations, and Maintenance

Space Station Control Center and Payload Center Automation. It appears that virtually all control functions for the Space Station systems in the restructured program will reside in the SSCC. By carefully planning for and incorporating existing automation technologies, considerable long-term cost benefits may be obtainable. Considering this in the formative stages of the SSCC would result in lower cost than if these technologies were added at a later time. In addition, the increased capabilities and reduced costs would be obtainable with implementation of advanced A&R in the Space Station Payload Center.

ATAC recommends 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, and their supporting facilities with eventual migration to onboard applications to ensure increased productivity and reduced overall operations costs.

Ground-Based SSF Robotics Teleoperation. The Fisher-Price study results in the need for heavy use of IVA in the support of robotic EVA operations. Indications are that such IVA resources will be in short supply, considering the scrub impact to onboard housekeeping automation. Currently technologies are not validated to ensure that such robotic systems can be safely operated from the ground. If IVA resource constraints are uncovered later in the SSF development program, there will be inadequate time available to accomplish the technology development and testbed demonstrations to allow robotic remote ground operations. Ground-based SSF robotics teleoperation may have become more important due to the increased duration of the MTC unmanned phases.

ATAC recommends that SSFP 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.

Onboard SSF Science, Operations, and Maintenance

Science Productivity. In the schedule on the restructured SSFP, there is a long period (3 years) that the Space Station will be man-tended. The science productivity during the unmanned phases could be greatly increased through the incorporation of relatively simple structured automation and robotics. An example of this could be in the form of devices that change out samples in material processing experiments.

ATAC recommends that SSFP 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.

SSF Dexterous Robots. A robotic standards document has been generated. This is excellent and should be implemented by the work package contractors. Even though it appears the FTS has been eliminated from the Space Station Program, the SPDM is a capable robotic device that should be used to the extent practical, in particular for dexterous robotic tasks.

ATAC recommends that SSFP develop and implement a plan prior to CDR for integration of dexterous robots into the onboard SSF operations, maintenance, and science activities.

A&R Evolution

Technology Transfer and Implementation. Currently, NASA experiences a significant gap between technology development and implementation of the technology into an operational environment. Some successes can be found, but these tend to be the exception instead of the norm.

The Report of the Advisory Committee (Chaired by Norm Augustine) on the Future of the U.S. Space Program states "there is a widely held opinion that although NASA continues to do excellent research, both in its Centers and in its affiliated universities, the results of the work are not being efficiently transferred into applications."

Although it is recognized that program managers must move forward on a schedule commensurate with a limited budget, it appears that NASA programs tend to totally lock out advanced technology opportunities that are not brought forward by anyone other than a prime contractor. The Agency has invested considerable amounts of manpower and dollar resources in testbed activities at all of the NASA Centers. These testbeds received active support during the Phase A and B feasibility and definition phases of the SSF Program. However, these testbeds seem to have suffered a disproportionate share of the budget reduction activities of the past year. Yet, it is these testbeds and the Agency inhouse expertise they foster that will be required for assessment and recommended corrective actions when problems occur late in the development and verification cycle of the program.

A more disturbing perception is one in which the inhouse technology side of the Agency is virtually discouraged by SSFP project managers from making recommendations to the program. Currently, for inhouse technology contributions to the program to occur, the technology development must be carried forward independently by the technology organizations of the Agency with minimum to no encouragement from the programmatic organizations of the Agency. This puts the burden for initial, and sometimes additional, flight qualification on technology developers who do not have adequate insight into program requirements. The result is often total inadequacy to sufficiently carry a proposal to a satisfactory conclusion.

In contrast, the contractor development or IR&D organizations can come forward with proposals which may also be just as inadequate initially, but have access to all the capability of the funded side of their companies. If they can demonstrate a capability which reduces cost or increases reliability, these contractor proposals are brought forward through the prime contract. If the proposal is unsuccessful, the contractor writes off the loss as a business expense; if successful, NASA pays an incentive bonus for a good idea and then pays to develop the concept into an operational entity.

ATAC's concern is how to achieve the appropriate level of parity in the inhouse technology side of the Agency so that it has an equal opportunity to compete with the contractor community. ATAC believes that many of the characteristics and features of the Space Station are a direct result of concepts and techniques developed in both technology and operational Center testbeds during the early formative period of the Station. However, the flow of ideas from these testbeds has virtually ceased during the past 3-4 years. Could it be that the loss of this inhouse support and thought process has played a larger role than recognized in the problems which have plagued the SSF since the beginning of the Phase C period?

Program managers must openly encourage input from the technology Centers by stating areas of concern. If the solution requires some form of flight demonstration, the programs need to provide some assurances to the technology Centers that their concepts will be considered if technology funds are expended for the flight demonstrations. Joint cost sharing is a more positive indicator of interest. ATAC is also aware that the technology Centers and researchers must be more sensitive to program needs and schedules.

Finally, ATAC suggests that some form of incentive program must be developed for the contractor community so they will be receptive to technology developed from within the Agency. At the present time there is no particular reason for contractors to support NASA technology, especially if it might reduce their award fee.

ATAC recommends that SSFP strengthen cooperation between the technology and programmatic (user) sides of the Agency, and provide the SSF Advanced Development Program with a funding level commensurate with that required to transfer and implement advanced A&R technologies into SSF operational environments.

Flight Telerobotic Servicer. The decision to remove the FTS from the SSFP and place it in OAET as a research and technology program should be carefully planned. ATAC feels the FTS should be developed (perhaps on a relaxed schedule), and the SSF should be designed to be compatible with it and able to incorporate it in a useful role at a later date. This is important for retaining a U.S. robotic capability as part of the SSFP. Consideration should also be given to utilizing the FTS or its technologies in other NASA Programs (for example, EOS).

ATAC recommends that SSP encourage OAET 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. dexterous robots onto Space Station Freedom.

SSF Life-Cycle Costs. ATAC has been concerned about life-cycle costs for many years. ATAC also recognizes the extreme budget pressures on the near term development phase. However, large life-cycle costs can be very burdensome to NASA (the large operational costs on the Space Shuttle Program are an example). ATAC feels it is imperative that life-cycle costs be considered. This can be done in some cases through modest investments in the design and development phase to ensure that the introduction of automation and robotics is not precluded at a later date.

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

ATAC Progress Report 12 Recommendations

Ground-Based SSF Science, Operations, and Maintenance

Recommendation I: Space Station Control Center and Payload Center Automation.

"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, and their supporting facilities with eventual migration to onboard applications to ensure increased productivity and reduced overall operations costs."

Recommendation II: Ground-Based SSF Robotics 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."

Onboard SSF Science, Operations, and Maintenance

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."

Recommendation IV: SSF Dexterous Robots.

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

A&R Evolution

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 a funding level commensurate with that required to transfer and implement advanced A&R technologies into SSF operational environments."

Recommendation VI: Flight Telerobotic Servicer (FTS).

"Encourage OAET 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. dexterous robots onto Space Station Freedom."

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."

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Appendix A

Space Station Freedom Program A&R Progress

The Space Station Freedom Program (SSFP) policy for A&R reflects a commitment to apply A&R technologies to the design, development, and operation of the baseline Space Station. A&R applications will be utilized when found to be appropriate within the context of the overall system design, when found to have a favorable cost-to-benefit ratio, and where the enabling technology is sufficiently mature. The program recognizes A&R technologies experience rapid change, exhibit varying levels of technology readiness, and have unique requirements for successful integration with conventional design approaches and system engineering methodologies. Consequently, an important component of SSFP A&R policy is the provision for design accommodations and mature technologies which permit the program to fully capitalize on A&R advances occurring during the development and evolution of Space Station Freedom. Lastly, for all program phases, the program intends to leverage the significant momentum in A&R research and technology development within other government, industrial, and academic initiatives.

Progress has been made by the SSFP in each of the above areas and will be described in the following sections.

A&R Progress Within the Level I Advanced Development Program

The Advanced Development Programs activity at Level I is 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, and 11, Appendix A. The Advanced Programs activity is managed by the Level I Space Station Engineering organization and involves all the NASA centers and SSFP work packages.

The Advanced Development Program enhances baseline Station capabilities and, in the future, will enable Station evolution in support of advanced missions (e.g., the Space Exploration Initiative missions). Specifically, the program tasks are targeted to improve the productivity and reliability of flight and ground systems, reduce operations and sustaining engineering costs, and overcome obsolescence by providing a flexible, upgradable system. Products of the Advanced Development Program which underpin these objectives include engineering fidelity demonstrations and evaluations on Space Station development testbeds, design accommodations which permit insertion of new applications and/or maturing technology into Station flight and ground systems, and the associated tools required to develop and support advanced technology applications, especially in the A&R area.

Currently, the majority of the Advanced Development Program's FY91 budget of \$6.9M is dedicated to A&R applications and technology development. Nineteen tasks are divided between Flight and Ground System Automation (\$2.6M), Space Station Information Systems (\$2.4M), Advanced Software Engineering (\$1.3M), and Telerobotic Systems Technology (\$530K). Thirteen of the tasks are leveraged by joint funding from the Office of Aeronautics, Exploration and Technology (OAET), the Space Transportation System Program, the

U.S. Air Force (USAF), and the Defense Advanced Research Projects Agency (DARPA). The joint funding adds $7.4M to the tasks and enables the Advanced Development Program 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 Advanced Development Program. Several have focused their own internal Independent Research & Development funding to address complimentary objectives with the Advanced Development Program. This joint funding and coordination significantly augments the amount of resources devoted to building SSF A&R applications and facilitating the technology transition to the baseline station.

During FY91, the continuing resolution process allowed distribution of $1.8M in October and November of 1990. Continued funding has been delayed pursuant to decisions based on the current SSF restructuring activity. It is expected that the remaining FY91 funding authority will be finalized in February 1991, and that funding will be distributed in one or two increments. The result of this program exercise has been numerous schedule slips and consequent uncertainty in continuing tasks in the Level I Advanced Development Program. At this time, given the transition of the FTS from OSF to OAET, it is uncertain how Telerobotics Technology will be addressed in the restructured SSF Program. As a result, it is expected that the Level I Advanced Development Program will continue to fund the current Telerobotics Technology tasks, while developing an FTS transition plan and an assessment of the role of robotics in the restructured station.

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 reconfiguration. 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 first successful test of this linkage demonstrated the ability for MSFC to schedule load, LeRC to issue a power reduction warning, and MSFC to automatically shed all low priority loads. It is planned to continue linked testbed demonstrations to further integrate power generation and power distribution automation. Additional Human-System interface improvements have been reviewed and documented on the PMAD testbed.

ECLSS work on a potable water quality monitor prototype continues by using input from a high-fidelity simulation. Prototypes of the Hygiene Water System and Vapor Compression Distillation subsystems have been facilitated by using other KBS development tools. This prototype activity will continue in FY91 and will be demonstrated on the ECLSS testbed at MSFC.

The RTDS has been selected as the development migration path for the MCC Upgrade and potentially for SSCC. Recently the Flight Director Wind Monitor system was operated by Flight Directors during STS-41, STS-38, and STS-35. In addition, new Data Acquisition Status and Control Expert Systems will soon be on-line in the Shuttle MCC. The technologies deployed in the MCC include bit-mapped color graphics, real-time telemetry-driven visualizations (schematics, three-dimensional graphics, flight instrument emulation), rule-based and model based expert systems for monitoring, FDIR, and task automation, and software development tools which permit the end user (i.e., the Mission Controller) to personally develop the application software required for his or her position. RTDS applications have been developed for the following console positions: Communications, Main Engine Monitoring, Guidance, Navigation & Control, Mechanical Systems (Tire Pressure, Payload Bay Doors), the Remote Manipulator System, and the Emergency Mission Control Center. All these applications have made a positive impact on MCC operations by providing monitoring and fault detection capabilities well beyond those available in the mainframe computer. Additionally, the RTDS hardware and software architecture permits less expensive and faster insertion of new applications and technology into the MCC. The success of RTDS will significantly influence the design and architecture of both the MCC Upgrade and the SSCC. RTDS is a joint development of OAET, STS, and SSF advanced development.

A prototype KBS 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 (manifested on SLS-1 and SLS-2). 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 onboard trouble shooting of experiment equipment. The system, known as the Astronaut Scientific Associate, was ground tested in the Spacelab Baseline Data Collection Facility in preparation for, and will be used in support of, the SLS-1 mission on STS-40. The prototype system will be flown and used in-flight on SLS-2 on STS-63. Crew members and the experiment's Principal Investigator are actively involved in the development and evaluation. Results of this task will be used to influence design requirements for Space Station Freedom laboratory experiment interfaces to ensure that analogous capabilities are provided during MTC and at PMC.

In the Space Station Information Systems area, advanced data management applications and the computer and network architectures required to enable them are being addressed. Applications and technologies for the Space Station Operations Management System (OMS) and the onboard Data Management System (DMS) are under development. Strategic supporting technology issues are being addressed for computer and network functionality and performance. The most significant accomplishments during this reporting period follow.

The DMS Evolution Architectures Study was published. A number of important issues were addressed regarding DMS growth options with emphasis on 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. An evaluation of baseline DMS performance and recommended growth and evolution options will be reported annually. Continuing benchmark evaluations are being communicated to cognizant SSFP and contractor management and staff.

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-41 using a Macintosh portable evaluated cursor control hardware, use of on-line manuals, word processing, management of diskettes, and a number of other user interface oriented issues. A future STS DTO is scheduled for STS-43 to perform further evaluations, with eventual tests on a system more closely resembling an SSF DMS environment.

In Advanced Software Engineering, environments and architectures are being pursued which support the design, development, and maintenance of SSFP advanced automation applications. Tasks include developing and evaluating Ada cross-compilers for existing KBS tools, and benchmarking their performance using operational advanced automation prototypes; creating toolkits which support the reuse of design information; and developing and demonstrating verification, validation, testing, and maintenance tools and techniques for flight and ground software. The most significant accomplishments during this reporting period follow.

A final report was published evaluating two prototype Ada-based KBS programming tools. One prototype is derived from a commercial product while the other is developed internally by NASA. Each was evaluated using existing KBS applications. Results indicated that KBS applications can be developed in Ada and still retain their efficiency and effectiveness. Detailed design requirements for transitioning tools to support KBS application development within the Software Support Environment (SSE) were collected. These programming tools allow development of advanced automation applications in the language baselined for flight system software.

SSF is expected to require significantly large amounts of application and support software to operate. As a result, there will be large demands for training operations staff and crew. Current training approaches involve cumbersome overhead for scheduling computer simulations and staff.

Intelligent Computer Aided Training (ICAT) technology improves training by reducing the overhead involved in setting up training environments and scheduling classes and simulations. In addition, ICAT technology can be used as an "anytime you need it" capability for on-line training. Recently, ICAT technology has been transferred to the MOD orbit design section, McDonnell Douglas Space Systems Company (MDSSC) WP2, and JSC IRM computer operations. Currently, MDSSC is developing an ICAT application to support the SSF Thermal Control System at WP2.

Telerobotic Systems Technology focuses on the reduction of IVA teleoperation time for dexterous robotics tasks and the eventual provision of a ground-based operation mode for Station robotic systems. Advanced telerobotics reduces an operator's workload by allowing robot control of 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 ground-based operators in the presence of significant communications time delay. Such ground-remote operations 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 have been developed and demonstrated under the NASREM interface standards on the JPL Telerobotics Testbed. User Macro Interface technology has been transferred from JPL to GSFC. This technology facilitates the incorporation of shared control and force reflection technology into the GSFC testbed, and eventual transition to Martin Marietta.

Operator Controlled Machine Vision (OCMV) software has been developed giving the local operator the capability to help a telerobot interpret data from remote vision sensors and plan appropriate collision free motion. With OCMV, operators can use several screen cursors to overlay graphic edges and vertices on a video object and then match that object to a CAD model. By installing shared control software at the remote site and controlling the Martin Marietta manipulators through the OCMV interface at JPL, the task will again operate manipulators in a NASREM-based development environment while performing FTS DTF-like tasks in the presence of realtime delay over great distances. This activity surpasses the 1989 successful operation of the Kennedy Space Center prototype robotic inspection system under time delay which simulated ground-to-space robot operation. Recent OCMV tests at JPL have demonstrated the hands-on replanning of a detailed maintenance task in 6 minutes, indicating that this technology has potential for allowing very productive ground-remote-teleoperation of SSF robots.

Accomplishments with the Collision Avoidance Sensing Skin task at Goddard include successfully testing a single element sensor built from materials already space qualified and flown; reducing a single sensor element to 6.4 mm width and 0.8 mm standoff. The sensor (see Figure A1) has also been demonstrated to avoid objects approaching within 0.3 meters of a Puma robot. This "capaciflector" technology has successfully passed tests for EMI and thermal constraints. Both Program officials and the FTS prime contractor have formally reviewed the capaciflector sensor skin and recommended it be used as a primary collision avoidance system for the FTS and all SSF telerobots. A study has been initiated for potential applications to all SSF external ORUs and payloads.

Level II A&R Progress

Presentations were provided to the ATAC by Level II management and working level personnel concerning Level II progress in Automation and Robotics. Division managers from the Level II System Engineering Office and Avionics Systems Office provided briefings on Level II A&R organization, Integrated Systems Preliminary Design Review (ISPDR) baseline, and recommendations from the recent program restructuring activity.

Level II has added an additional full-time civil servant to the Robotics area. The Canadian Mobile Servicing System (MSS) program continues to be handled by the other full time civil servant in the System Engineering Office. The Space Station Engineering and Integration Contractor (SSEIC) and an SSEIC subcontractor, Ocean Systems Engineering, provide additional robotic systems support by adding another six individuals.

Restructuring has resulted in the recommendation to transfer the Flight Telerobotic Servicer to OAET and use the Canadian Special Purpose Dexterous Manipulator (SPDM) and Extravehicular Activity (EVA) for dexterous external maintenance tasks in the initial phases of the program. The Canadian MSS would also be simplified to eliminate Mobile Transporter rotation and plane change capabilities and to provide for MSS translation on a simplified rail system as opposed to translation by stepping from one set of node pins to another.

Onorbit Advanced Automation provisions have been impacted by the 1990 Turbo Team decisions and by program restructuring recommendations. Both the number of Standard Data Processors (SDP) and sensors available on orbit have decreased. Recommended restructuring of the Data Management System (DMS) will result in six SDPs in the core system with two of these SDPs running "hot." This recommended program restructuring has impacted the capability of the baseline station to support onorbit applications of advanced automation and robotics. The reduction of SDPs and distributed sensors was necessary to remain within power resource allocations. As a result, many functions are being moved to the ground.

Initially, the program will automate functions in the ground system. Sensors are being located to support automation by closing the loop on the ground. Thus, add-back of SDPs later in the program to support onorbit advanced automation remains a possibility. Migration of automated functions from the ground to orbit will occur consistent with available program funding and onorbit requirements.

The development status of engineering design standards for robotic system interfaces was presented. Robotic interface classes being addressed are shown in Figure A2. Significant progress has been made in this area since ATAC report #11. The Canadian Program "H handle," micro-ORU, and visual target have been selected as program standards for all "box-type" ORUs. This selection was made through the Robotic Systems Integration Standards (RSIS) Interface Design Review (IDR) activity. This activity will continue to select standard design interfaces between box type ORUs and the station. (Refer to written response to ATAC Report #11, Recommendation I, for additional information.)

The status of a Dexterous Task Identification Study was also presented. This task will identify and document in the PDRD, a list of dexterous tasks which can and should be designed for robotic system compatibility. These tasks will be required to comply with the requirements of RSIS, Volume I, which establishes requirements for robotic system compatible task design.

The status of robotic system collision avoidance requirements was also presented. Collision Avoidance requirements were summarized as direct (cupola) and indirect (camera) views for crew control of collision free robotic system operations. Backup systems for onorbit automated collision prediction and warning and ground-based collision-free path planning will be implemented consistent with available resources.

Program activity in the area of integrated robotic system simulations was presented by SSEIC. SSEIC is responsible for non-real time simulation of the Multibody Interactive Dynamics of Arms and Spacecraft (MIDAS). SSEIC is developing the simulation based on attitude control system models supplied from JSC/MDSSC/Honeywell, SSRMS simulation data to be provided from CSA/SPAR, and structural dynamic models developed by SSEIC engineers.

Program status in the area of external maintenance demands and associated EVA/IVA resource allocation issues were presented. The External Maintenance Solutions Team (EMST) activity (follow-on to EMTT) has recommended incorporating most recommendations of the EMTT. In addition, program and project-level onorbit maintenance managers have been appointed and an In-flight Maintenance (IFM) Working Group has been established as a program level forum for both external and internal maintenance issues. Restructuring efforts, particularly in the intensive Pre-Integrated Truss (PIT) team activity, has considered "maintenance friendly" design as a priority issue. A study to project internal maintenance demand will be conducted using the same methodologies employed by the EMST and the PIT design teams to project external maintenance demand. IVA demand will include both the crew time required to perform IVA maintenance and the crew time required to support robotic system operations and EVA. Assembly and operations demands are not currently projected or estimated using EMTT methods. The EMTT study encompassed external maintenance (EVA/robotic) demand only. Assembly and operations resources will be estimated by other means as a function of the crew time allocation process.

Work Package 1 A&R Progress

With a planned minimum 30-year operational lifetime, significantly large amounts of Space Station Freedom design knowledge and experience concerning the different subsystems and components are, and will continue to be generated. Trade studies, alternative designs, configuration simulations, and prototype systems will be commissioned and conducted to produce a flow of knowledge and experience throughout the whole spectrum of engineering and scientific disciplines. To capture and hold available the many solution/option sets generated from this work, Design Knowledge Capture (DKC) has become even more critical within the SSF program.

To support the DKC requirements of WP1, several tools are currently being developed. These are the Design Alternatives/Rationale Tool (DART), Environmental Control and Life-Support System (ECLSS) Simulator, Module Rack Integration Analysis and Optimization Tool, Packaging Manager (PACKMAN) and Automated Logistics Element Planning System (ALEPS). Though funding for these efforts has been curtailed, progress has been made.

Two tools currently provide support to WP1 design capture efforts. These are the MacQuinas (BAE trade study rationale) and

NASA DART. The DART in particular collects design knowledge from all work packages into a standard format. It is a descendant of MacQuinas, and is intended to collect data for incorporation into the Level II TMIS system.

Module Rack Integration (and optimization) Analysis Tool models the layout of SSF modules, including resources and constraints, in order to give the user operational efficiency, coordination, and requirement compliance information. The software system has been developed using commercial off-the-shelf software. Data has been stored via Excel and is currently being ported to Oracle. The object templates and rack integration knowledge is stored in a commercial expert system shell with the point/click graphical user interface supported by Hypercard.

ECLSS Advanced Simulation includes six major subsystems which work together to provide a safe working environment for the crew. The ECLSS simulation of ORU level models are currently complete, with work begun on air revitalization. Color capability has been added to this tool.

Automated Logistics Element Planning System combines object oriented programming, knowledge-based search, and advanced optimization techniques to allow automated preparation of a packing plan. This system being developed in LISP is currently planned to be converted to Ada.

A plan has been established to provide for hooks and scars to allow future upgrades to SSF in automation and robotics capabilities. Software hooks and hardware scars accompanied with interface specifications are necessary to accommodate the baseline SSF with enhanced automation growth potential. Once candidate applications for automation and potential robotic manipulation are identified, these hooks and scars may be defined. This preliminary design will take place in a prioritized fashion so that the most beneficial automation applications may be addressed first.

Hooks and scars for robotics applications allow inclusion of IVA robotics during evolutionary growth, or at whatever point in time the life-cycle cost and operations/logistics needs warrant their use. The move toward a longer Man-Tended phase, and the resulting reduction in crew hours available for test and maintenance, creates a greater opportunity for IVA robotics to handle scheduled and non-scheduled critical maintenance. Hooks and scars based on standard IVA crew designs will smooth the transition to IVA robotics while minimizing interference to crew operations. Use of advanced manipulators, dexterous end effectors, and knowledge-based control systems will allow use of "gentler" hooks and scars. As Boeing prepares its Robotics Plan, the RSIS standards as well as the recommendations of the ATAC will be incorporated.

WP1 has supported and continues to support the RSIS efforts to establish interface standards. In particular, the Robot-to-ORU standards recently proposed H-Handle configuration was reviewed by WP1. Boeing design teams have been continuously updated with RSIS status and inputs from other work packages, and contact/dialog with other work packages and contractors has been encouraged. Recent effort has been in the Logistics areas, with interface between SSRMS and logistics carriers of prime interest.

Boeing Independent Research and Development seeks to increase crew effectiveness and productivity by using automation and robotic systems. Restructuring is resulting in a longer Man-Tended phase of SSF (a duration of 3 years). This extended Man-Tended phase 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 Capability 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 to verify both the low level of risk and enhanced station operational capabilities expected from robotics application prior to the permanently manned phase.

A system has been developed for automated fault detection, isolation, and recovery for selected components of the SSF Environmental Control and Life-Support System. A dexterous three-fingered robotic gripper using force feedback control is being integrated with the robotic workspace. The present focus integrates the automated components for planning and replanning, simulation, execution, and diagnosis. This integration takes place in a testbed mockup of a common module providing an environment for exhibiting housekeeping, maintenance, and payload operations.

Results Driven Design (RDD) system is a computer aided engineering software tool adopted by Boeing to replace RT2 as a method to automate (generate and simulate) via a graphical hierarchy, in a sequential and functional manner, the development of system specifications from client requirements. This system provides and maintains traceability to customer and derived requirements and is already proving to be an asset in reducing manpower needed to ensure requirements are satisfied. RDD will deliver complete and tested system requirements to SSF design engineers while providing a tool to enhance configuration control. This tool is currently being used to develop the specifications for IVA robotics concurrently with research and development efforts.

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. These activities are couched in terms of the overall effect of restructuring on the Space Station in general, and automation and robotics in particular.

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).

Since the last ATAC meeting, three activities have impacted the program's A&R content: Resource Scrub, Pre-Integrated Truss, and Restructuring. The first two had minimal impact, but Restructuring may defer the program's Assembly Complete (AC) which could have a significant effect. The PIT activity resulted in better robotic accommodation in terms of access and robotic device mobility.

Pre-Integrated truss concepts for ORU accessibility are shown in Figure A3. JSC is now working with the Canadians to ensure that WP2 ORUs are compatible with the SPDM and EVA astronauts.

The WP2 prime contractor's A&R group was organized similarly to the JSC organization. Three main groups are managed within systems 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 the high maintenance external ORUs are robotically compatible. A defined process for evaluation of robotic compatibility has also been developed. The first step is the Robotic ORU Assembly and Maintenance (ROAM) methodology which provides a preliminary assessment of an ORU's robotic compatibility. Computer simulations and 1-g testing are used for verification of robot friendly design concepts. These robot and EVA astronaut compatible design concepts have been documented and included in the EVA/Robotics Design Standards (EVARDS).

Due to the PIT activity, the mobile transporter no longer requires plane change and rotation capability, so the astronaut positioning system is no longer needed and FTS accommodations have been deleted. Subcontractor and A&R activities have been greatly reduced. An A&R report was submitted to support the ATAC meeting and a new A&R plan will be submitted 90 days prior to project critical design review. The last three A&R reports have addressed all applicable ATAC recommendations.

Two planned onboard AI applications were reported at the ATAC meeting. The software scrub moved the functionality of one, a medical expert system, to the ground. The second, an onboard fault management function using parsed sets, is being evaluated for inclusion in the new software architecture's Integrated Station Executive (ISE). The Level I Advanced Development Program fund Thermal Control System automation task is proceeding on schedule, and will be deployed on the ground initially in the Engineering Support Center. This task leverages previous work in the Thermal Expert System (TEXSYS) project. The lessons learned are particularly applicable considering the currently baselined mechanically pumped thermal bus is similar to that used in TEXSYS. The DMS system management AI demonstration has evolved from being an A&R prototyping activity to being a useful component of the Fault Detection, Isolation, and Recovery design process.

The DMS and software are still in the process of being restructured so definite statements of content and capability are currently not possible. The SSE has no known plan to support A&R development, but Level I through Advanced Development funding is maintaining activities to develop such capabilities. The restructuring has had an impact on the planned capabilities of the Space Station Control Center, sliding many advanced capabilities into the future.

Work Package 3 A&R Progress

See Appendix B, "Flight Telerobotic Servicer," for automation and robotics progress in WP3.

Work Package 4 A&R Progress

Space Station Freedom's electrical power system provides the necessary power to operate station subsystems and payloads. Using automation reduces the human intervention required for daily maintenance and monitoring of the power system and will subsequently increase crew productivity. The Level I Advanced Development Program activities at WP4 are described in the following material.

The APEX and TROUBLE III diagnostics expert systems are being integrated into a single system. The best features of both designs are being combined to produce one system for the entire power management and control function. Failure detection rules come from the APEX system while general failure knowledge is taken from TROUBLE III. Failure hypothesis generation and probable failure cause identification are a blend of the techniques from both systems. The power system failure detection knowledge has been expanded and the integration, verification, and validation of the diagnostic features continue.

Automated resource scheduling work has produced a design architecture that identifies roles and responsibilities for suppliers and consumers onboard the spacecraft. A hierarchical partitioning of authority permits bargaining among resource consumers and resource suppliers under the guidance of a free-market coordinator. This concept uses distributed computing to produce an optimum schedule. Software modules have been produced for numerous payloads, electric power, thermal, life support, navigation, and crew systems. Experiments have been conducted to evaluate pricing strategies and value structures required during the bidding for resources. A prototype scheduler, using many of these concepts but running on a single processor, has been developed by DSA, Inc., and evaluated. Many of the features of this prototype have been incorporated into the distributed scheduler design. The scheduling system will be used to automate load management onboard the spacecraft.

Advanced automation products are being integrated into the Lewis Power System Testbed. Several different options for communicating among expert systems, their development environments, and the testbed computer systems have shown the need for both a standard and customized network interface. Basic designs for these interfaces have been completed, and their development is under way. Procurements have been initiated for distributed computing software that will facilitate the message passing involved when integrating these expert systems.

The Marshall Common Module Power Testbed has been linked with a 20kHZ Lewis Power System Testbed to demonstrate cooperative problem solving between power supplier and consumer. A simple automated transaction involving curtailment of power to the module has been demonstrated. Future demonstrations will increase the transaction complexity to identify design requirements for cooperating expert systems.

Robotics requirements focus on ORU telerobotic maintenance capabilities to minimize EVA time for onorbit maintenance (see Table A1). Standard telerobotic interfaces are provided to facilitate remote assembly, removal and replacement of ORUs. Robot compatible interfaces and operations are being tested and evaluated in collaboration with GSFC, JSC, CSA/SPAR, Martin Marietta, and Rockwell International. Test and evaluation methods include computer simulations (GSFC, JSC, CSA/SPAR), 1-g remote manipulator tests (JSC), 1-g dexterous manipulator tests (GSFC, Martin Marietta), neutral buoyancy tests (JSC, MSFC), and development test flights. Recently, the 1-g dexterous manipulator tests were successfully completed at Goddard. These tests investigated ORU replacement times, evaluated alignment features, verified proper meshing of radiant heat exchanger fins, determined optimum camera views, and validated the procedures used by telerobotic operators. From this experiment, complete telerobotic changeout of a power system ORU using FTS and SSRMS was estimated at 50 minutes.

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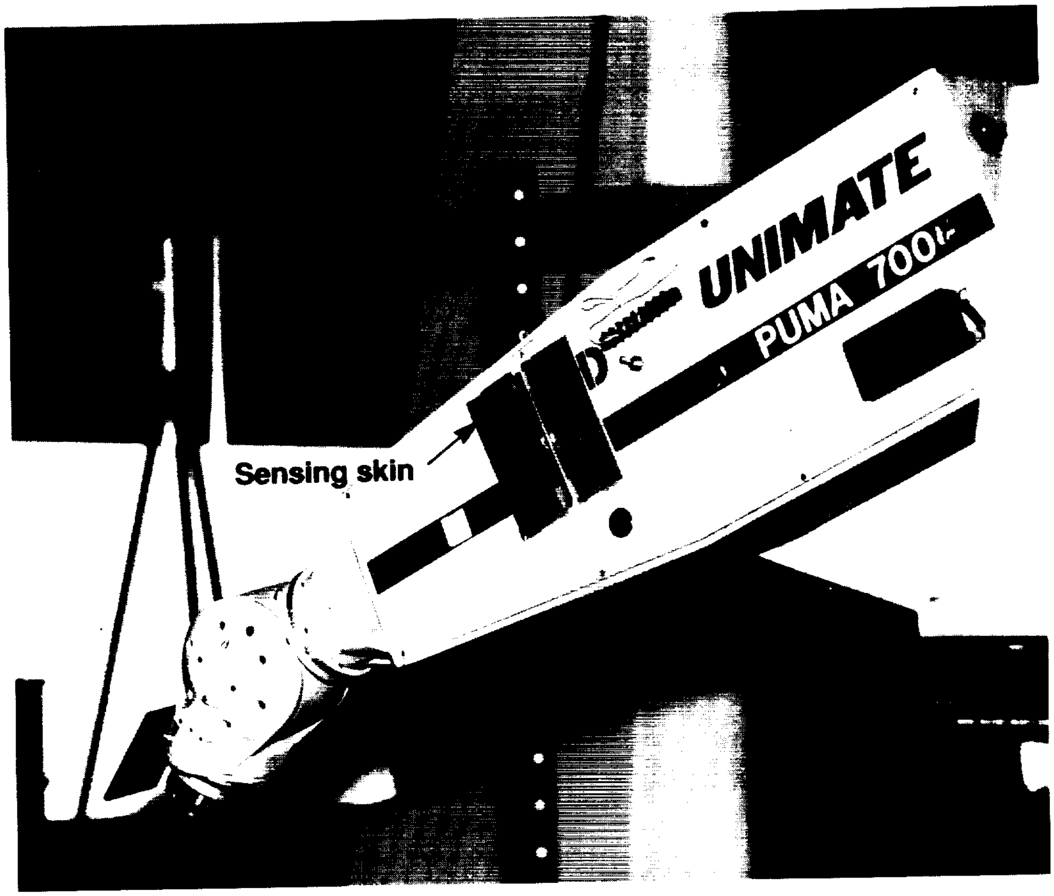

Figure A1. Collision avoidance sensing skin attached to Puma robot arm for testing.

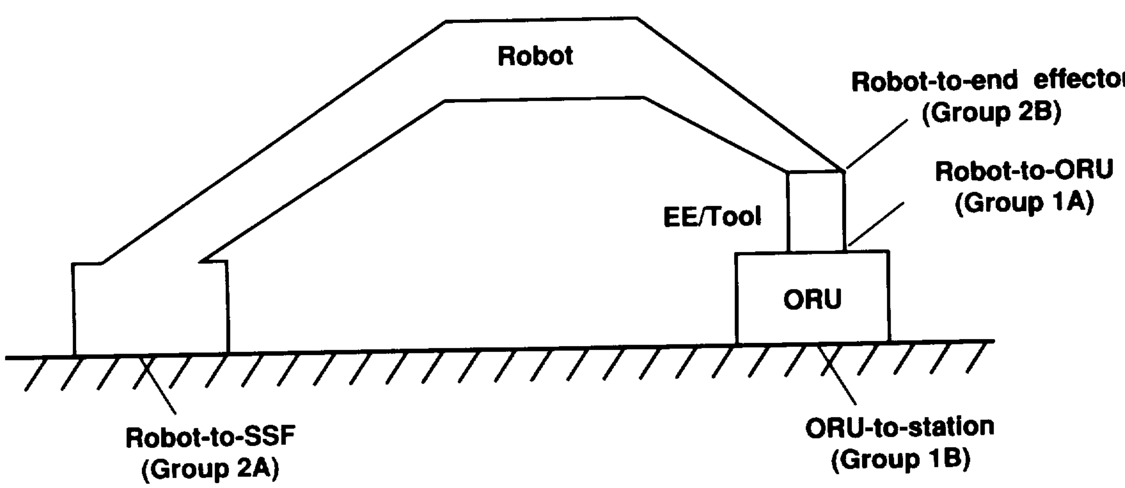

Figure A2. Robotic interface classes being addressed by SSFP RSIS activity

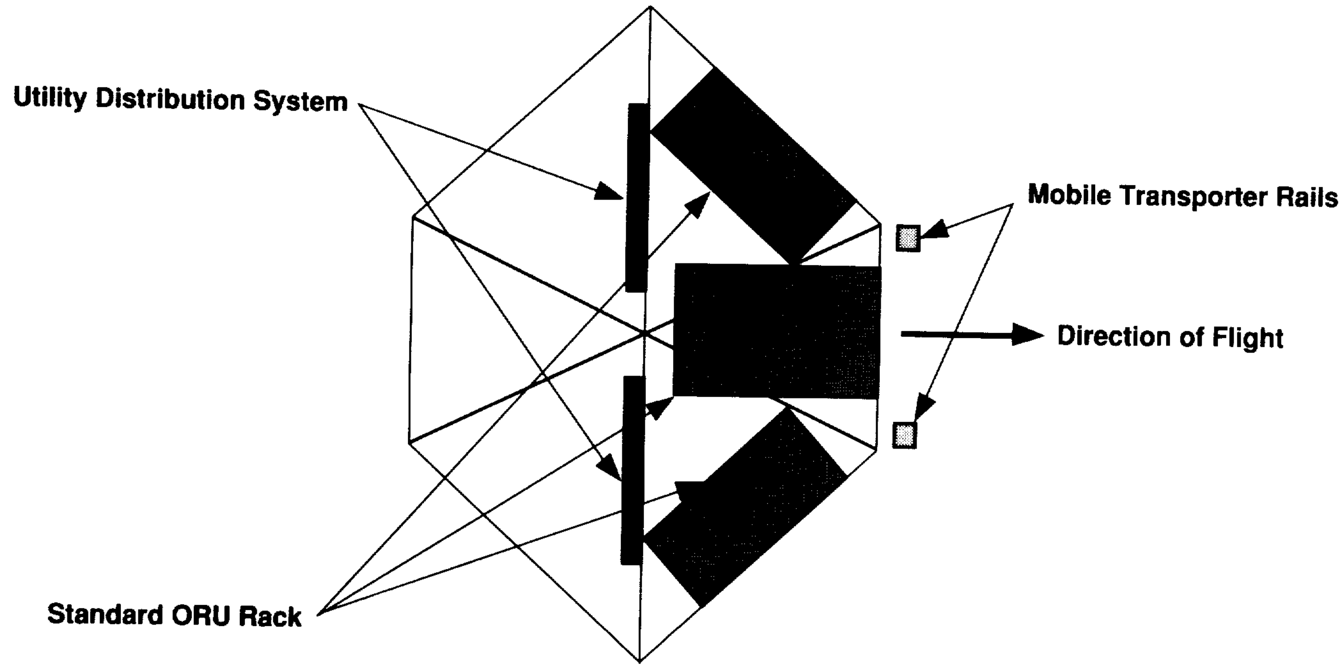

Figure A3. Pre-Integrated Truss concepts for ORU accessibility.

Table A1. WP4 ORU TELEROBOTIC REPLACEMENT CANDIDATES.

EXTERNAL ORU	QUANTITY	LOCATION	REPLACEMENT OPTIONS
Battery Subassembly	48	IEA	MSC/SSRMS/FTS
BCDU	24	IEA	MSC/SSRMS/FTS
DCSU	8	IEA	MSC/SSRMS/FTS
DDCU-IEA	8	IEA	MSC/SSRMS/FTS
PVCU	8	IEA	MSC/SSRMS/FTS
PV Cable Set	4	IEA	EVA with MSC/SSRMS/FTS
IEA	4	IEA	EVA with MSC/SSRMS
IEA Transition Struc Set	4	IEA	EVA with MSC/SSRMS
Pump	8	IEA	MSC/SSRMS/FTS
Cable Tray	8	IEA	TBD
Cable Box	16	IEA	MSC/SSRMS/FTS
Radiator Assembly	4	IEA	EVA with MSC/SSRMS
MBSU	4	PMAD Pallet	MSC/SSRMS/FTS
DDCU	32	Pallet & Modules	MSC/SSRMS/FTS
RPCM	TBD	ITA Pallets	MSC/SSRMS/FTS
PMAD Cable Set	2	ITA	EVA with MSC/SSRMS/FTS
Deployable Mast & Cann	8	Solar Array Wing	EVA with MSC/SSRMS/FTS
PV Blanket & Box	16	Solar Array Wing	EVA with MSC/SSRMS/FTS
SSU	8	Beta Gimbal	MSC/SSRMS/FTS
Bearing/Gear	8	Beta Gimbal	EVA
Roll Ring Subassembly	8	Beta Gimbal	EVA
Drive Motor Subassembly	8	Beta Gimbal	MSC/SSRMS/FTS
Electronics Control Unit	8	Beta Gimbal	MSC/SSRMS/FTS
Platform Subassembly	8	Beta Gimbal	EVA with MSC/SSRMS/FTS
Beta Gimbal Assembly	8	Beta Gimbal	EVA with MSC/SSRMS/FTS
BGA Transition Struc Set	8	Beta Gimbal	EVA with MSC/SSRMS/FTS

Appendix B

Flight Telerobotic Servicer Progress

Introduction

The Flight Telerobotic Servicer (FTS) has continued to progress technically while programmatically reacting to its changing role in the Space Station Freedom (SSF) Program and within NASA. Many technical problems have been resolved and considerable progress has been made on Development Test Flight (DTF-1). The first Flight Telerobotic Servicer industrial briefing took place in December 1990 and was well attended. Informative presentations were made by the prime contractor and all major subcontractors. Also, major strides were made in integrating the FTS with the SSF architecture prior to the decision to redirect FTS as an Office of Aeronautics, Exploration and Technology (OAET) technology program.

The transfer of FTS from the Office of Space Flight (OSF) to the OAET has created the need to develop a new program plan beyond DTF-1 and a new schedule for DTF-1 completion, consistent with projected funding profiles beyond FY 91. An effort to modify the FTS prime contract accordingly is under way.

Development Test Flight Progress

The DTF-1 mission was replanned following successful completion of the system level Critical Design Review (CDR) in October 1990. This produced an expected date for delivery to Kennedy Space Center of May 1992, with launch in December 1992. The schedule was considered optimistic but achievable with the proposed budget and was agreed to by the FTS prime contractor, Martin Marietta Astronautics Group. The development process continued to uncover and then solve technical problems in many areas. Most of these were minor and considered typical of a research and development program; however, two of them should be highlighted.

Manipulator controls simulations indicated stability problems due to a wide range of contract compliance conditions in the task hardware. For DTF-1, the solution to this problem is gain scheduling that tunes the system to the environmental stiffness.

The Orbiter safety requirements provide a major challenge for the space telerobotics designer. A computer controlled manipulator system must be watched by an independent computer system in order to provide an effective inhibitor to certain hazards, such as joint runaway. The safety rules require that there be a non-computer inhibit to each hazard. Additionally, the DTF-1 design requires that some fault tolerance value be assigned to processors in which a smart failure can cause a hazard. (A smart failure is one in which a computer processes bad data to make it look good and simultaneously processes good commands to generate bad instructions.) The space and weight limits do not allow for multiple independent computers at each joint to avoid this problem.

The safety panel at Johnson Space Center (JSC) has dedicated considerable time to understanding the DTF-1 design and treating these issues in a comprehensive, objective manner. It appears that added analysis and a thorough software validation program will satisfy the intent of the safety rules. The payloads of the SSF era will require generic guidelines for system design and implementation as this type of complex computerized mechanical device becomes more prevalent. The DTF-1 payload forms an excellent test case due to its geometric limits in the payload bay and its simple removable task hardware. The safety review process thus far has been extremely valuable in ensuring that FTS has a safe, reliable control architecture.

Mission Content and Status

DTF-1 deliverables are the flight system, a trainer, a simulator and a mockup. Figure B1 illustrates these elements. The flight system consists of a payload bay element and an aft flight deck element ready for integration with the Orbiter. The trainer is a form, fit, and function version of the flight system designed to prepare the flight crew to accomplish mission tasks. The simulator meets the requirements for real-time kinematic simulation, task scenario development, crew training and joint-integrated simulation support. The DTF-1 mockup is Weightless Environment Training Facility (WETF) compatible. All DTF-1 deliverables incorporate results from the CDR.

Open Orbiter integration issues continue to be resolved and documented. The Payload Integration Plan (PIP) was baselined in July 1990 and revision 1 was issued in January 1991. Presently the PIP is undergoing a review and incorporating additional change requests. All PIP annexes were reviewed at Goddard Space Flight Center and forwarded to JSC; an update to the flight operations support annex is expected in the last quarter of 1991. The payload-unique and middeck Interface Control Documents (ICDs) were published for review in October 1990. Both ICDs will be baselined in April 1991. The phase 2 safety review is scheduled for May 1991.

An analysis of the DTF-1 schedule shows two critical paths to meet current payload bay element plans. The primary critical path follows the design and production of motor controller boards, their installation in the shoulder controller, and the subsequent assembly of the manipulator. The secondary critical path follows the alternate control unit design, assembly and tests. These two paths converge for system integration and test at the end of September 1991.

Flight Telerobotic Servicer

Program Overview

The following summary of the original FTS Program, as approved for SSF in December 1986, is provided as a baseline from which to formulate a new program plan consistent with NASA objectives and funding. The original (prior to OAET transfer) FTS Program had two objectives. The first was to develop a telerobotic system for SSF. The second was to provide robotic technology transfer to United States industry.

Objectives

There are several specific goals for telerobotics. The first is to reduce dependence on crew Extravehicular Activity (EVA). FTS can accomplish this by adding flexibility to assembly flights and by helping to meet onorbit maintenance requirements. Another goal is to enhance crew utilization and improve crew safety. Still another goal is to provide a primary method for performance of high risk tasks, such as moving large objects, handling hazardous fluids, being exposed to energy release from deployable or pre-loaded items, working in locations with a possible focus of solar energy, and doing long duration tasks. These tasks were targeted for SSF, but are basically generic for most space applications.

Telerobotic technology transfer can be achieved by outreach programs, industrial briefings, publication of papers, and conferences such as NASA Technology 2000. Figure B2 shows possibilities for utilization of the technology developed by the FTS Project.

The FTS Project had two Orbiter-based test flights scheduled. Although the current contractual requirement for DTF-1 is December 1992, the flight is expected to occur in 1993. The current contractual requirement for the DTF-2 is June 1994. Figure B3 illustrates the planned progression from the test flights to the FTS operational configuration.

Development Test Flight

The DTF-1 mission objectives are to evaluate the design approach of the FTS manipulator and the workstation, to correlate system performance in zero gravity with ground simulation and analyses, to evaluate the human-machine interface and operator fatigue, to demonstrate telerobot potential capabilities, and to verify elements of FTS tasks. DTF-1 contains advanced robot control technologies. As such, it is a pathfinder in manned space flight robotic safety. The complex robot is controlled from the Orbiter workstation. It features force feedback to the operator in zero gravity. Although DTF-1 has just one manipulator, the dexterous manipulator technology has direct application to all FTS options for onorbit tasks. Figure B4 shows the DTF-1 configuration.

Flight Telerobotic Servicer Technical Approach

The technology integration required for FTS implementation will advance robotic state of-the-art. FTS combines technologies from existing nuclear, undersea and manufacturing robotic systems into a single system that must be reliable during space flight and also responsive to SSF assembly and maintenance needs. An operational telerobotic system with the required FTS capabilities has never been built.

There are several unresolved issues concerning the DTF-2 and FTS designs. They fall into the areas of controls, safety, packaging, thermal design, mobility, manipulator kinematics, human-machine interface, and evolution. Controls issues include force reflection (around-the-loop-timing), contact stability, and impedance control (active compliance). The safety concern is two-fault tolerance using computer inhibits. Packaging issues include the manipulator internal harness design (flat cable) and the joint controller boards (surface mount technology). In thermal design, the issue is whether to use passive surface coatings or heat pipes. The mobility issue consists of the number of degrees of freedom in the ASPS vs. required stiffness. The manipulator kinematics issue is the wrist configuration. The human-machine interface concern is the interleaving of teleoperation and autonomous capabilities. Evolution issues are data system architecture, and reserve compute throughput and memory.

FTS has the capability to evolve. The basic system has attributes that can support both teleoperation and autonomous control. It has designed-in capabilities for increased autonomous operation as technology advances. Evolution plans include the introduction of supervised autonomy. Under supervised autonomy, the operator performs image processing and real-time planning, while the robot, when properly positioned, performs a subtask. Examples of suitable subtasks are removal of a bolt or installation of a connector. Evolution plans also include development of techniques to add structure to the worksite, such as navigational aids and parts identification markings.

Space Station Freedom Integration and Restructuring

During the last 5 months of 1990, there was an emphasis on assembly tasks sanctioned for FTS accomplishment on SSF. These tasks are described in ATAC Progess Report 11. The task selections were based upon mission timing predictions, non-interference with crew EVA, availability of intravehicular activity crew support, and ability for end-to-end performance during a single session. Each task was subjected to detailed evaluation in the following areas: detailed scripts, interface assessments, computer aided design simulations, subtask analyses, orbital replaceable unit hardware testing, and validation plans. A task evaluation plan containing this material was produced for each task. An overall task evaluation report was published. All sanctioned tasks were found to be well within the capability of the FTS.

While the sanctioned task evaluations were being completed, the SSF restructuring exercises took place. In supporting these exercises, the role of FTS on a restructured SSF was examined. Alternative FTS design approaches were analyzed. New designs relied upon the maximum use of validated technologies, such as DTF-1, for dexterous robots, with an emphasis on the perceived needs of SSF during its 30-year life. The most promising suggested designs assumed FTS performance independent of other robotic systems. They also assumed that FTS could meet its requirements for mobility in transport to the worksite, stabilization at the worksite, and power, data and video supplied to the worksite. At the conclusion of the SSF restructuring exercises, however, planned SSF robotics no longer included FTS, FTS utility ports, or FTS accommodations.

Conclusion

The FTS Program progresses toward completion of the DTF-1 mission while in transition to a role in development of flight telerobotic technology. DTF-1 will provide a basic qualified set of hardware that can be used as a flying testbed to evaluate improvements and additions to this technology. Utilization of telerobotics in future space missions will become a low risk option as onorbit experience grows.

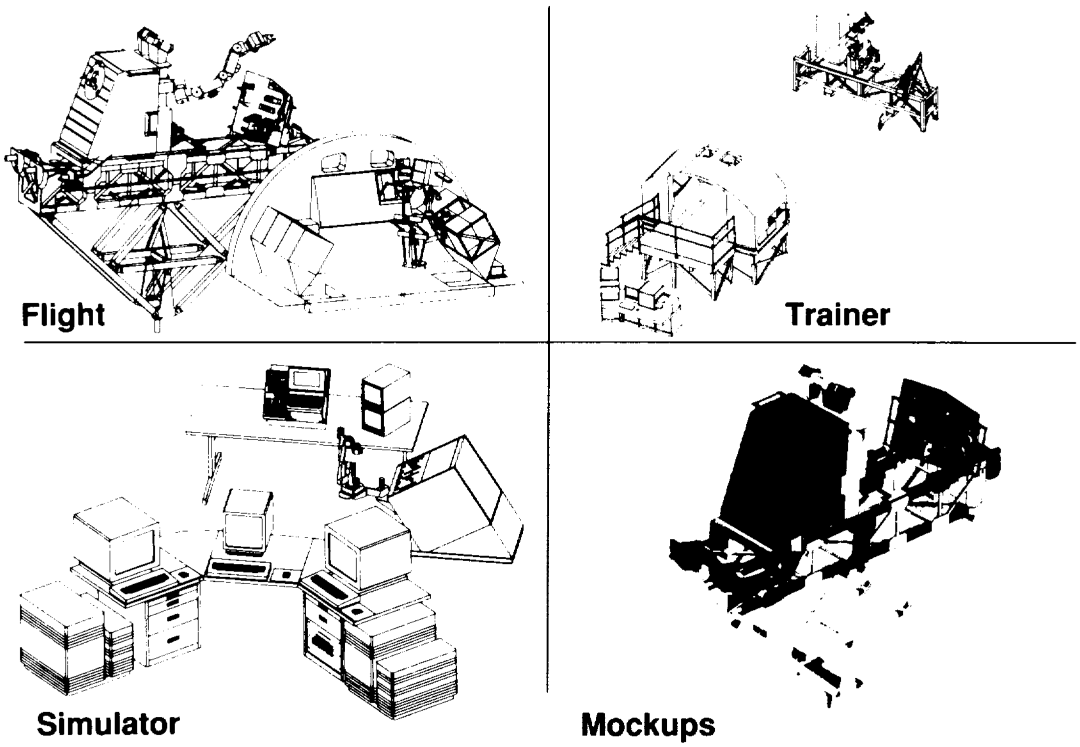

Figure B1. DTF-1 deliverables.

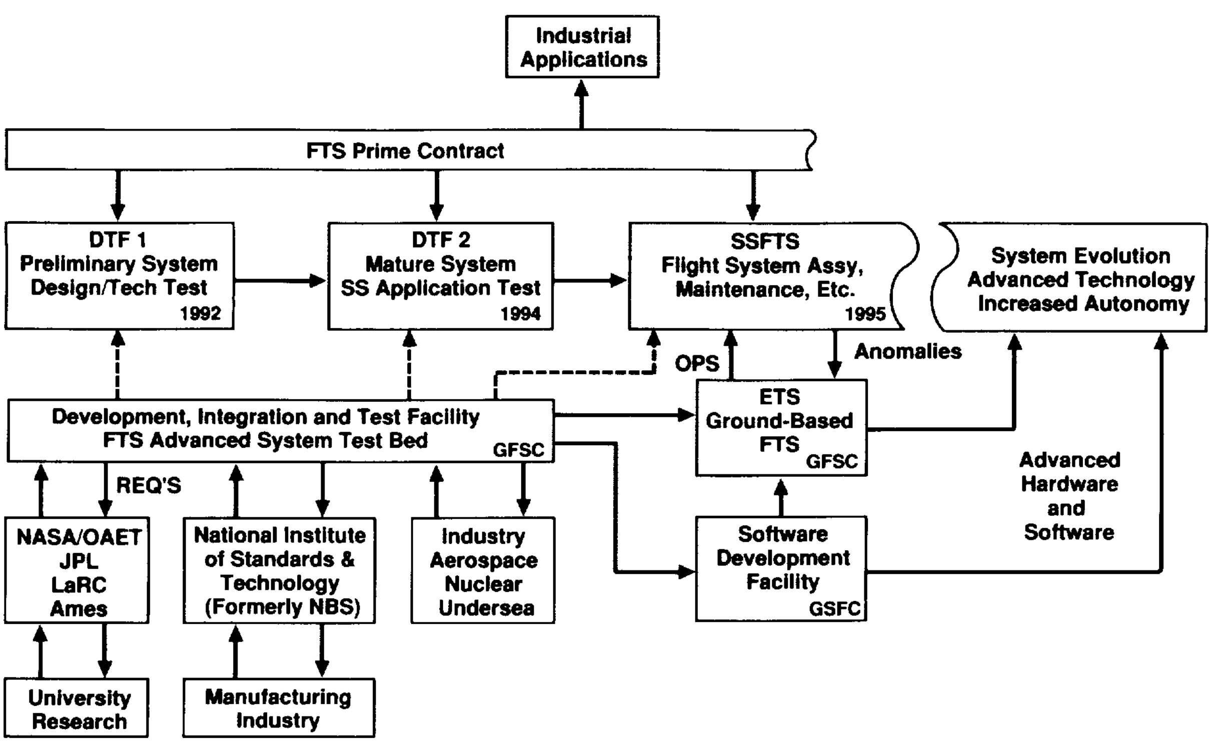

Figure B2. FTS development and technology utilization.

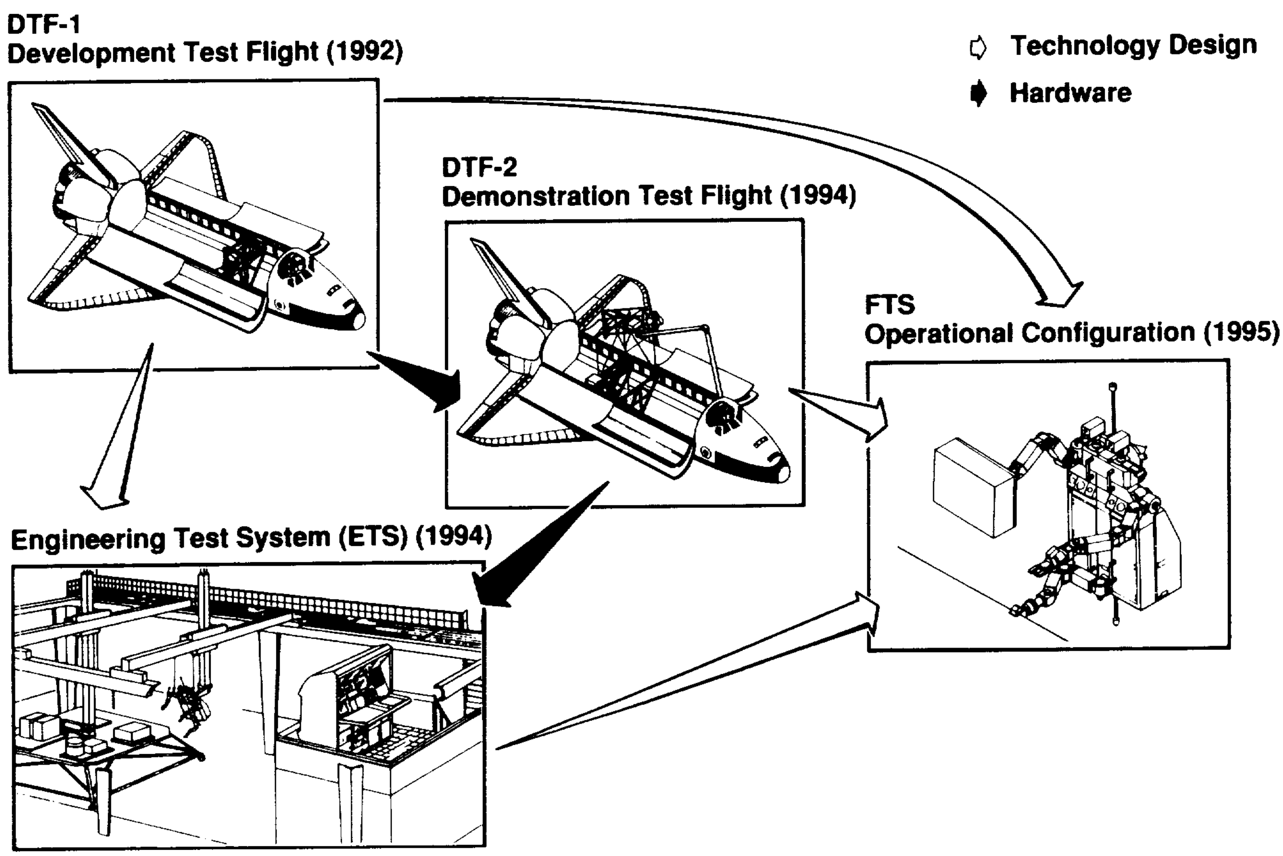

Figure B3. Flight Telerobotic Servicer mission flow.

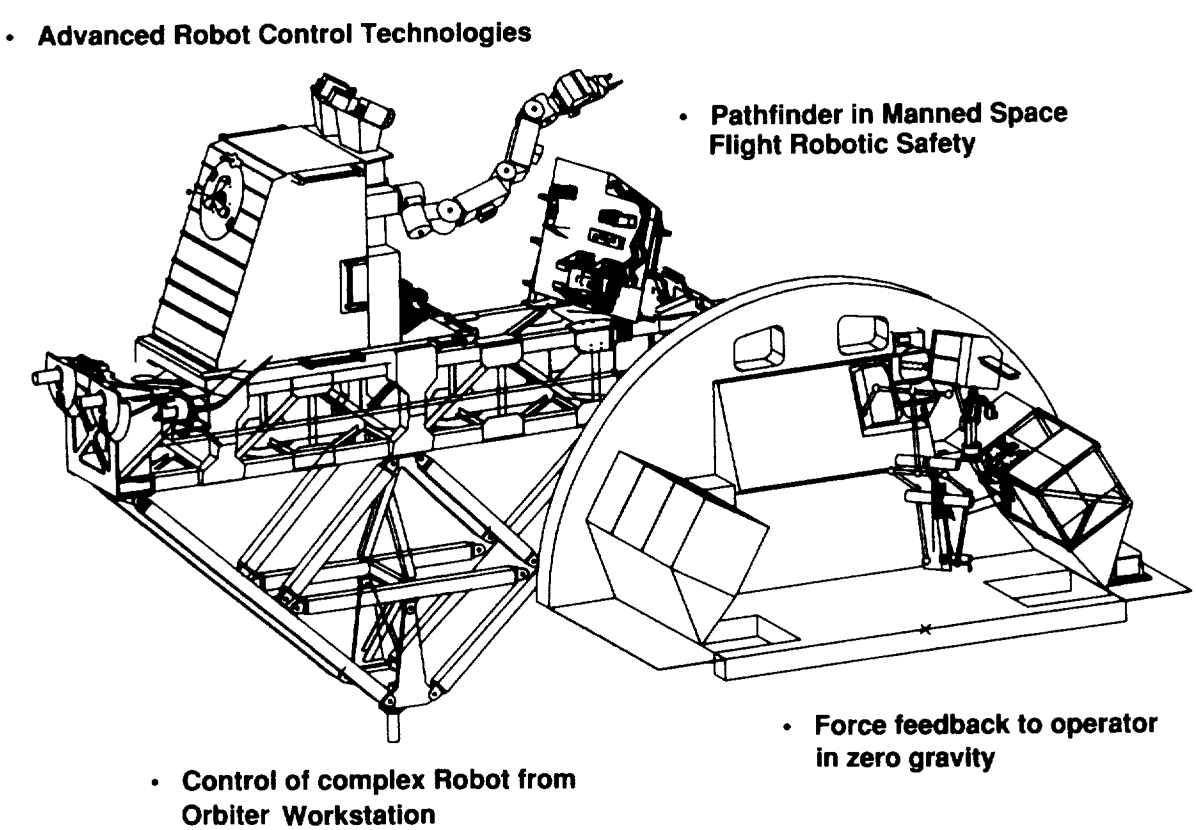

Figure B4. DTF-1 configuration.

Appendix C

Canadian Space Station Program A&R

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). 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 major hardware elements of the MSS are the Mobile Servicing Center which is the responsibility of Canada, and the mobile transporter (MT) which is United States supplied. The MT allows linear motion along the Station. The MT was removed as part of the Space Station Restructuring; however, transport function along one side of the Restructured SSF can be supplied using the Crew and Equipment Translation Aid (CETA).

The Mobile Servicing Center (MSC) shown in figure C1 is composed of three major components: the Mobile Remote Servicer Base System (MBS), the Space Station Remote Manipulator System (SSRMS), and the Special Purpose Dexterous Manipulator (SPDM). The MBS is the mechanical interface to the U. S.-supplied transporter and also includes the power, data, and communication systems for the MSC. The MBS accommodates the SSRMS, SPDM, tools and two Payload/ORU Accommodation (POA) systems for holding and transporting Orbital Replacement Units (ORU) and payloads. The MBS also includes an interface for the Flight Telerobotic Servicer (FTS).

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 the figure. The SPDM includes two identical 7-degree-of-freedom arms which are mounted on a body with an additional 4 degrees-of-freedom. The system includes stereo, wrist and body TV cameras, a tool changeout 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 dexterous capabilities required to accomplish these functions. SPDM functions include inspection and monitoring, ORU exchange, utility connect and disconnect, mate and demate of connectors, removal and installation of thermal covers and blankets, surface cleaning, and the positioning of tools and materials to support EVA.

To accomplish these Space Station functions, the MSS includes an impressive list of baseline A & R technologies. 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. The two SPDM manipulators include coordinated control, allowing the multi-arm handling and maneuvering of an object. Coordinated control is also incorporated for the SSRMS/SPDM combination, such that the operator can control the tip and all joint motions of the SSRMS and SPDM. 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.

The Canadian program includes an advanced technology development effort, with the aim of progressive evolution from teleoperation towards autonomous operations, to increase the operational effectiveness of the MSS. The program is focused in selected areas with the objective of developing new modules or add-on-type concepts. The program is structured to have proof-of-principle demonstrations prior to decision to proceed with the concept as part of the MSS design and development program.

Advanced technologies currently being studied include an MSS Command and Programming Language (MCPL); collision prevention and collision avoidance; and an advanced vision system for possible onorbit implementation and procedural expert systems, data bases, and planning systems for ground implementation to support MSS operations. The MSS Command and Programming Language is a flexible automation tool based on a hierarchical object-oriented world model for path planning and a priori simulation. MCPL was reviewed in February 1990 and has been recommended for incorporation. The collision prevention system which is also recommended for incorporation is a model-based system for detection of potential collisions of manipulators and their environment and for warning the operator. The collision avoidance system objectives include real-time control for obstacle avoidance and planning of collision-free trajectories. The advanced vision system work is addressing unlabelled object identification, shape determination, automatic target acquisition, and world model verification and update.

The advanced developments for ground-based support of MSS operations includes a hierarchical multi-media representation of all MSS engineering data and expert systems for failure resolution of MSS systems. The planning system element objective is to develop a tool for MSS operations planning and task analysis.

Canada has also established a program to generate and spin off technology development in A&R. This program, which is similar to the U. S. Small Business Innovative Research Program (SBIR), is called STEAR (Strategic Technologies in Automation and Robotics). STEAR has two interrelated objectives:

A. To develop strategically important automation and robotics technologies for potential incorporation into the MSS over its lifetime by contracting out industry led research.

B. To support national socio-economic development by directing STEAR expenditures so as to contribute to regional distribution targets; encouraging nationwide diffusion of information and capability regarding the technologies generated by STEAR; and fostering an environment conducive to bringing about industry led commercialization of technologies generated by STEAR.

The STEAR program funds parallel feasibility studies at $100K for 9 months and approximately half of these result in proof-of-concept phases of $1.0M over 2 to 3 years. This $70.0M program was initiated in 1987 and will run through 1998. Approximately half the funds have been committed to date. The seven A & R technology areas and the funds allocated, including future years, are:

1. Automation of Operations ($6.0M)
2. Automated Power Management ($1.1M)
3. Autonomous Robots ($8.1M)
4. Enhanced Vision System ($3.3M)
5. Enhanced Manipulator Control Systems ($3.1M)
6. Protection of Materials in Space ($3.6M)
7. Enhanced Sensors, Tactile ($3.6M)

These contracts must be led by industry with the MSS "Industrial Team" excluded to encourage the growth of small companies and the inclusion of universities and research labs.

The Preliminary Design Review (PDR) for the MSC is scheduled for March 1992. The Restructured Space Station launch dates are March 1996 for the SSRMS and March 1997 for the SPDM. There are no planned flight tests for the system, just a checkout phase when the equipment arrives onorbit. They feel this is adequate because of their experience with the Shuttle RMS. An SPDM ground testbed is in operation currently supporting both baseline and advanced development activities. A shuttle flight experiment in 1992 will evaluate the artificial vision system for automated berthing.

The Canadian program is an investment of $1.2B to develop and construct the MSS. The system design, baseline capabilities, and advanced program elements represent significant advancement in A & R technology. The exact level of capability currently operational could not be assessed from the review. With the removal of the FTS from the Restructured Space Station, the role of the MSS and particularly the SPDM will increase significantly. The Canadians have undertaken a detailed impact assessment and planning exercise to address the Restructuring issues. The engineering design and the program plan are well conceived and managed and the proper hooks and scars for evolution of the system are included.

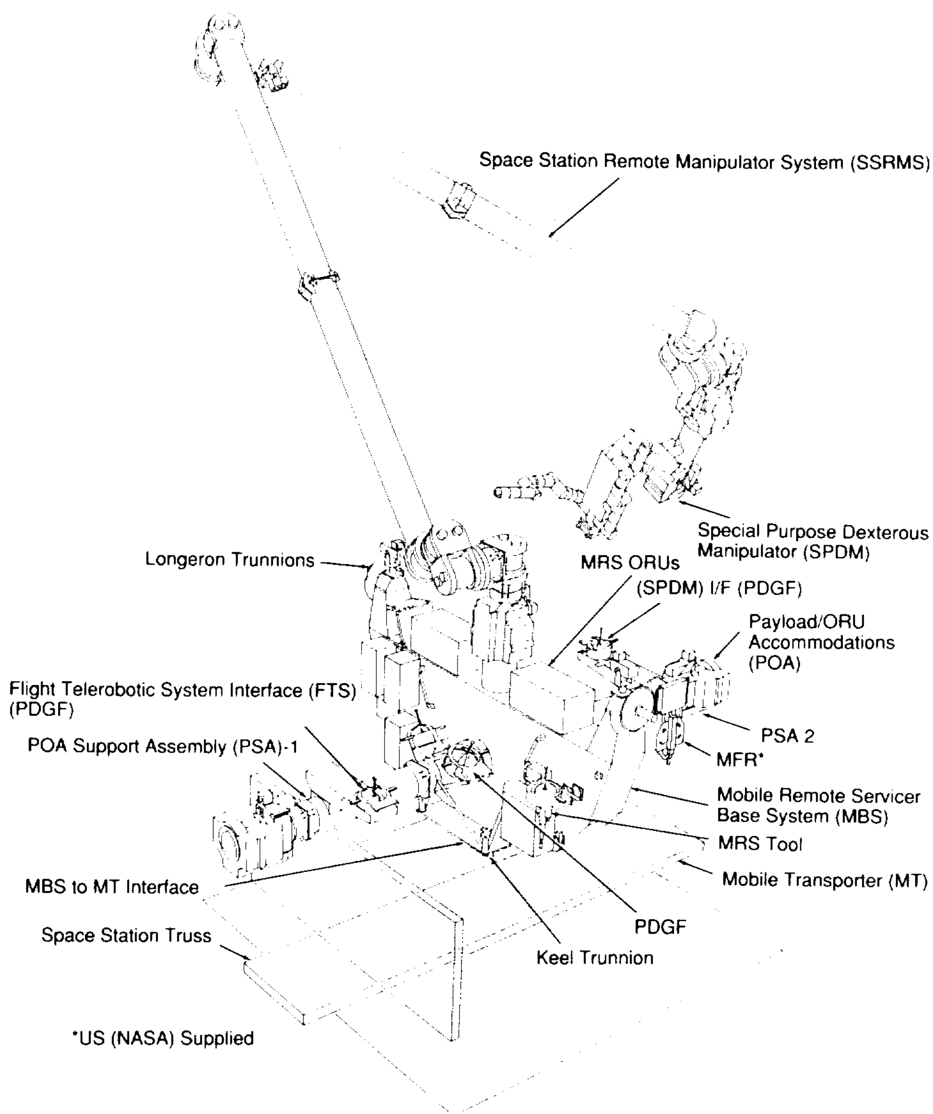

Figure C1. Mobile Servicing Center

Appendix D

Acronyms

A&R	Automation and Robotics
AC	Assembly Complete
ARC	Ames Research Center
ATAC	Advanced Technology Advisory Committee
AWP	Assembly Work Platform
C&T	Communications and Tracking
CDR	Critical Design Review
CETA	Crew and Equipment Translation Aid
Code 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
CR	Change Request
CSSP	Canadian Space Station Program
DARPA	Defense Advanced Research Projects Agency
DKC	Design Knowledge Capture
DMS	Data Management System
DTF-1	Development Test Flight (first FTS test flight)
DTLCC	Design to Life-Cycle Costs
ECLSS	Environmental Control Life-Support System
EMI	Electric-Magnetic Interference
EMST	External Maintenance Solutions Team
EPS	Electrical Power System
EVA	Extravehicular Activity
FDIR	Fault Detection, Isolation, and Recovery
FEL	First Element Launch
FSE	Flight Support Equipment
FTS	Flight Telerobotic Servicer
GN&C	Guidance, Navigation, and Control
GSFC	Goddard Space Flight Center
ISE	Integrated Station Executive
IDR	Integrated Design Review
IVA	Intravehicular Activity
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KBS	Knowledge-Based Systems
KSC	Kennedy Space Center
LaRC	Langley Research Center
LCC	Life-Cycle Cost
LeRC	Lewis Research Center

Acronyms—continued

MSC	Mobile Servicing Center
MSFC	Marshall Space Flight Center
MTC	Man-Tended Capability
MUT	Mission Utilization Team
NASA	National Aeronautics and Space Administration
OAET	Office of Aeronautics, Exploration and Technology
OMS	Operations Management System
ORU	Operational Replacement Unit
PDR	Preliminary Design Review
PDRD	PDR Document
PIT	Pre-Integrated Truss
PMAD	Power Management and Distribution
PMC	Permanently Manned Capability
POP	Program Operating Plan
RSIS	Robotic Systems Integration Standards
RTDS	Real-Time Data System
SDP	Standard Data Processor
SDTM	Station Design Tradeoff Model
SPDM	Special Purpose Dexterous Manipulator
SSCC	Space Station Control Center
SSE	Software Support Environment
SSF	Space Station Freedom
SSFP	Space Station Freedom Program
TCS	Thermal Control System
TEXSYS	Thermal Expert System
WETF	Weightless Environmental Test Facility
WP	Work Package

Appendix E

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16. Abstract

In April 1985, as required by Public Law 98-371, the NASA Advanced Technology Advisory Committee (ATAC) reported to Congress the results of its studies on advanced automation and robotics technology for use on 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 twelfth in a series of progress updates and covers the period August 23, 1990, through February 14, 1991. The report describes the progress made by Levels I, II, and III of the Office of Space Station 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 11, the status of the Flight Telerobotic Servicer, and the status of the Advanced Development Program. In addition, an assessment is provided of the automation and robotics status of the Canadian Space Station Program.

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