NASA Technical Memorandum 102872

Progress Report **11**
November 1990

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

NASA

Advanced Technology Advisory Committee

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✓ Progress Report 11
February 14, 1990, through August 23, 1990

Advanced Technology Advisory Committee
National Aeronautics and Space Administration

Submitted to the
**United States Congress**
**November 1990**

NASA
National Aeronautics and
Space Administration

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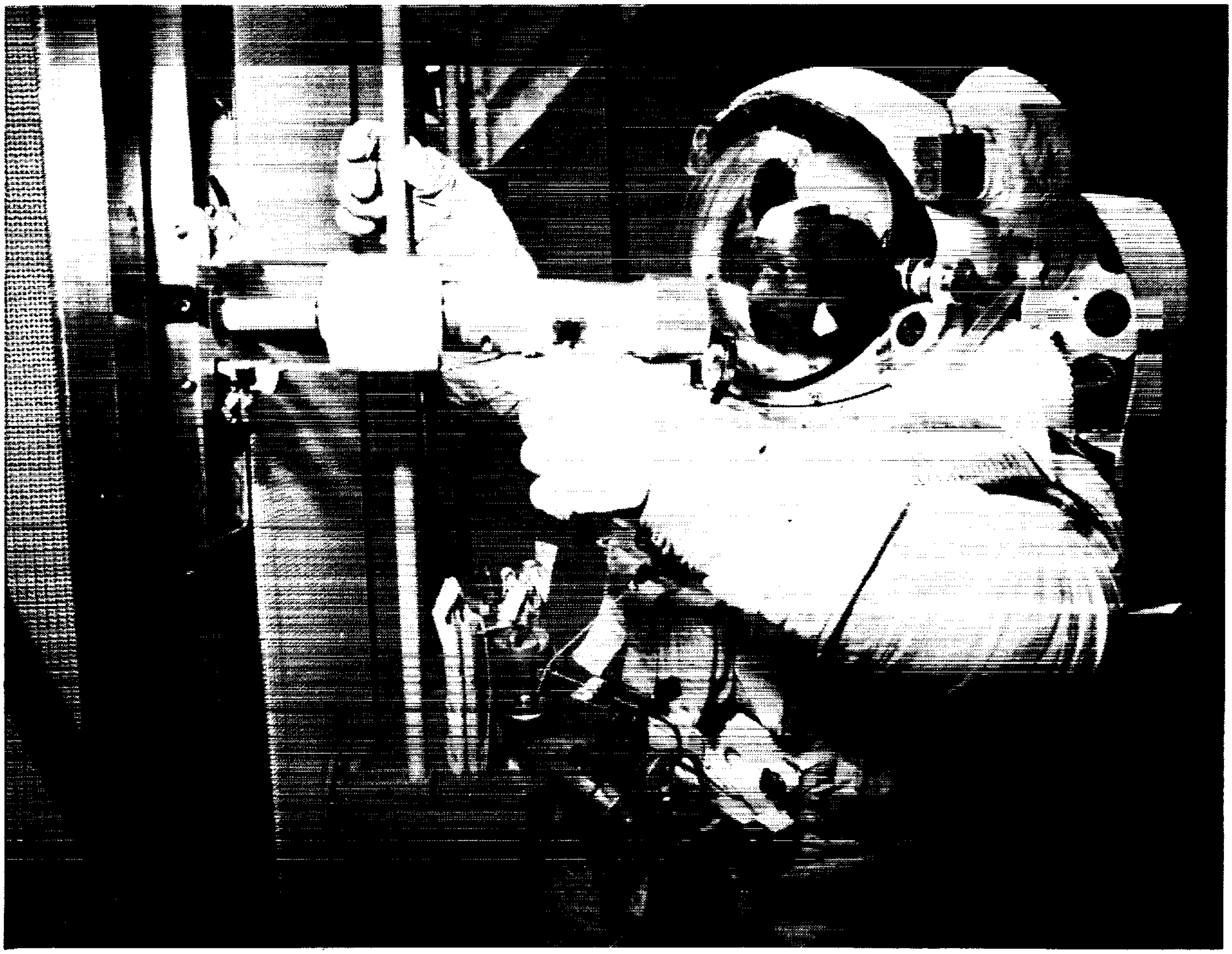

***Astronaut in WETF at JSC practices Space Station Freedom maintenance tasks with the aid of a robotic tool***

The Space Station Freedom External Maintenance Task Team Final Report was published in July 1990. Known as the "Fisher-Price" study in recognition of its authors, the report provided results of seven months of analysis on the amount of external maintenance that could be expected for Space Station Freedom. The task team provided nearly 100 recommendations related to appropriate development and use of EVA astronauts and robots that could reduce the external maintenance requirements from 3,276 hours per year to 1,241 hours per year. ATAC strongly supports the Report's recommendation to design all ORUs for mutual EVA and robotic compatibility with standard interfaces, and require implementation of that standard across the Space Station Freedom Program. See Appendix E for a list of all of the Fisher-Price study robotics recommendations.

# 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 to 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 10 (refs. 2-11). Progress Reports 1 through 5 covered the definition and preliminary design phase (Phase B) of Space Station Freedom. Progress Reports 6 through 10 covered the start-up of the design and development phase (phase C/D) of the SSF. Phase C/D leads to a completely assembled station to be operational in the late-1990's.

This report is the eleventh in the series of progress updates and covers the period of February 14, 1990 through August 23, 1990. 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 10. Also, summaries of progress in A & R in the Space Station Program Office, the Flight Telerobotic Servicer (FTS), and Office of Aeronautics, Exploration and Technology (OAET) 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 August 21-23, 1990, for the purposes of reviewing the SSFP A&R activities and formulating the points of this report.

## CLIMATE

The Space Station Freedom has undergone several significant changes since the last ATAC Report, number 10 dated June 1990, which may have an effect on post-permanently manned capability (PMC) advanced automation and robotics. At the time of the ATAC meeting in August 1990, SSF was undergoing a major design scrub activity in an effort to meet required power and weight reductions. **Because the scrub activity was still in progress and results not available, ATAC is unable to draw definite conclusions in this report to fully assess the onboard SSF capabilities to support implementation and evolution of advanced automation and robotics.**

The latest design scrub activities have apparently reduced the operational margin of the Data Management System (DMS) infrastructure; reduced the sensor instrumentation; and, effectively transferred all but safety critical items of the Operations Management Application (OMA) to the ground. The overall implication is that all previous onboard advanced automation has now been removed from the baseline SSF; and any remaining advanced automation will be implemented in ground mission operations, to be possibly migrated back onboard SSF at some future date. **ATAC is concerned that the advanced automation functions moved to the ground may be implemented with conventional methodologies instead of knowledge-based systems techniques, resulting in more labor intensive ground mission operations and increased costs.**

In reviewing the Fisher-Price study, it is apparent that robotics must play an important part in the assembly and maintenance of the Space Station and will complement the astronaut EVA activities. However, as crew EVA requirements are reduced through greater use of robotics for assembly and maintenance, crew IVA activities to support robotic activities are increased. In addition, if sufficient Station housekeeping and monitoring functions are not automated, there is a probability that crew IVA requirements will be overly subscribed. **ATAC is concerned that Station configuration and capabilities resulting from scrub activities may not support increased IVA requirements essential for EVA and robotics activities relative to Station assembly, operation, and maintenance.**

In addition to the lack of advanced automation for support of IVA activities, it became apparent that there are insufficient standards for robotic interfaces and orbital replacement units (ORU). As a result, various robotic activities may not be accomplished by the several robotic arms being planned for Space Station Freedom. **Common ORU design standards must be defined and implemented as soon as possible to permit effective use of robotics during Station assembly and maintenance.**

Level I and the Work Package contractors have undertaken programs to evaluate and understand the advanced automation and robotics technologies using IR&D funds and funding support from the Level I Advanced Development Program. They have gone as far as evaluating some of these technologies in their development program testbeds. ATAC has strongly recommended in previous reports that plans for incorporating these technologies into Space Station Freedom be developed, and ATAC had been verbally assured by SSFP management that these plans would be developed. **However, a plan has not been developed by either Level II or Level III for incorporating these technologies after PMC.**

# 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 scrub activities. A review of the progress toward the recommendations from ATAC's most recent report, Progress Report 10, will be discussed first, followed by a review of topics explicitly addressed during the August 21-23, 1990 ATAC meeting, and then a discussion of new A&R issues.

## ASSESSMENT OF PROGRESS ON ATAC REPORT 10 RECOMMENDATIONS

ATAC Progress Report 10 Recommendation I was as follows:

**"I. The Space Station Freedom Program Directive Number 22 concerning Design to Life-Cycle Costs (DTLCC) should be enforced for analysis of automation and robotics proposals. Objective standards should be developed for use in these analyses which are applicable to all SSFP technologies including A & R."**

ATAC feels that little progress has been made in this area. A presentation was made for Level II by the Level I Advanced Development Program Manager. This presentation covered aspects of the Level II efforts in the implementation of Life-Cycle Cost analysis (LCC) requirements and indicated that input criteria are being developed, but the status and general applicability of this effort are uncertain to ATAC. There was an implication that Level II has held workshops on the application of LCC methodologies and tools which were attended by Levels I, II, III, and IV, but no specific details on the outcome, conclusions and/or implementation of a LCC plan were evident to ATAC. There was also an implication that a LCC analysis process is under development for routine screening and assessment of Change Requests (CR) that go before the Level II Space Station Control Board.

ATAC was unofficially informed that all future Change Requests will require LCC analyses as part of the CR approval process, but ATAC has not seen formal documentation implementing such a procedure. ATAC feels that such a process should be formally implemented in keeping with the Space Station Freedom Directive Number 22 and be specifically directed at evaluation of advanced automation technologies.

ATAC Progress Report 10 Recommendation II was as follows:

**"II. The current focus on DTLCC analysis of FTS applications should be changed to focus on automation applications, e.g., ground support system advanced automation, because FTS applications have been accepted by the program. There is a more important need to ensure that the automation proposals receive proper attention during the preliminary design review process. The ATAC recognizes that automation cost savings factors are difficult to quantify, however, reasonable values can be developed. The ATAC strongly recommends that an agreed-upon (by the relevant working groups) input data base be developed, appropriate policy decisions be made where important (e.g., discount rates), and a measure of merit be defined for consistent evaluations and assessments of impacts of advanced technologies on SSF, and that this effort begin immediately".**

ATAC perceives that little or no progress has been made in this area. However, because of the possible impacts of the results of the Fisher-Price study on the space station robotics the use of DTLCC on the various robotic scenarios should continue. But, ATAC stresses that this effort should not go on at the expense of other technologies especially advanced automation technologies. ATAC strongly feels that increased emphasis on DTLCC evaluations should be implemented for various advanced automation technologies which may show benefit for application to space station. ATAC is of the opinion that it is extremely important to ensure that advanced automation technologies receive proper attention especially those that have potential for implementation and cost savings on the baseline space station.

ATAC is also not aware that any effort has been made to develop input DTLCC data bases that have the collective agreement of the relevant working groups. ATAC strongly feels that such representative and agreed upon data bases are a firm requirement in order to ensure that all LCC technology assessments are compatible and are evaluated to a common baseline. Level II has held workshops on the application of LCC methodologies and tools, but no specific details of a LCC plan or criteria appear to have been established. ATAC notes that the WP2 contractor has developed criteria for evaluating all SSFP technologies, including A & R but ATAC has no assurance that this criteria is compatible (or is the same) as that being developed by Level II. ATAC strongly recommends that such criteria, including a Figure-of-Merit for ranking of the various SSF technologies, be developed and put under Configuration Control by Level II to ensure that all parties are using the same criteria and that all technologies are evaluated to a common set of groundrules.

ATAC Progress Report 10 Recommendation III was as follows.

**"III. Funding stability for the Level I advanced Development program must be ensured and funding increases should be emphasized because the Level I program is the major driver for evolution of automation and robotics for the Space Station Freedom."**

ATAC notes that without Level II funding for the High-Leverage Prototyping program, the Level I Advanced Development Program has become the sponsor for elements which are appropriate to the High-Leverage Prototyping Program. Thus ATAC feels that the Level I Advanced Development program has become the primary mechanism, as of the present, for introduction of A & R technologies which have potential for the Space Station Freedom Program. For this reason ATAC feels it is mandatory that funding stability for the Advanced Development Program be ensured and that funding increases for this program be emphasized.

The history of the Advanced Development Program indicates that this item is subject to severe budget fluctuations which undermines the implementation of advanced A&R technologies on the Space Station Freedom.

The Advanced Development Program budget projections, as of August 1990, are for a $12M program for 1991 growing to $16M for 1992. This is in comparison to $6M budget for 1990 (which at one time was projected at $17M). Out year projections start at $16.7M for 1993 growing to $19.5M in 1996. ATAC feels that this represents a minimum budget scenario for technology development and demonstration, but is probably not adequate to ensure effective transfer and implementation of the technology.

ATAC Progress Report 10 Recommendation IV was as follows:

**"IV. Maintain and enforce the Level II requirement, as noted in ATAC Progress Report 9, that Level II Group Directors for Operations and Utilization and Systems Engineering and Integration provide semiannual reports in the area of Automation and Robotics to the Associate Director of SSFP Level II. These reports will help ensure that proper attention is given to automation and robotics during the intense preliminary design review (PDR) cycle now taking place."**

No progress is evident on Recommendation IV. SSFP Level II has not provided the A & R semiannual status reports. Any concern Level II may have about the incorporation of advanced automation and robotics appears to be overridden by other higher priorities.

ATAC Progress Report 10 Recommendation V was as follows:

**"V. The preliminary design reviews should include plans and provisions for SSF transition from permanently manned configuration (PMC) to assembly complete (AC). The PDRs should be required to address the subject of hooks, scars, and other provisions needed to support the PMC/AC transition as well as the automation and robotics applications required to support such transitions."**

Very little progress is evident on Recommendation V. Level II has not yet completed the guidelines related to standards and commonality required for the integration of robotics to SSF. This has made the sanctioned FTS assembly tasks more difficult to implement due to lack of the proper interface standards. The system design architecture and infrastructure applicable to hooks, scars, and other provisions necessary to support PMC/AC transition are not in place and plans have not been presented.

ATAC Progress Report 10 Recommendation VI was as follows:

**"VI. The Flight Telerobotic Servicer (FTS) overall infrastructure, operational scenarios and mobility requirements need to be addressed to ensure that all SSFP robotic support tasks are operationally integrated with respect to IVA and EVA."**

Good progress was made on defining FTS operational scenarios, mobility requirements to perform tasks, and the infrastructure to support performing the tasks. Identification of FTS Sanctioned Tasks shows very good progress in establishing FTS as a vital part of Space Station operations. Using the Sanctioned Tasks, scripts are being developed which analyze and simulate the requirements and motions of the FTS. This will make the operations requirements for FTS better integrated with EVA activities.

Progress has also been made in integrating FTS with EVA activities. Task allocation guidelines include reducing EVA burden without overly complicating the assembly process. However, it is not clear how the FTS IVA requirements will fit within EVA time constraints. Definition of activities with the joint use of EVA/FTS in cooperative tasks has not been started.

With the expansion of the FTS activities to perform external maintenance activities it is not clear that the mobility requirements to perform these activities has been considered. With the limited number of data/power ports accessible to the FTS, the mobility requirements for the FTS should be revisited in light of the Fisher-Price Study results.

ATAC Progress Report 10 Recommendation VII was as follows:
**"VII. User and automation and robotics requirements for the Data Management System and Operations Management System must be identified as soon as possible to ensure that the baseline system designs will support SSFP transition and evolution, especially A&R implementations."**

As reported in the last report of the ATAC, IBM has internal IR&D plans for Intel 80x86 family upgrades through the 80786 processor, allowing a pathway for some upgrade with optional cards allowing further capability. However, this family of upgrades is not being actively pursued by NASA. It is still unclear that the current closed-architecture of the DMS will accommodate new and/or innovative computer technologies such as multiprocessors or possibly photonic processors. MIL-STD-1553B local buses may restrict some local traffic forcing "smarter" devices to be embedded (subsystem components as well as payloads).

DMS support compatible with the robotic requirements identified in the Fisher-Price study for FTS teleoperations does not appear to be accommodated in the DMS design. The ATAC is concerned, as previously stated in Progress Report 10, that FTS control latency is not well understood for the case when FTS uses the DMS as the communication path for teleoperations control. Concern of the ATAC still exists that the DMS design may not support current user requirements.

Without a strong and flexible data processing/communications infrastructure, the Space Station Freedom will be hard-pressed to provide effective support for increased levels of advanced automation over a thirty-year lifetime. Instead, embedded systems and experiments will be forced to employ various microcontroller hardware and firmware approaches to meet eventual onboard automation requirements. This will probably lead to non-standard approaches resulting in higher integration, validation, and maintenance costs over the life of the Space Station Freedom.

The current DMS/OMS design scrub forces most, if not all, FDIR software to reside on the ground. The SSFP should rigorously evaluate whether all fault management activities can be effectively performed on the ground. This evaluation should be performed in light of safety, reliability, cost and performance criteria.

ATAC Progress Report 10 Recommendation VIII was as follows:
**"VIII. The baseline SSFP should have an Operations Management System test bed to ensure that the software and other items are properly integrated and to provide a means for automation technology testing and and comparative analyses with non-automated methodologies."**

The OMS test bed at JSC is not part of the in-line development effort of WP2. Instead, it serves as an engineering development/testing platform. The Operations Management Application (OMA) Event Management was the only WP2 baseline advanced automation application, and it may now be in jeopardy as all OMA software must reside in only 1 MB of memory.

The OMS test bed has proven quite useful from an early engineering requirements assessment perspective. However, the OMS test bed would be of greater utility if recognized as an integral part of the SSFP in-line development since it would provide a systems integration and evaluation platform for investigating significant issues such as global fault management (FDIR) and latency. The OMS testbed is now being terminated and replaced with the Avionics Integrated Environment (AIE) testbed. The AIE testbed is being developed by MDSCC, but apparently will be primarily a WP2 contractor facility only. The ATAC is concerned that there will be a period of time prior to AIE becoming operational in which there will be no testbed available for OMS testing.

## A&R STATUS REVIEW OF LEVELS I AND II; AND WP1, WP2, WP3, AND WP4

**Assessment of Level I.**

Organizational Change.

Level I is creating an engineering organization to serve as a technical arm to the program director. The role and significance of this Level I engineering responsibility are not fully understood by ATAC at the present time.

Advanced Development Program

The current advanced development program has a strong emphasis on advanced automation and robotics. Unfortunately, due to funding limitations, maturing these technologies in a timely manner and transferring them into the program will be very difficult. This is largely due to the lack of resources for systems integration and validation. In the area of robotics, there is a focused effort between the ongoing activities and the FTS evolutionary technology plan with emphasis on improving FTS task efficiency and increasing its level of autonomy. The Advanced Development Program has initiated an effort to develop and demonstrate the capability to perform ground-based SSF robotic system operation as recommended in the Fisher-Price study. The OAET A&R Program should be coordinated with the Advanced Development Program to address these SSF technology needs.

**Funds should be provided for integrating these A&R technologies into existing testbeds for demonstration, performance evaluation, and preliminary verification and validation.**

**Assessment of Level II**

For the past two ATAC reviews, ATAC has requested and has not received an in-depth presentation of Level II activities including actions taken to resolve prior ATAC issues and concerns. It is difficult for ATAC to properly assess A&R progress by Level II without a more responsive Level II briefing.

An overview of the Level II activities was presented by the Level I representative but the information lacked sufficient content to allow ATAC to assess the overall status. There appears to be a lack of personnel and/or staff at Level II to investigate, evaluate, prioritize, and implement an effective A & R program which may be of benefit to the Space Station Freedom over its entire lifetime. Lack of attention to the A & R issues raises the following issues regarding the role of EVA, robotics, and IVA relative to the assembly, construction, and maintenance of the Space Station Freedom:

- The DMS and OMS infrastructures were scrubbed with no rationale described to ATAC for the deletion of sensor instrumentation, data communications networks, and data processors. This recent scrub appears to remove future evolution and implementation of advanced automation and robotics without significantly increased costs.

- Design standards for robotic system accommodation have not been defined, developed, and implemented by Level II. As a result, robotics interfaces and interaction of the crew with robotic systems including ORUs, and EMI could impose serious problems. Standards, if developed early, will have significant cost savings over the lifetime of the Station and result in more efficient use of the robotic systems for assembly, construction, and maintenance. Configuration should be controlled by Level II to ensure that all WPs adhere to a common robotic interface and performance assessment.

- A set of criteria is not being developed for ALL robotic simulations and ALL computer models so that the performance assessments of these robotic systems can be made on a one-to-one basis. The criteria, standards, and performance models should also be subject to configuration control by Level 2.

- Life-Cycle Costs criteria do not appear to exist. Level II has held workshops on the application of LCC methodologies and tools, but no specific details of a LCC plan or criteria appear to have been established. Criteria for evaluating and ranking various SSF technologies need to be developed and put under control of Level II to ensure that technologies are evaluated to a common set of ground rules.

- Level II is not performing adequate systems engineering oversight and guidance in the areas addressed by this report. As an example, procedures and facilities for test and replacement of equipment onboard the Station do not exist. Because of this deficiency, it appears that additional time will be required to determine if the "spare" is a functioning item for replacement of the defective component.

**Lack of response of Level II management to ATAC issues and concerns leaves several significant questions open regarding the rationale used in the tradeoffs and decisions during the recent scrub activities.**

**Assessment of Work Package 1**

Contracted Effort in A&R.

WP1 is funding Boeing to develop a design knowledge capture (DKC) system which has been applied to a microbial growth design trade study. This tool may be useful in providing design alternatives and rationale for a life support system. Several expert systems for equipment rack placement analysis and logistics packing are being used as design aids.

Advanced Development and IR&D.

The PMAD testbed hardware and software configuration has been changed to reflect the change to 120 VDC. Systems being developed for autonomous control of a regenerative life support as well as one for power management and distribution (PMAD) are proceeding smoothly. However in both cases there is little likelihood that they will be transferred to flight due to severe reductions in sensors and instrumentation, the elimination of hooks and scars and a reduced DMS growth capability.

Robotics.

An IVA robot has been proposed as a possible future evolution candidate to serve as a "lab assistant" and aid the crew in housekeeping and maintenance activities. However, very little effort has been put in this area, and many issues need to be addressed with regard to IVA robots in proximity of the crew.

**In summary, there is no advanced A&R flight hardware nor software in WP1 that is in the baseline SSF program.**

### Assessment of Work Package 2

Progress has been made in the WP2 advanced automation and robotics area. The contractor, MDSSC-SSD, has responded to the ATAC recommendations of ATAC Report 9 and has detailed his approach to meeting these recommendations. ATAC commends the WP2 organizations in interfacing and working with other relevant organizations in both the robotics and the advanced automation area.

In the robotics area, the contractor WP2 direct support is in the area of the mobile transporter and in making WP2 derived hardware robotic friendly for assembly, servicing and maintaining of the ORUs. To support this effort a high level robotic modeling system has been established with appropriate data exchange activity with other SSF contractors/organizations. In the advanced automation area the contractor has active tasks in Advanced Automation Methodology Project (AAMP) whose output is a procedures document; Communication and Tracking Advanced Automation (C&T) which will result in a system demonstration; and a Data Management System (DMS) which will also result in a systems demonstration. The contractor is, in addition, working on an Operations Management Application (OMA) task which will result in onboard diagnostics software; Thermal Control System-Thermal Advanced Automation Project (TCS- TAAP) which will result in a systems demonstration; Guidance, Navigation and Control (GN&C) which results in a system demonstration; Crew Health Care System (CHeCS) which will result in onboard software; and Systems Engineering and Integration Support (SE&I) projects.

In the area of robotics, ATAC notes that WP2 has the largest number of ORUs of the four work packages. ATAC also notes that the WP2 robotic standards which are being developed appear to be developed only for WP2 robotic activities. ATAC is concerned that mandatory and universal robotic standards, agreed upon by all relevant working groups, are not being developed and maintained. Configuration should be controlled by Level II to ensure that all WPs adhere to a common robotic interface and performance assessment.

In the area of advanced automation ATAC also notes that controlled software data bases and input data to evaluate automation technologies continue to be lacking. Very little progress has been made in this area as noted earlier in this report in the progress assessment of Recommendation I of Progress Report 10.

ATAC notes that the OMA system was affected by the recent "scrub". The only items apparently remaining "onboard" are those that are related to time critical and safety critical considerations. There exists a high degree of uncertainty in the memory requirements, and the current allocation of 1 MByte is considered marginal. The provision of adequate hooks and scars for future evolution of advanced automation appears highly doubtful under the present scenario.

The OMA provides considerable potential for onboard advanced automation in the areas of planning and plan management and event management. The ATAC feels that the issues surrounding the OMA should be revisited and the OMA should be reinstated to a Knowledge Based System level to realize its full potential.

Adherence to Directive 22 and its intent, relative to LCC assessments is lacking at this point in the evaluation of SSF advanced automation and robotics technologies. Preliminary work by the WP2 contractor has indicated a positive impact on LCC by incorporating advanced A&R technologies. However, as noted earlier in this report in the progress assessment of Progress Report 10 Recommendation I, very little progress has been made in this area.

ATAC is unaware of the formal and detailed implementation scenarios for the advanced technologies, both robotic and automation, being developed under WP2. As a result of the recent scrub it appears that many automation and robotics functions will be "evolved" by being initially performed on the ground. ATAC is concerned that there is no detailed implementation plan which indicates specifics of how these technologies will finally evolve and migrate to onboard SSF to perform their intended functions.

**In summary, WP2 has the largest number of ORUs of any work package contractor and design standards need to be coordinated with other WPs; it appears that all advanced automation applications have been eliminated from the baseline configuration, and there is ATAC concern that the current scrub activity may seriously jeopardize advanced automation and robotics evolution.**

### Assessment of Work Package 3

Previously, one of ATAC's greatest concerns for the FTS was that the FTS was not accepted by the Space Station Freedom Program as an integral component. Specific tasks had not been assigned to the FTS. Attitudes towards robotics on Space Station have changed dramatically in the last year, in part due to the Fisher-Price study on external maintenance which pointed out that maintenance of Space Station will be impossible without robots. FTS and other robots are now an in-line requirement for space station operation. Robotics are considered the primary method for ORU exchange and EVA is to be used as a backup for ORUs which are robot compatible. ATAC applauds this change of attitude.

Specific progress for the FTS Program includes establishing FTS Sanctioned Tasks. These tasks include deployment and installation of platforms, pallets and transporters along with inspections and some Space Shuttle payload bay operations (Appendix B has more details). Although these "Sanctioned Tasks" are not yet assigned to the FTS, the program is proceeding with implementation plans for FTS to perform these tasks for Space Station. The Mission Utilization Team is preparing a Sanctioned Task Validation Plan. This plan establishes the required testing at JSC, GSFC, and with the DTF-2 flight to validate FTS capability. The Mission Utilization Team is also preparing a Task Evaluation Plan for each FTS Sanctioned Task which documents analyses, issues, simulations, scripts and test results. Detailed simulations of each task will be performed by GSFC and integrated into end-to-end assembly simulations by JSC.

The FTS Development Test Flight 1 (DTF-1) is progressing. Mission timelines for the experiment were prepared which allocate tasks during three worksessions of eight hours each. The DTF-1 Task Panel is designed as is the general layout of the Space Shuttle Aft Flight Deck for the DTF-1 Operator Control Station. The mission content of DTF-1 is firm with a safety review completed in April, 1990. The FTS DTF-1 Critical Design Review is scheduled for September 1990 with a scheduled launch date of December 1991. However, ATAC is concerned that the scheduled launch date has very little contingency margin.

General Robotic Issues.

Commonality among the many robotic systems for the space station remains as a major area of concern. The handcontroller commonality study is underway at JSC. This study is a good step in defining some problems and some possible solutions for the handcontroller part of the issue. These tests, however, do not test end-to-end systems and system capability. Significant issues on the operator-machine interface and the differing "feel" of the devices from the control laws in diverse software for multiple systems remains to be investigated. Contributions from international partners greatly complicate the issues involved. In general, it will be difficult to train, plan, operate, control and repair these diverse systems. Many of the issues related to robotic commonality are not known and defined at this time. As in report 10, ATAC continues to be concerned that all of the proposed SSF robotic systems are not being tested in some common laboratory environment.

Work is progressing to evaluate the ORU designs from each work package. It is imperative that a standard ORU design be picked for Space Station and implemented by the international partners as well as all of the work packages. "Robot Friendly" design standards have been prepared and submitted for review. This is a good step in the development of a Level II Robotics Integration Plan. Ensuring robot compatible designs is now a critical issue for Space Station.

**In summary, the Space Station attitude toward robotics has changed dramatically as a result of the Fisher-Price study, and the Flight Telerobotic Servicer continues to increase in significance in the Space Station Automation and Robotics Program.**

### Assessment of Work Package 4

The presentation of Work Package 4 Automation and Robotics progress was given by Rocketdyne Division of Rockwell International. The focus of this work is the SSF Electric Power System (EPS). Emphasis was given to the robotic and EVA friendliness of the various Orbital Replaceable Units (ORUs) in the EPS.

WP4 is commended by the Fisher-Price study of external maintenance because the WP4 ORU designs are the most robotic friendly of any work package. However, one of the ORU designs shown to ATAC required an existing satellite servicing tool that is not currently in the baseline design. In addition, a few ORUs are not accessible to the FTS.

The interpretation of EPS automation requirements by Rocketdyne has resulted in preliminary designs using conventional automation to manage electrical energy, to provide system protection, and to report operating status. No advanced automation is proposed for the baseline design. Further, no design accommodations for the evolution of advanced automation were presented to ATAC.

Both Lewis Research Center (code MT and RC funded) advanced development teams are applying knowledge-based approaches for automating power operation to provide alternatives for automation growth. However, the advanced development activities of Lewis Research Center and Rocketdyne are not formally coordinated with each other and are not likely to significantly impact current SSF baseline design.

**In summary, WP4 ORUs are the most robot friendly of any of the work packages, but no advanced automation is proposed for the EPS in the baseline.**

# NEW A&R ISSUES

### A&R Standards

ORU Standards.

The importance of robotic-extravehicular astronaut activity design standards has become very apparent to ATAC. The need for these standards and adherence to them have been identified by the panel and team activities described above. For the past two years Level II has been working on robot-EVA compatible interface standards in the form of the Robotics Systems Interface Standards document, of which a draft version is now undergoing review. In addition, Level II now has an activity to broaden the scope of this document to include common engineering design standards for external ORUs, EVA tools, robotic system end effectors, and worksite attachment interfaces. ATAC is not certain about the progress in this activity, because Level II was not represented at the August ATAC meeting. However, from presentation charts sent to ATAC from Level II, it appears that the first of these standards will be selected in September 1990, with all standards being baselined in December 1990.

Presentations to the August 1990 ATAC review by all work packages indicated that their ORUs are not being designed to a standard that would meet the FTS and/or operational requirements of all SSF robotic systems. This situation will require different and unique FTS and EVA tools to allow ORU removal and replacement. Such a situation will add considerable additional costs to the SSF development at a future date.

**ATAC recommends that SSFP 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.**

A&R Development Tools.

There is currently no standard method to model an end-to-end scenario using all of the robotic systems that will be present on the Space Station Freedom because common primitives, simulation systems, and modeling tools are not specified. Also, it is not currently possible for the different robotic systems developers to exchange information with other designers because of the lack of common tools and systems. This lack of standard development tools providing for end-to-end testing could result in systems that are not adequately tested for mission suitability in the context of the total system.

**ATAC recommends that the SSFP 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.**

End-to-End Software Integration.

There was considerable concern expressed at the August 1990 ATAC meeting by the developers of SSF software that standard methods were not being adhered to and that a plan did not exist to test all SSF software in an end-to-end integrated manner. The lack of a good software plan, development environment, and test methodology could result in an expensive schedule slip due to last minute software rewrite effort.

**ATAC recommends that SSFP develop and implement prior to CDR software standards, Software Support Environment standards, and a plan to provide the end-to-end software integration for both flight and ground applications.**

### Station Assembly and Maintenance

Several presentations at the August 1990 ATAC meeting addressed the topic of robotic and extravehicular astronaut activity (EVA) inter-actions concerned with station assembly and maintenance. ATAC commends the Space Station Project Office for their aggressive investigations of these issues.

Assembly Sequence Review.

A panel led by David Walker has been planning the assembly sequence for Space Station Freedom given the requirements and configuration defined by the SSFP Level II. Eventually, the assembly plan details will be contained in the Assembly and Maintenance Implementation Definition Document. The sequence which was presented to ATAC was based upon the November 1989 Space Station Freedom configuration which requires 29 flights (including logistics) over almost four and one-half years to be completely assembled. The panel has found several tasks for which the Flight Telerobotic Servicer would be useful for the first three assembly flights. The panel estimates that EVA astronaut time could be reduced by 9 to 22 hours per flight depending upon the flight. These tasks sanctioned by the panel are listed in Appendix D, "FTS Assembly Tasks". The term "sanctioned" means that the tasks are recommended by the panel but have not been approved or baselined by the SSFP, a process requiring about three months. There are still issues to be resolved, such as possible IVA time constraints and EVA backup for FTS tasks. ATAC encourages resolution of these issues and approval of the sanctioned tasks by the SSFP as quickly as possible.

Fisher-Price Study.

A seven-month study was completed during this reporting period by the External Maintenance Task Team which was co-chaired by William F. Fisher and Charles R. Price, both of NASA Johnson Space Center. This study is often referred to as the Fisher-Price study. The purpose of the study was to evaluate the maintenance requirements in more detail than had been done previously and to quantify both the performance of the EVA astronauts and the Space Station Freedom robots in conducting anticipated maintenance for Space Station Freedom. The results of the study indicated that an estimated average of 3276 EVA hours per year would be required for maintenance activities over thirty-five years. However, there are only 408 crew EVA hours available per year, not including prebreathing or other EVA preparation, or the IVA crewperson's time required to monitor the EVAs. Thus, there is an average shortfall of required EVA time of about 2868 hours per year. The team listed many recommendations for reducing this shortfall. The use of robotics and offloading some actions to be performed from the ground were the two of the major ways of reducing the EVA shortfall. Of particular interest to ATAC were the recommendations related to robotics. These are listed in Appendix E, "Fisher-Price Recommendations". The team concluded that if all of their recommendations were followed, including those related to robotics, then the EVA time required by astronauts for external maintenance activities could be reduced to 1241 hours per year. Even with this remarkable reduction, there is still a shortfall of 833 hours which is being addressed by the External Maintenance Solution Team (see below).

IVA Study.

The study team also performed some analyses to predict required IVA time for the use of robotics instead of astronaut EVA and found that there is increased IVA time, although they were not able to fully determine the amount. These IVA requirements are not well defined for housekeeping, research, or space exploration activities, and now, for increased time to control robotic systems. Furthermore, as was done for the external activities, techniques for both IVA robotics (with and without ground control) and advanced automation to reduce the IVA astronaut requirements should be studied and implemented. Humans involved both on the ground and on-orbit should be used in ways best suited to them, and not required to perform mundane and inefficient tasks.

Crew time allocation and productivity on Space Station continue to be a concern. Allocation of many external maintenance tasks to FTS and other robots relieves some of the pressure on EVA astronaut time. However, this increases the pressure on IVA astronaut time. A study needs to be conducted on the requirements for IVA time to operate robotic devices, and should include the potential for operating the SSF robots from the ground on specific tasks to reduce the IVA time requirements on SSF.

**ATAC recommends that SSFP 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.**

ATAC applauds the efforts of the External Maintenance Task Team and feels that the study was conducted well and thoroughly, considering the brief time allowed for its completion.

External Maintenance Solution Team.

This is a follow-on activity to the External Maintenance Task Team study that is being conducted by the External Maintenance Solution Team at JSC. This team is evaluating the effects of proposed solutions to the EVA maintenance hour shortfall. They have been examining the effect of the implementation of Fisher-Price recommended EVA changes and ORU compatibility,in addition to updated maintenance data, refinements of maintenance overhead factors, preventative maintenance allowances, and the application of robotics to external maintenance. With the implementation of all these changes, the required EVA hours is reduced to 485 hours per year. This is much closer to the allocated 408 hours. The team has been directed to continue its efforts and to develop plans to implement specific recommendations of both the External Maintenance Task and Solution teams. ATAC is pleased that robotics is being considered as a viable solution to the EVA maintenance hour problem. However, attention needs to be given to the IVA requirements and ways that robotics integrated with advanced automation can reduce these requirements.

SSF Ground-based 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 assure 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 test bed demonstrations to allow robotic remote ground operations.

**ATAC recommends that SSFP 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.**

## A&R Evolution.

Scrub Impact on DMS/OMS A&R Evolution.

Briefings to the ATAC indicated that Life-Cycle Cost (LCC) considerations in the SSFP were apparently ignored during the recent scrub activities. It appears that no measures were taken to protect "hooks and scars" that would allow future growth and upgrade of the SSF.

Specifically, the Operations Management Application (OMA) was affected in the following ways: (1) inventory management functionality has been removed; (2) short term plan storage has been reduced from a period covering 48 hours to 24 hours; and (3) event management capability, in all likelihood, has been reduced due to a new requirement that all OMS software reside in only 1MB of memory. In effect, most monitoring and automated control capability has been removed from onboard functionality to the ground.

These impacts cause the ATAC to have serious concerns about the DMS/OMA providing an infrastructure that ensures available data processing capability for future advanced automation roles in the various subsystems. Presently, most monitoring functions are planned to be discharged on the ground. During periods of loss of signal or quickly developing contingencies, the crew may find themselves in a very difficult position trying to effectively respond to complex subsystems on board. In addition, a plan is not available for computational architecture evolution leading to higher performance systems compatible with post-AC mission projections.

All of the SSF work package representatives at the August 1990 ATAC review indicated that the ongoing scrub activity removed capabilities which would allow the future implementation of advanced A&R systems within the proposed baseline configuration. These concerns are especially evident considering the major reduction in the implementation of sensors in the baseline configuration, with the apparent inability to add sensors at a later date due to scrub-caused limitations in the network distribution system and the DMS.

**ATAC recommends that at the completion of the Space Station Freedom scrub activity and prior to CDR, determine the extent to which the planned Space Station Freedom baseline configuration at Assembly Complete will support the implementation of advanced automation and robotics applications, with emphasis on the Data Management System (DMS) architecture and sensor instrumentation.**

Advanced A&R Technology Implementation Funding.

The SSFP Level I Advanced Development Program and the OAET A&R Program have been the primary mechanisms for introduction of advanced A&R technologies onto SSF. However, the history of the Advanced Development Program indicates that it is subject to severe budget fluctuations. The OAET A&R Program has contributed strongly to research and development, but has very limited funding levels required for technology transfer and implementation. These unstable and inadequate advanced technology development program funding levels undermine the validation, transfer, and implementation of advanced A&R technologies on the Space Station Freedom. It is important that adequate funding be provided for technology transfer and implementation as well as the technology development phases.

**ATAC recommends that SSFP ensure funding stability for SSF advanced A&R technology development and emphasize funding levels commensurate with that required to transfer and implement these technologies into the SSF operational environment.**

# ATAC RECOMMENDATIONS

## A&R STANDARDS

**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."

**Recommendation II: A&R Development Tools.**
"Develop and implement prior to CDR a common set of robotic primitives, simulation systems, modeling tools for use by all the robotic systems developers across all work packages."

**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."

## STATION ASSEMBLY AND MAINTENANCE

**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."

**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."

## A&R EVOLUTION

**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."

**Recommendation VII: Advanced A&R Technology Implementation Funding.**
"Ensure funding stability for SSF advanced A&R technology development and emphasize funding levels commensurate with that required to transfer and implement these technologies into the SSF operational environments."

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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, to have a favorable cost-to-benefit ratio, and where the enabling technology is sufficiently mature. The program recognizes A&R technologies are experiencing rapid change, exhibiting varying levels of technology readiness, and have unique requirements for successful integration with conventional design approaches and system engineering methodologies. Consequently, 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 phases of the program, the program intends to leverage the significant momentum in A&R research and technology development on-going 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.

**Level I A&R Progress**

The Advanced 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." 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 enables Station evolution in support of advanced missions (e.g., transportation node for 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 prevent technological obsolescence. 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 applications, especially in the A&R area.

Currently, the majority of the Advanced Development Program's FY90 budget of $5.9M is dedicated to A&R applications and technology development. Thirty-four tasks are divided between Flight System Automation ($1.6M), Ground Operations & Information Systems ($1.9M), Advanced Automation Software & Hardware ($1.4M), and Robotic Systems Technology ($1.0M). Seventeen of the tasks are leveraged by joint funding from the Office of Aeronautics and Exploration Technology (OAET), the Space Transportation System Program, the United States Air Force (USAF), and the Defense Advanced Research Projects Agency (DARPA). The joint funding results in an addition of $14.0M 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 on Advanced Development efforts. Thus, greatly boosting the amount of resources devoted to building SSF A&R applications. and facilitating the technology transition to the baseline station.

FY90 funding for the Advanced Development Program was delayed and eventually released in March and July. This caused numerous schedule slips and consequently impacted the ability to define and incorporate A&R design accommodations into the baseline Station during the Preliminary Design Review (PDR) process.

In the Flight Systems area, advanced automation applications are being developed for Power Management and Distribution (PMAD) at Work Package 1, Power Management and Control (PMAC) at Work Package 4, the Environmental Control and Life Support System (ECLSS) at Work Package 1, the Thermal Control System (TCS) at Work Package 2, 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 the Station 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.

Mature PMAD FDIR application and user interface software on the Marshall Space Flight Center (MSFC) PMAD testbed has been re hosted to a computer architecture compatible with the Station Data Management System (DMS) hardware and software to closely evaluate DMS implementation and performance issues. Analysis of KBS interface and communications requirements for a distributed, cooperating KBS demonstration has been completed and a link with the Lewis Research Center (LeRC) Power Management and Control (PMAC) testbed was established. Improvements to the Human-System interface have been reviewed and documented.

An ECLSS design accommodation analysis has been completed which examined automation requirements and implementation issues for KBS FDIR of major ECLSS sub systems. A potable water quality monitor prototype was developed and demonstrated using inputs from a high-fidelity simulation. An Ada based KBS development tool was evaluated. Models of the Hygiene Water System and reverse osmosis process have been facilitated by using other KBS development tools. Additional prototypes will be developed in FY91 and demonstrated on the ECLSS testbed at MSFC.

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 KBS techniques can significantly improve an astronaut's ability to perform in-flight science and provides protocol flexibility, detection of interesting phenomena, improved user interface for experiment control, real-time data acquisition, monitoring, and on-board trouble shooting of experiment equipment. The system, known as PI-in-a-box, was ground-tested in the Spacelab Baseline Data Collection Facility in preparation for, and will be used in support of, the SLS-1 mission. The prototype system will be flown and used in-flight on SLS-2. 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.

In Ground Operations and Information Systems, advanced automation applications and the computer and network architectures required to enable them are being addressed. Applications for the Mission Control Center (MCC) and Space Station Control Center (SSCC), the Space Station Operations Management System (OMS), the onboard Data Management System (DMS), the Software Support Environment (SSE), and the Technical and Management Information System (TMIS) are under development. Each application mixes conventional and KBS techniques and includes comprehensive user interfaces to support interactions when used in an advisory mode. The most significant accomplishments during this reporting period follow.

Several new technologies have been introduced to the MCC at JSC by the Real Time Data Systems (RTDS) task. RTDS is an outgrowth of the earlier Integrated Communications Officer (INCO) Expert System task which was co-funded by OAET's Artificial Intelligence Program, the Space Station Advanced Development Program, and the Shuttle Advanced Development Program (INCO was described at length in ATAC Progress Reports 7 and 8). 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. Recently, weather, fuel cell, and data communication applications were developed. 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.

The DMS Advanced Development Plan was updated and reflects the results of the advanced operating system study of Ada language and multiprocessor architecture impacts. Interfaces and configuration commonality requirements between the Johnson Space Center (JSC) DMS testbed and the ARC Advanced Architectures Testbed were defined. Joint 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. A DMS Network Test Procedure Executive KBS supervising operating system utilities, workload processes, and network monitoring applications was developed for the ARC Advanced Architectures Testbed and transitioned to the JSC DMS testbed. An evaluation of baseline DMS performance and recommended growth and evolution options will be completed prior to program PDR.

In Advanced Automation Software & Hardware tools, environments and architectures are being pursued which support the design, development, and maintenance of SSFP advanced automation applications. Products of this area are intended to reduce the cost, time to develop, and maintenance of conventional flight and ground system software. Tasks include developing 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 KBS software. The most significant accomplishments during this reporting period follow.

The development and evaluation of Ada based KBS programming tools and run-time environments yielded two prototypes for evaluation, one is derived from a commercial product and the other is based on the NASA/JSC developed CLIPS tool. Each was evaluated using existing KBS applications. Detailed design requirements for transition of 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 Ada programming language which has been baselined for flight system software.

The Automated Software Development Workstation (ASDW) prototype continues to be evaluated by the Mission Operations Directorate for use in MCC software maintenance. ASDW provides a KBS interface which assists the programmer in rapidly developing large programs through the reuse of existing Ada software modules. ASDW is under evaluation for incorporation in the Space Station SSE to support Station software development and maintenance. Although many similarities exist between conventional and KBS software verification and validation (V&V), the differences require specific tools and techniques to provide truly effective V&V. The KBS V&V task conducted a state-of practice survey and identified many promising approaches but few have been tested and fewer put into operational use. In FY91, requirements will be evaluated and potential technology areas developed which provide solutions to meet KBS V&V requirements.

In Robotic Systems Technology software, hardware, and testing of telerobotic capabilities for the Flight Telerobotic Servicer (FTS) are being pursued. Straight teleoperation of SSF manipulators requires an on-orbit operator to plan and execute each step of a task. The IVA crew, in trying to use teleoperation to combat the oversubscription of crew EVA predicted by the External Maintenance Task team (EMTT) Final Report, may become oversubscribed themselves. Advanced telerobotics will reduce the operator's workload by allowing the robot to control fine parameters (such as force exerted against a surface) while the operator directs the task. With improved sensing, planning and reasoning, and displays and controls, simple tasks like unobstructed inspections and translations may be accomplished by ground-based operators in the presence of significant communications time delay. Such ground-remote operations will free the on-orbit crew from routine, repetitive, and boring maintenance tasks whenever possible. Tasks funded by the Advanced Development Program in this area are focused at the reduction of IVA teleoperation time for FTS tasks and the eventual provision of a ground-based operation mode for Station robotic systems such as the FTS and Mobile Transporter. The most significant accomplishments during this reporting period follow.

Shared control software algorithms that permit the mutual control of the robot arm and end-effector combination using simultaneous human and computer-generated control have been developed and demonstrated under the NASREM interface standards on the JPL Telerobotics Testbed. When complete, shared control and traded control may enable supervised autonomous operations and the eventual ground-remote teleoperation of the FTS. In the near term, shared control permits fine control of telerobotic manipulation tasks and significantly increases operator efficiency. In response to the FTS DTF 1 requirement for contour following while maintaining a continuous surface clearance height, the shared control algorithms have been rewritten to integrate directly to the NASREM based GSFC DITFAC and the FTS prime contractor testbeds. This work resulted in a landmark "Local-Remote Interface Subsystem Design" document written cooperatively by JPL and GSFC/NIST. The actual hosting, debugging and testing of the software in these labs commences in FY91.

The ongoing Telerobotics Ground Remote Operations (TGRO) task integrates and tests both sides of the telerobotics interface (local and remote) to permit ground control of telerobots. For the remote site, an interface box to control the Martin Marietta (MMAG) FTS development manipulators in Denver, CO from JPL in Pasadena, CA has been designed and is in fabrication. To give the local operator the capability to help the telerobot interpret input from remote vision sensors and plan appropriate motion, Human-Coached Machine Vision (HCMV) software has been developed. With HCMV, operators can use any of several screen cursors to overlay graphic edges and vertices on a video object and then aid in matching that object to a CAD model. By installing the shared control software in the interface box at the remote site and controlling the MMAG manipulators through the HCMV interface at JPL, the TGRO task will again operate in the presence of real time delay over great distances. The significant improvement is that manipulators in a NASREM based development environment will perform FTS DTF-like tasks, starting with 6-dof, single arm motions. This activity will surpass the 1989 successful operation of the Kennedy Space Center (KSC) prototype robotic inspection system under time delay.

Further out in the post-SSF assembly era, the Langley Research Center (LaRC) Automated Construction Testbed continues progressing well. The tailored dual-end effector for handling and/or installing truss struts has completed assembling the dual-ring tetrahedral truss structure in sequences and is preparing for a one-shot dual ring truss assembly test. A single-end effector design is in bench test. Lessons learned in the assembly tests have generated a set of assembly rules sent to JPL, RPI, and other sections in LaRC. Assembly sequences received back from these evaluators reveal marked differences, leading to an evaluation of the rules for accuracy and a simultaneous evaluation of each recipient's planning software.

GSFC continues aggressively pursuing a telerobot tri-modal sensing skin. Two modes (proximity and tactile) based on an unusual conformal (zero standoff) capacitive sensor and custom flexible circuit boards developed within this task are being evaluated. Combination of sensors into an array, software matrix manipulation and analysis of array output for object range, direction, and location with respect to the skinned telerobot are in work. Development of advanced algorithms for object edge detection has begun. If successful, this project could provide up to three more levels of safety in collision avoidance (an External Maintenance Task Team, External Maintenance Solutions Team, and crew recommendation for all telerobots).

Level 1 investment in a design study for an EVA crew/object retrieval robot (EVA Retriever) is winding up with successful integration of transputer-based AI planning and reasoning software, vision, laser scanning and robot control algorithms. This parallel-processor based activity, unlike anything currently baselined, has successfully explored newer and faster architectures for telerobotic system control in the presence of a very difficult problem: location, identification, tracking, rendezvous, grappling and retrieval of a free-floating object in space by an autonomous free-flyer. If brought to fruition, the EVA Retriever robot promises a viable means of retrieving objects which inadvertently become separated from the Space Station.

**Level II A&R Progress**

The Level II Representative was unable to attend the August ATAC meeting due to his program obligations to support the Canadian Mobile Servicing System Interim Design Review held in Toronto August 20-31, 1990. In light of this conflict, Mr. Gregg Swietek offered to present the Level II briefing materials.

A Robotics Integration Plan is being prepared in response to the ATAC recommendation for a Level II A&R Implementation Plan. Copies of this draft plan were provided to Level I. The final version of this plan will be complete by October 1990. Plans are being made to move some advanced automation of SSMB control functions from the manned base to the ground as a result of constraints in DMS and power resource allocations. This approach does not mean abandonment of Advanced Automation for the Space Station Freedom Program. Rather, it will result in a potentially more vigorous program since automation processing resources are much more available on the ground. After refinement and improvements to Advanced Automation concepts in a ground environment, they can be migrated onboard as DMS resources are added. An Advanced Automation Implementation Plan will be prepared for this approach as soon as the PDRD changes implementing this approach are in place.

Progress has been made in establishing common "EVA and Robot Friendly" Tool, End Effector and ORU interfaces. As a part of the Robotic Systems Integration Standards (RSIS) development, Interface standards are being proposed by all Work Packages and International Partners. These proposed standards will be reviewed by an Interface Design Review Committee under the auspices of the Robotics Working Group and the EVA Systems Working Group. This standards selection activity will be completed in November 1990 and will be incorporated in RSIS to support the Level II Integrated Systems PDR.

Plans for Task Analysis and Task Allocation are being included in the Robotics Integration Plan. Task analysis will be performed using computer kinematic simulations. Task verification will be performed using dynamic computer simulations, 1-G laboratory simulations, and flight demonstrations where necessary. The results of these simulations and verifications will support task allocations in the Assembly and Maintenance Implementation Definition Document (AMIDD) and the Servicing System Implementation Definition Document (SSIDD). Task simulations will be performed by both the Robotic System providers and by integrated simulation facilities at JSC.

At Level II direction, JSC is performing a Handcontroller Commonality evaluation. A Joint Evaluation Test Team (JETT), under the direction of Mr. Dean Jensen at JSC, will report the results of testing and make a program recommendation by the end of September 1990.

Due to program concentration on resource convergence activities (Turbo Team and Boiler Room), little progress could be reported on some ATAC recommendations. Progress on recommendations for Robotic Systems Integration was reported relative to the draft Robotics Integration Plan and the Interface Design Review Committee plans for selecting common EVA and Robotic End Effector, Tool, and ORU interfaces by the end of November 1990. Level II plans to continue to support the ATAC, and is looking forward to addressing issues of programmatic interest in future ATAC meetings.

**Work Package 1 A&R Progress**

Since Space Station Freedom has a planned minimum 30-year operational lifetime, vast amounts of Space Station design knowledge and experience concerning the different subsystems and components will be generated. Trade studies will be performed, alternative designs will be analyzed, different subsystem configurations will be simulated, and prototype systems will be constructed. This knowledge and experience will naturally be accumulated by many different design engineers. Many of which, will not be available as designs change. Engineers will retire, change organizations, and take reassignment. To reduce the impact of this organizational atrophy, Design Knowledge Capture attempts to collect all information and knowledge associated with the design specification of Space Station Freedom and make it available throughout its lifetime and beyond. Work Package One acquires salient design knowledge within the budgetary constraints of the Space Station Freedom Program. Current efforts focus on collecting information with a design alternatives tool and with specialized knowledge based systems.

The Design Alternatives /Rationale Tool (DART) collects trade study information. For example, alternative solutions (e.g., ozone, silver, etc. - along the X axis) for microbial growth control in the potable water system are described according to their characterizing criteria (weight, volume, etc. - along the Y axis) in a matrix form. Furthermore, the cells in the matrix represent the relative value of each criteria for each solution (see figure A1).

Once a knowledge base has been constructed in DART, one or more consultations can be initiated to study how design trade-offs affect subsystem design. In the example, the respective criteria values are entered as preferences and results which rank the alternative solutions are produced. In the case shown, iodine is the best design alternative (with a rating of 50 out of a possible 100) for the preferences given. The benefit of a consultation is in the form of feedback to the engineer. If running a consultation does not produce results consistent with what the engineer expects, the matrix of solutions and attributes can be refined. Knowledge of criteria used to choose a solution is collected in the matrix, iteratively refined, and retained. This knowledge captured is a justification of a design decision and also a rejection of alternative designs which are not as suitable. Specialized knowledge-based systems are under development which capture other Work Package One design knowledge. These include Environmental Control and Life Support simulation and diagnosis, Space Station module rack integration, logistics element planning and packaging, and automation and robotics. Each of these systems embody design knowledge collected from the target domain.

The Environmental Control and Life Support System (ECLSS) simulation comprises six major subsystems which must all work together to provide a safe working environment for the crew. By developing simulations of the subsystems it is possible to detect problems with the basic design and subsystem integration at an early stage in development. State of the art process simulation software is being used to simulate the ECLSS. The software provides a graphical interface with iconic representations of the system components which may be manipulated even as the simulation is in progress. Behind the graphical interface, knowledge regarding the actual behavior of the system is modeled through the use of quantitative simulation formula, procedures, and rules.

The Module Rack Integration Analysis Tool models the layout of space station modules, including information on what resources are available in the module, what resources are used by racks to be integrated into the module, and what constraints (physical, functional, and operational) under which the module and the racks must operate. The system uses this model to help the user consider operational efficiency, compliance with requirements and constraints, and coordination with other organizations. The model supports the user by dealing with layout changes, long durations of implementation, multiple constraints and requirements, and inputs from a variety of disciplines.

The Rack Equipment Integration and Optimization Tool models the layout of a given space station module, including information on what resources are available in the module, what resources are used by rack equipment to be integrated into the module, and what constraints (physical, functional, and operational) under which the module and the equipment must operate. The system uses this model to assist users with the placement of equipment into the Space Station racks. It is a natural progression of the work done on the Module Rack Integration Analysis Tool by supporting the user in the complicated task of studying the effects of a large set of interlaced constraints.

The Packaging Manager (PACKMAN) for the Automated Logistics Element Planning System (ALEPS) effort produces computer algorithms for the efficient packaging of cargo into the Pressurized Logistics Module (PLM). Packaging plans must be generated for varying degrees of detail: for placement of individual cargo items, placement of drawers within a rack, and the placement of racks within the PLM. The ALEPS system is being developed to support logistics operations for SSF. The system requirements include generation of near optimal load plans and plan verification. Current estimates indicate that a 5% improvement in packaging efficiency for volume limited launches could save more than $800 Million (approximately four shuttle launches) over the life of the program.

Automation and Robotics IR&D

Boeing Independent Research and Development seeks to increase spacecraft crew effectiveness and productivity by using automation and robotic systems. Since crew time is always in great demand, activities that normally require high levels of crew interaction for mundane chores, such as housekeeping and maintenance, are considered for automation. Towards addressing these automation considerations, a testbed has been established for developing automated and robotic systems. Monitoring and evaluation of autonomously generated operations plans during execution is being addressed by the integration of model-based diagnosis techniques. These techniques will provide the capability to automatically isolate and diagnose failures found in normal operation of spacecraft subsystems as well as failures detected in either the generation or execution of the plans.

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 of the research integrates the automated components for planning/replanning, simulation, execution, and diagnosis. This integration takes place in a testbed mockup of a SSF common module that provides an environment for exhibiting housekeeping, maintenance, and payload operations (see figure A2).

ECLSS Advanced Automation Project

The Environmental Control and Life Support System aboard Space Station Freedom will sustain a safe shirt sleeve environment for its crew and payloads. Development has been divided into six functionally interconnected subsystems: Temperature and Humidity Control (THC), Waste Management (WM), Fire Detection and Suppression (FDS), Atmosphere Control and Supply (ACS), Water Recovery Management (WRM), and Air Revitalization (AR). The last two subsystems, WRM and AR, close air and water environmental loops to an extent never before attempted in space, and will require new technologies which are now undergoing extensive test and analysis. The current objectives for the ECLSS Advanced Automation Project are to demonstrate fault detection, isolation and recovery capabilities at the subsystem level for the Potable Water, Hygiene Water, $CO_2$ Reduction and $CO_2$ Removal Processes, and ECLSS system level control, diagnostics, and trends. Since the ECLSS is such a complex system and will require close monitoring, one of the goals for this project is to demonstrate and document a growth path for baseline software functions into intelligent systems. Evaluation of the baselined and evolutionary ECLSS water recovery and air revitalization subsystems is continuing in NASA's Core Module Integration Facility (CMIF) and in several SSFP Work Package One development testbeds.

These testbeds provide an enclosed environment in which regenerative ECLSS components are developed and tested for extended durations, while data is gathered and distributed to various analysis computers and personnel. Additionally, the testbeds provide a hardware system in which to test ECLSS automation technologies.

**Work Package 2 A&R Progress**

The following paragraphs describe advanced automation projects being developed within Work Package 2 at JSC and under IR&D by the WP2 Prime Contractor. The applications described are not presently within the baseline program, but have the potential to influence the baseline design to better support advanced automation, and, if successful and with appropriate funding, to be incorporated in the baseline program at a later date.

The requirements for autonomy, automation and robotics for WP2 include words and phrases which make them "soft" and open to interpretation, such as, "whenever practical and cost effective," "where practical," and "upward compatibility." Based on flowdown of program requirements, advanced automation in the onboard system is not being considered, except for sensor/actuator considerations, until assembly complete. Although the on-orbit deployment is looking more questionable as the design progresses, Advanced Automation application deployment on the ground is receiving much more positive consideration. Requirements developed within the Space Station Control Center include requirements that will drive significant sophistication into the design of this facility.

While there is no strong contractual requirement for advanced automation and robotics, MDSSC has taken the initiative in baseline station design and in company funded projects to develop automation and robotics. However, due to the computational resources available during the early stages of the space station assembly through the assembly complete configuration, the feasibility of fielding onboard advanced automation applications appears unlikely.

MDSSC has updated their internal A&R Plan to reflect changes in NASA's direction related to the programmatic rephasing activities, and to reflect activities through the project Critical Design Review.

Advanced Automation

MDSSC is defining a migration/transition plan to allow the development and testing of knowledge-based systems on the ground with migration to onboard as computer resources are increased. The current plan calls for various WP2 knowledge-based systems to initially be developed against system simulations, then moved to testbeds and calibrated against real hardware, and finally moved to a supporting role in the Engineering Support Center. This Center will handle requests from the Space Station Control Center and turn them over to either the Integrated Truss Assembly and Verification (ITAV) or Avionics Development Facility (ADF). The ITAV facility will be used for integrated testing of flight hardware in each of the assembly configurations, while the ADF will handle the integrated flight software testing. From the Engineering Support Center, WP2 knowledge- based systems may be transitioned through the ADF to onboard use or to the Space Station Control Center. This transition plan is the framework into which advanced automation applications will be deployed and utilized (see figure A3). The following guidelines have been established for these applications: 1) Subcontractor participation; 2.) Augment not replace baselined systems; 3) System Management should be the focus- including Fault Detection Isolation and Recovery (FDIR), predictive maintenance, and redundancy management; 4) Designed to meet onboard computational requirements (i.e. Ada, Lynx, 80386, XWindows, Runtime Object Data Base, etc.); 5) Assist human operators by providing intelligent information integration (too many sensors for humans to monitor).

The Thermal Advanced Automation Project (TAAP) examines the feasibility of using advanced automation techniques by developing a prototype system to support FDIR of the Active Thermal Control System (ATCS). Paralleling this activity is the development and documentation of modeling techniques utilized in the creation of a high fidelity simulation of the ATCS. This parallel effort will result in the ability to understand how simulation development can be leveraged to support knowledge acquisition for model-based reasoning approaches to Advanced Automation applications. This project applies technology developed in the Thermal Expert System (TEXSYS) project. In a related company funded project, the extent to which software costs can be controlled by utilizing horizontal and vertical commonality is being investigated (see figure A4).

The Advanced Automation Methodology Project (AAMP) defines engineering methodologies (both software and hardware) which allow the evolution of advanced automation onto the Space Station Freedom platform. A successful Preliminary Design Review of the Recovery Procedure Selection Application (RPSA) was completed August 1990, and the final demonstration is planned for June 1991. The initial Ada prototyping of the RPSA has been completed and work continues with the graphical user interface designs and prototyping using DECWindows.

The Data Management System (DMS) fault detection, isolation and recovery demonstration has been initiated. Some early design work and knowledge acquisition has been undertaken, and a simulation is being developed. The Maintenance Diagnostic System (MDS) demonstration, developed for the guidance navigation and control system, has been upgraded to handle more faults and can now predict a wider range of failures. This is the only WP2 application addressing the area of "predictive maintenance" (i.e. maintenance based on impending failure, not scheduled maintenance or actual failure). This system also provides intelligent training, and access to online CAD data.

Several medical diagnosis expert systems are being investigated for the Crew Health Care System (CHeCS). This has high priority since a physician may not always be available onboard or on the ground. There is also the possibility of communications black outs, whether due to a onboard failure, a tracking data relay satellite system, or some failure in the links between the White Sands test facility and Johnson Space Center. A project called Emergency Medical Protocol Hypermedia Assistant (EMPHAsis) is developing an intelligent assistant to aid the Crew Medical Officer in the performance of crew member treatment during cardiac emergencies. Completion and demonstration of a prototype system is due by June 1991.

The Advanced Automation Methodology Project is developing two Advanced Automation applications. One developed by JSC and the other developed by the Work Package 2 Prime Contractor. The Advanced Automation Network Monitoring System project demonstrates the advantages of automated fault detection, isolation and reconfiguration, as well as trend analysis of network behavior. The Diagnostic Reasoner/Recovery Expert (DR/Rx) project prototypes the FDIR functions within the Operations Management Application in support of Operations Management System testbed efforts. The project integrates model-based reasoning and procedural reasoning techniques. Each uses strict software engineering practices by utilizing the SMAP 4.3 standards. Verification of the applicability of these practices to Advanced Automation development ensures manageability and testability.

The Plan Monitor project aids the Operations Management System testbed efforts by monitoring the execution of the Onboard Short Term Plan. Although currently developed with conventional approaches , extensions are planned for intelligently performing the same function.

A number of design applications are being pursued. 'Analysis of Design for Automation,' analyzes system design to ensure proper support of system and element functioning by Advanced Automation implementations. In addition, it identifies potential weight, power, volume, etc. savings that Advanced Automation could provide by allowing the minimization of instrumentation requirements. To date, several design analysis tools (such as the Failure Environment Analysis Tool (FEAT)) are being acquired, and analyzed. Effort has also begun on planning a prototype development project of a mission controller support FDIR system called Fault Impacts Assessment Tool (FIAT). This tool would integrate the FEAT system with other Advanced Automation technology.

Development of the CONFIG system modeling and analysis environment, which enables and/or partially automates SE&I design analysis and operations procedure generation, provides support to automation software engineering, design knowledge capture and real-time fault management. The Propulsion Unit Fault Finder has been completed and demonstrated in September 1990. The developed system is a stand-alone prototype of a FDIR system for the Propulsion Electrolyzer of the Integrated Propulsion Test Article. The system will effectively demonstrate the feasibility of supporting engineering ground facility operations with Advanced Automation technology.

Robotics

WP2 robotics activity focuses on making WP2 hardware robotically compatible for assembly, servicing and maintenance. The EVA/Robotics Design Standards (EVARDS) document provides design guidance with more detail than that provided by Robotic Systems Integration Standards. It consists of a catalog of connectors, fasteners, tethers, handles, grapple fixtures, and other hardware components. Designers may then select components from this catalog, to insure commonality across designs within WP2. A Robot Friendly Working Group provides a technical forum for the hardware designers and robot engineers to reach consensus on how to design robotically compatible ORUs.

A wide variety of activities are ongoing in the area of robotics. CIMSTATION has been chosen as the high fidelity robotic modelling tool. It supports 3 dimensional models with collision and near miss detection and helps define work envelopes, and assessment of robotic friendliness of current designs. Quick connect/disconnect connectors are being tested in the JSC robotics labs. Ocean Systems Engineering has been testing some of the preliminary designs. WP2 is developing a FTS integration plan which addresses FTS to SSF interfaces, ORU design and testing, and connector design. WP2 is also providing hardware mockups to GSFC for testing in the FTS operations Simulation Facility.

Summary

Overall significant progress has been made in the area of advanced automation. The projects and plan here represent a low cost, low risk, technically feasible approach to incorporating more advanced software techniques into the Space Station Freedom Program. The importance of designing external ORUs to be robot compatible is understood and being worked by the pertinent engineers.

## 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. To develop this automation, LeRC has embarked on a three-faceted R&D approach. The first involves the Level I Advanced Development Program which aggressively prototypes and demonstrates advanced automation and robotic technologies. The second seeks to evolve automation within the prime program. The third establishes relationships with industry to leverage their technology advancements.

Advanced Development Program activities at WP4 are described in the following material. Because electrical power system management is a mature terrestrial discipline, tried and true operating philosophies and techniques exist that can be applied directly to Space Station Freedom. In terrestrial power systems, algorithmic decision aids are used by experienced dispatchers to guide their command and control considerations. The Advanced Development Program augments this approach by developing expert systems to perform the closed-loop command and control functions of diagnosis, security analysis, and overall coordination; and uses conventional algorithms for power scheduling.

The command and control cycle begins with sample data from the electric power simulation. Expert systems process this data to recognize and classify the power system operating state and then proceed to perform specialized tasks based upon results of the classification cycle. Security monitoring and analysis software assesses the current power system operating states and analyzes the overload risk from possible failure modes. The diagnosis software determines the most likely cause of abnormal operation. Like the security analysis software, it too generates constraints upon the scheduling and distribution of electric power. Two expert systems are being developed for this diagnosis function. The first, APEX, has been developed in KEE for use with 20kHz switchgear. APEX detects anomalies such as; insulation breakdown in transformers, contact depletion in mechanical switches, and thermal conductivity degradation in power semiconductors. APEX can also replan power distribution after diagnosing the failure cause. An automated scheduler produces an optimum load profile and activates the failure detection to find deviations from the optimum plan. The second diagnostic expert system, TROUBLE III, is being developed in ART for use with the photovoltaic generation and nickel-hydrogen battery storage systems. TROUBLE III uses a standard reliability analysis tool---the failure modes and effects analysis---to produce a symptom and failure data base.

The Arbiter expert system coordinates Operations Management Application software requests, security analysis results, and diagnostic conclusions by specifying appropriate system operating constraints and electrical loads to a scheduling algorithm. The Arbiter software determines which schedule and operating plan is to be used given the current state of power system operation. A battery management expert system is being designed which extends battery life without sacrificing load scheduling flexibility. This system performs life prediction and state-of-charge estimation by compiling and analyzing trends in battery data.

A number of methods are being pursued which demonstrate the validity and feasibility of advanced automation applications. One uses the APEX switchgear diagnostic system and a zero one, constrained optimization scheduling algorithm to produce load shedding or reconfiguration commands for a small 20kHZ test-bed. The objectives are: to demonstrate switchgear failure detection and diagnosis; to explore cooperative problem solving between planning and/or diagnostic systems; and to integrate a LISP-based development computer with an Ada-implemented distributed control system. A second uses simulations of resource consumers and producers to create an experimental environment in which to bargain for resources. A third involves cooperative problem solving and uses the Lewis Power System Test-bed and the Marshall Common Module Power Test-bed linked as supplier and consumer. Scenarios are being developed and executed to investigate elementary scheduling and replanning under normal and degraded operating conditions.

Automation is an integral part of the SSF EPS and is being designed for evolutionary growth. The second facet of LeRC's approach implements current technology for the automation and diagnostic features with hooks for possible future incorporation of artificial intelligence, trend analysis, and advanced diagnostics applications. The current EPS architecture provides multiple power generation sources and a power distribution network to deliver power to system loads. Control over the power delivery and distribution is through an integrated system of highly functional switchgear, programmable power conversion equipment, and high-performance control processors. System control and energy resource management capabilities are treated as dynamic programming problems and providing automated optimal planning of source power demands, system configuration and other resource utilization. To ensure stable operation during system failures, the current design offers design redundancy and automated switchover protection. The current design also provides for the detection of system failures through on-line monitoring, built-in tests and data correlation and analysis algorithms. The baseline design does not, however, provide trend analysis or predictive capabilities for detection of incipient failures.

Developing and implementing expert systems will result in lower operational costs, faster and more consistent decision-making, and the examination of possibilities which humans might overlook. No expert systems are currently baselined. All automation development is, however, being done in the prime testing facility and efforts continue to integrate them with baseline control software. A blackboard environment will be developed to interface advanced automation with conventional software.

Robotics requirements focus on ORU telerobotic maintenance capabilities to minimize EVA time for on-orbit maintenance. Standard telerobotic interfaces are provided to facilitate remote assembly, removal and replacement of ORUs. Several changes have been recently implemented. A cable ORU has been defined which enables easy replacement of portions of the interconnecting cables in the event of damage or failure of a cable, connector, or their interconnections. This redesign utilizes the same standard ORU specifications for size and installation procedure. However, using the module service tool for on-orbit installation of ORU boxes is a problem as this tool no longer is a viable candidate for inclusion on SSF. Development of a special tool must be addressed. Robot compatible interfaces and operations will be 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 (see figure A5).

The third facet of LeRC's approach leverages Rocketdyne's IR&D. Rocketdyne has been evaluating fault diagnosis on its electrical power system testbeds in the Space Power Electronics Laboratory, SPEL. These expert systems detect faults within the remote bus isolator (RBI) and power distribution control unit (PDCU). Detected failures included short circuits, over currents, loss of power, power surges and communication losses. Currently, the expert systems are being enhanced and integrated even more closely with the power control system. An Integrated Power Advisory Controller (IPAC) was evaluated in the SPEL, the primary test facility for SSF's electric power system. Three modes of operation were identified and built: system monitor, fault detection and diagnosis, and system simulation. One major thrust of IPAC development detects multiple system faults and determines possible corrective actions. This work complements the Lewis advanced development work on single failure detection and diagnosis. Technological interchange meetings and IR&D reviews have been the primary mechanisms for coordinating Rocketdyne advanced development with Lewis' automation initiatives.

Conclusions

LeRC seeks to realistically develop and transition technology by prudently integrating expert systems with conventional algorithms to significantly reduce SSF's operating costs and IVA crew time. Efforts in the prime program are being defined and operated conventionally leaving the advanced development program to investigate expert systems to improve power system operation. The Lewis-Rocketdyne relationship leverages internal Rocketdyne R&D and Level I Advanced Development Program & OAET-funded activities. The end goal is the design of a competent, highly-automated electric power system that quickly amortizes its development expense and yields increased productivity.

```
Knowledge Base: Microbial Growth
Problem      : Growth Control
Engineer     : Ron Dickinson
                                                          Weight Type Criteria
---------------------------------------------
9   5   5   5   9   9   6  |        0.90 INT Weight        {1 - Low, 9 - High}
9   5   5   9   9   9   7  |        0.80 INT Volume        {1 - Low, 9 - High}
9   5   5   5   9   8   7  |        0.90 INT Power {1 - Low, 9 - High}
9   5   5   5   9   9   7  |        0.30 INT Cost  {1 - Low, 9 - High}
5   5   3   5   5   5   3  |        0.90 INT Effectiveness        {1 - Low, 9 - High}
9   7   7   5   1   1   7  |        0.90 INT Side Effects {1 - Low, 9 High}
7   6   6   5   3   3   9  |        0.60 INT Maintenance {1 - Low, 9 - High}
7   5   5   5   9   9   7  |        0.40 INT Complexity  {1 - Low, 9 - High}
5   5   5   5   1   1   9  |        0.30 INT Disposal Concerns {1 - Low, 9 - High}
5   5   5   5   7   9   3  |        0.60 INT Water Purity       {1 - Low, 9 - High}
7   7   7   5   9   9   9  |        0.90 INT Customer Impact   {1 - Low, 9 - High}
1   3   3   5   1   1   2  |        0.70 INT Lifetime        {1 - Low, 9 - High}
---------------------------------------------
|   |   |   |   |   |   |                          Solution Weight
|   |   |   |   |   |   Filtration                     <none>
|   |   |   |   |   Pasteurization                     <none>
|   |   |   |   Sterilization                          <none>
|   |   |   Iodine                                     <none>
|   |   Copper                                         <none>
|   Silver                                             <none>
Ozone                                                  <none>
```

Figure A1. WP1 Microbial Growth Control Trade Study Matrix Using DART.

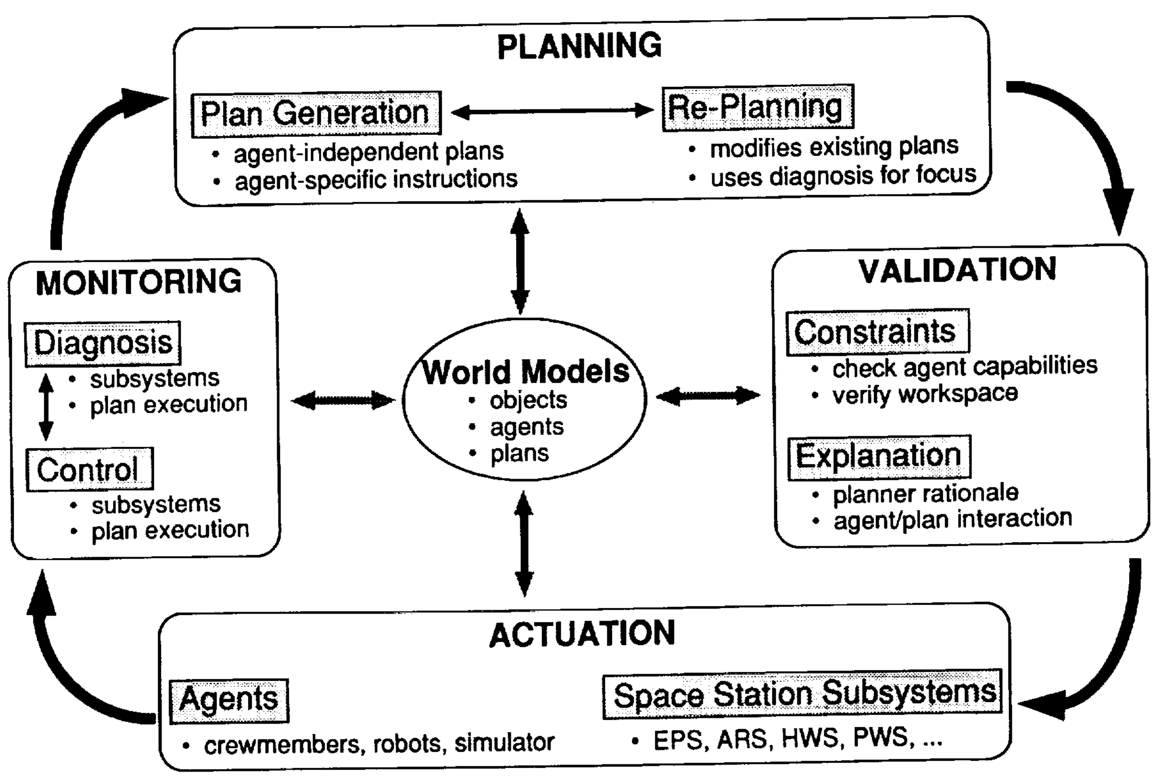


Figure A2. WP1 Automation and Robotics IR&D Functional Architecture.

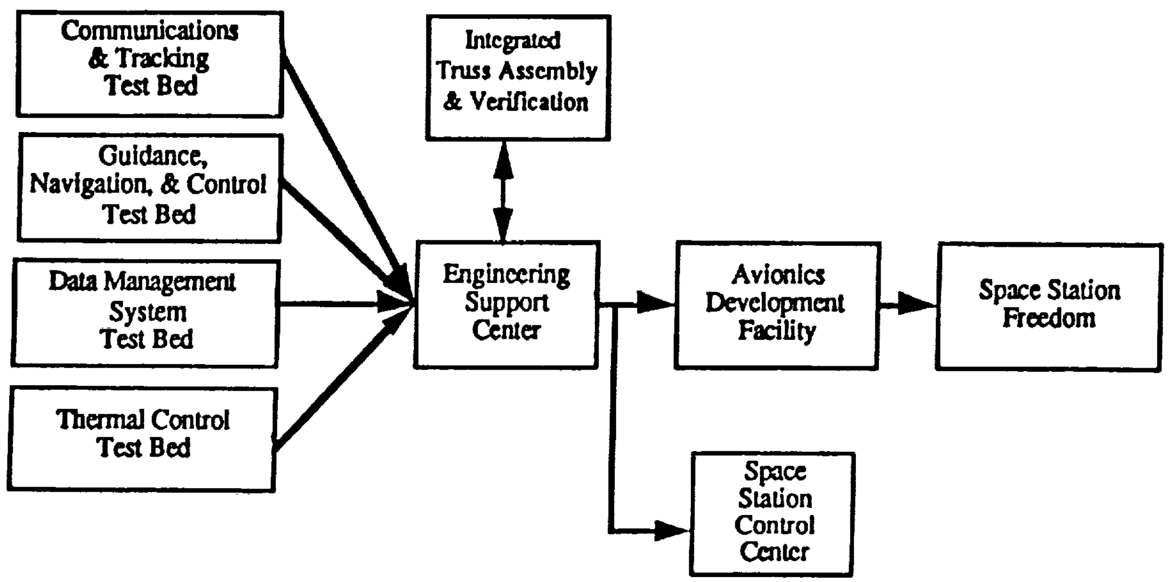


Figure A3. WP2 Advanced Automation Evolution/Transition Plan.

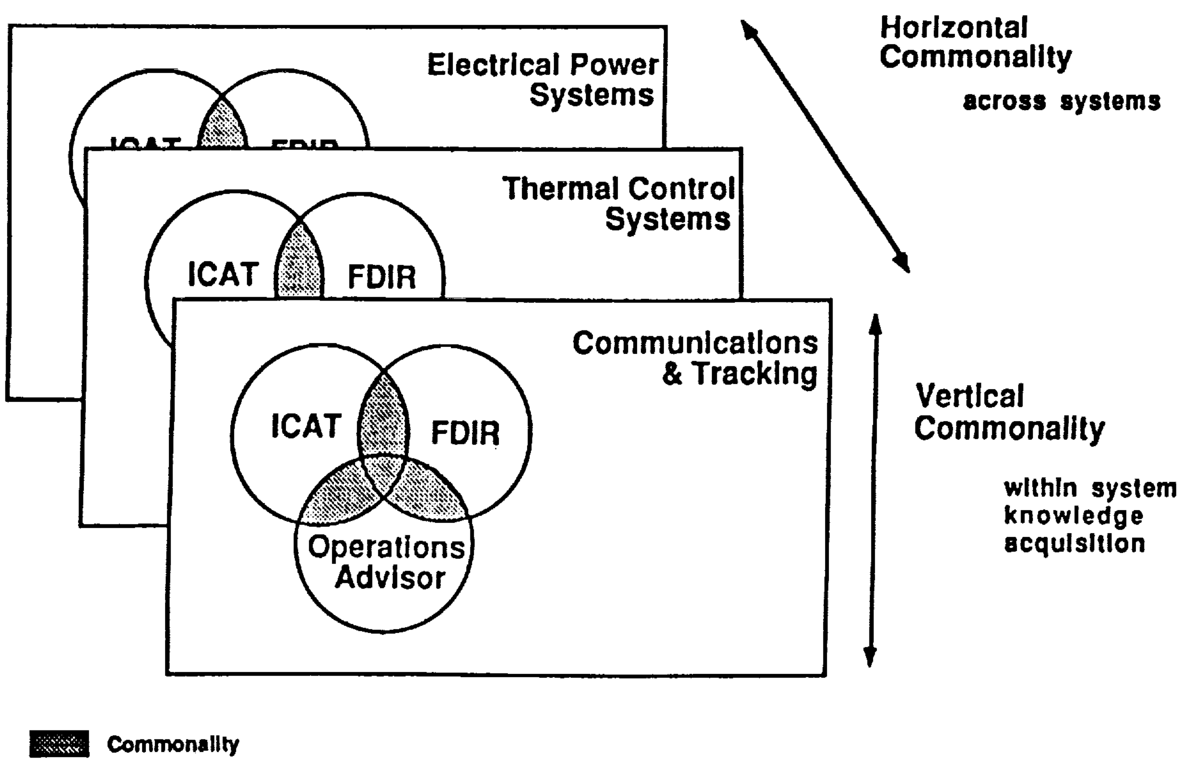


Figure A4. WP2 Horizontal and Vertical Software Commonality Cost Savings.

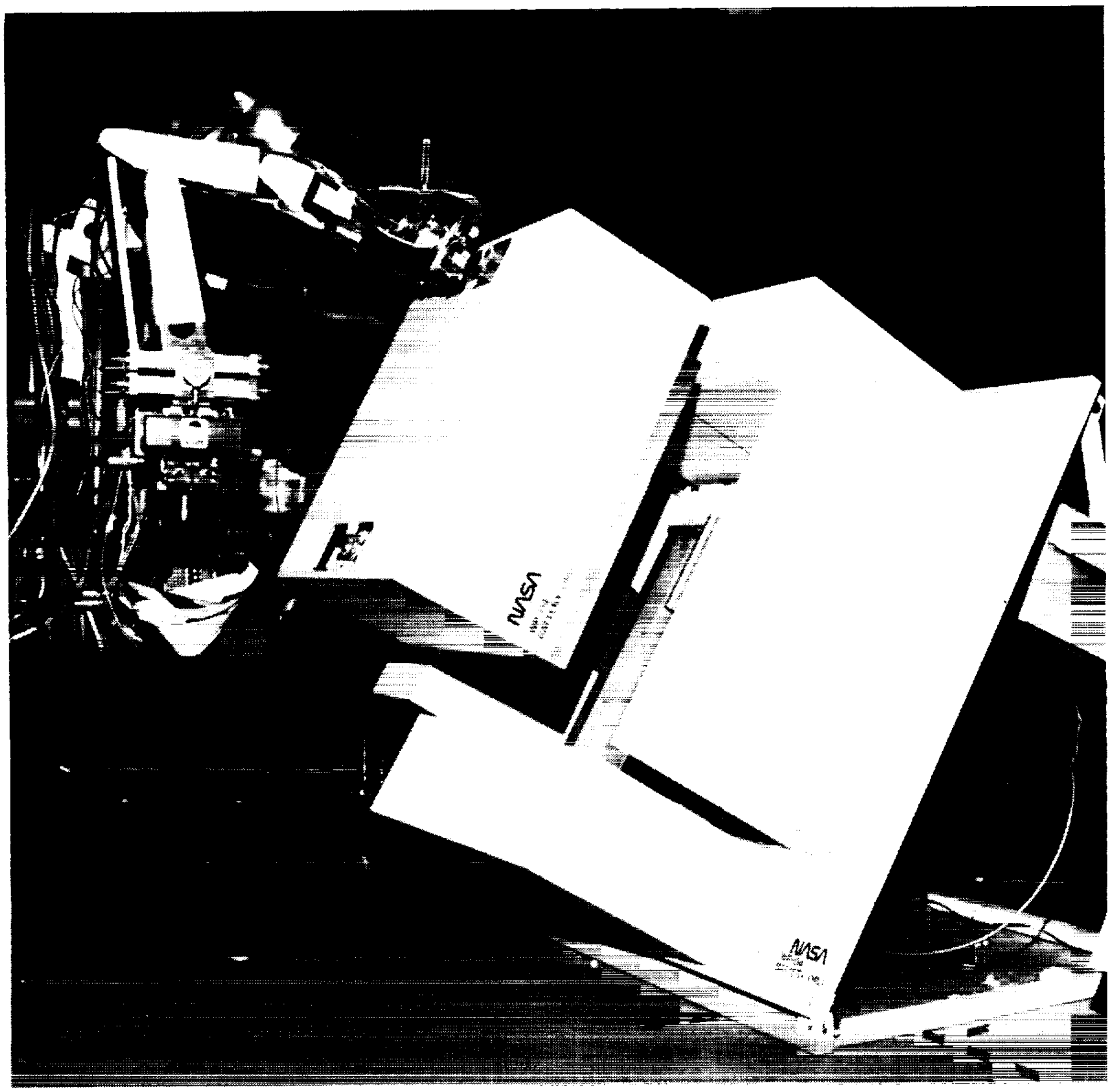

Figure A5. WP4 Tests for EPS ORU Robotic Removal in GSFC Development Facility.

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# APPENDIX B

## Flight Telerobotic Servicer Progress

The Flight Telerobotic Servicer has continued to make significant progress toward its test flights and Space Station Freedom operational missions. Specific assembly tasks have been sanctioned for detailed analysis and development to insure their compatibility with the FTS. This in turn has enabled the development of fundamental requirements for the DTF-2 (Demonstration Test Flight) mission. The DTF-1 (Development Test Flight) is well into the detailed design phase. Initial STS integration documentation and safety reviews for this first test flight have been accomplished. Also, an operational simulator for the DTF-1 payload has been delivered and installed at JSC for easy access and evaluation by the astronaut corps.

A number of time consuming technical issues that were encountered during the design process have completely eroded the schedule reserve for DTF-1. This, aggravated by the overhead of earlier program restructuring, makes the original launch goal of December 1991 unrealistic. A revised DTF-1 schedule will be committed to after a full technical assessment is made at the Critical Design Review during the first week in October.

### Prime Contract Status

The majority of the prime contractors effort has been focused on the detailed design for the FTS manipulator and associated hardware and software to be flown on DTF-1. The adequacy of this design is currently undergoing a Critical Design Review(CDR) process. Each subsystem is being reviewed by the GSFC FTS Project Team. A system level CDR will be conducted during the first week of October. The panel for the system CDR review consists of individuals independent from the FTS project and includes representatives from other centers and a astronaut from JSC.

The subcontracts with Schaeffer Magnetics (actuators), Western Space & Marine (trainer manipulator), Teledyne Brown Engineering (DTF-1 support structure) and JR3 (force torque sensors) have all been formally signed. The IBM (computer) and SMTEK (controller board fabrication) subcontracts have been negotiated by the prime contractor, approved by the FTS project and only require signatures to be fully executed. Subcontracts with Ford Aerospace (end of arm tooling), and Loral Fairchild (video cameras) are still in negotiation.

The development of the major subsystems is progressing in an orderly manner but at a slower than hoped for rate. There are two major development areas in the Data Management and Processing Subsystem (DMPS). The remote processors for control of distributed functions are made up of a stack of circuit boards with very high density packing of micro chips. These boards have all been specified, and designed and many of the circuits have been tested with a resulting commitment to fabricate development units in a size that will fit inside the FTS manipulator. The main telerobot control computer is a SSF Standard Data Processor that is being procured from IBM. A successful CDR was conducted on this item and a unit with equivalent flight functions has been delivered to support software development.

Software development is proceeding according to plan. The availability of flight equivalent hardware for software validation is a great asset in this process. It is expected that full implementation of software in the ADA language can be accommodated and that the software structure will support the NASREM functional architecture. Significant reductions in timing have been achieved by compiling the ADA code on a "bare" machine and eliminating the general purpose operating system overhead. The net result should be an FTS system with more responsive performance.

The manipulator design is essentially complete now that final decisions have been made concerning cabling requirements. These requirements were driven by the choice of motor voltage, redundancy of motor windings and sensor implementation strategy to satisfy safety and reliability considerations. An extremely complex set of trade off analyses was conducted to satisfy all the considerations. Following CDRs on the force torque sensor, thermal design, and the complete manipulator, structural detail and assembly drawings have been released for fabrication of the first FTS manipulator. Figure B1 shows the general layout and joint characteristics of this configuration.

A comprehensive rebaselining of the program schedule and funding profiles is in progress. Considerable flexibility can achieved with the acceptance of some risk by early commitment to piece parts and designs that have been demonstrated on orbit. Several key logic relationships must however be preserved in this process. These relationships are shown in figure B2.

### SSF Integration

The integration of FTS with SSF was continued with an emphasis on the identification of assembly tasks sanctioned for FTS ac-complishment. The process described in ATAC Report #10 was successfully employed to converge on these tasks which are listed in Appendix D. These have all been evaluated for their appropriate location in the assembly sequence, their feasibility, and high rate of return for adding EVA margin to the assembly process. Each of the sanctioned tasks will have and evaluation package established that will collect the required information to completely define its accomplishment by the FTS. The responsibility for the development of the required information is distributed between Work Package 2 at JSC the FTS Project at GSFC and their respective prime contractors. The FTS is treating these tasks as our baseline assignments and expects to execute them on orbit during the assembly of SSF. A snapshot of the kinematic graphic simulation used in the feasibility analysis for the pallet installation task is shown in figure B3.

The concern for excessive EVA requirements to keep SSF maintained in the operational phase was a significant issue in this reporting period. The FTS project supported the intense effort to resolve this concern. A major element in the solution of the EVA shortfall is the application of telerobotic systems such as the FTS. A complete report on this study of external maintenance requirements with recommendations and solutions was presented by JSC.

**Demonstration Test Flight (DTF-2)**

With the identification of specific assembly tasks for FTS the development of a meaningful DTF-2 baseline has begun. Four major requirements that drive the definition of this mission have been identified. The first is to demonstrate the mechanical electrical and operational compatibility with all the expected types of support interfaces on SSF. This includes utility ports at work sites, mobility devices such as the Astronaut Positioning System (APS), umbilicals, and structural load points for the FTS to push against. Secondly, the ability to move and manipulate all the assembly hardware for the sanctioned tasks must be demonstrated. A third requirement is to measure the FTS performance over the entire range of its capabilities. This will be accomplished mainly during the task demonstrations but may include special tests to reach the performance envelope. The final requirement is to provide an operator work station that matches the form fit and function of what is expected for the actual SSF assembly flights. A great number of valuable on orbit crew hours will be spent at this work station and it must be evaluated for efficiency. A set of design requirements that flow down from these four are now being developed. The design requirements and a mission time line that supports them will be reviewed during the second week in October. The formal review of the total system concept to accomplish the DTF-2 mission is scheduled for March of next year.

**Development Test Flight (DTF-1)**

The most significant aspect of this mission is that for over nine months the mission content and configuration have not changed. All of the major decisions have been made and the source and availability of all the components have been verified. The detailed step by step operator procedures are written and the time to execute the procedures has been established. This exercise resulted in a increase to twenty-four total hours for DTF-1 experiment time during the STS mission.

Most of the open Orbiter integration issues have been resolved and documented. The Payload Integration Plan has been signed and all except one of the thirteen annexes have been delivered for review by the STS integration organization. The Interface Control Documents (ICD's) have been marked up and will be published for review in October. The safety process has been completed through phases 0 and 1. During this process it became apparent that a dexterous machine with broad capabilities can, by its very nature, be postulated to fail in untimely and pathological ways to cause safety concerns. Solutions have been developed either in designs or procedures such that no wavers to the safety rules are required at this time. The safety solutions that required design changes were carefully evaluated and considered for their impact on the complete design for DTF-2 and SSFTS before implementation.

A DTF-1 prototype graphic simulator was delivered to JSC for evaluation and comment by the astronaut corps. The simulator consists of a real time graphics generator that presents camera eye view(s) of the work site as if presented by the TV camera(s) on the DTF-1 mission. The manipulator graphic simulation is positioned by a hand controller that is a prototype for the FTS. The functions and display menus of the DTF-1 control and display panel are emulated by a second computer that coordinates the entire simulator. This simulator is expected to provide significant inputs to the design of the work stations for the SSFTS and has already provided a common center for understanding the FTS concept. A photograph of the simulator is shown in figure B4.

**Evolution and Advanced Applications**

A structured functional architecture that enables the FTS concept to evolve, be used for future space missions, and promote spin-offs to other applications continues to be a fundamental tenet of the FTS program.

A near term evolution plan that has been developed provides a path for the research community to contribute to full potential of the first hardware manifestation of the FTS system for SSF.

A commercialization plan has been delivered which shows how the FTS prime contractor will fulfill the requirement to foster commercial applications of FTS technology developments. A highlight of this plan is a commercialization conference to be held at Martin Marietta in December.

The reconfiguration of FTS and utilization of FTS elements to accomplish future space missions is consistently being applied to the agency's planning efforts. This is possible through the use of a structured functional architecture to accomplish mechanical manipulation at remote locations. The various future mission specific configurations are all driven by the same hierarchy of control, the same functional steps, and much of the software that is being developed for FTS. The reconfiguration and growth concept is visualized in figure B5.

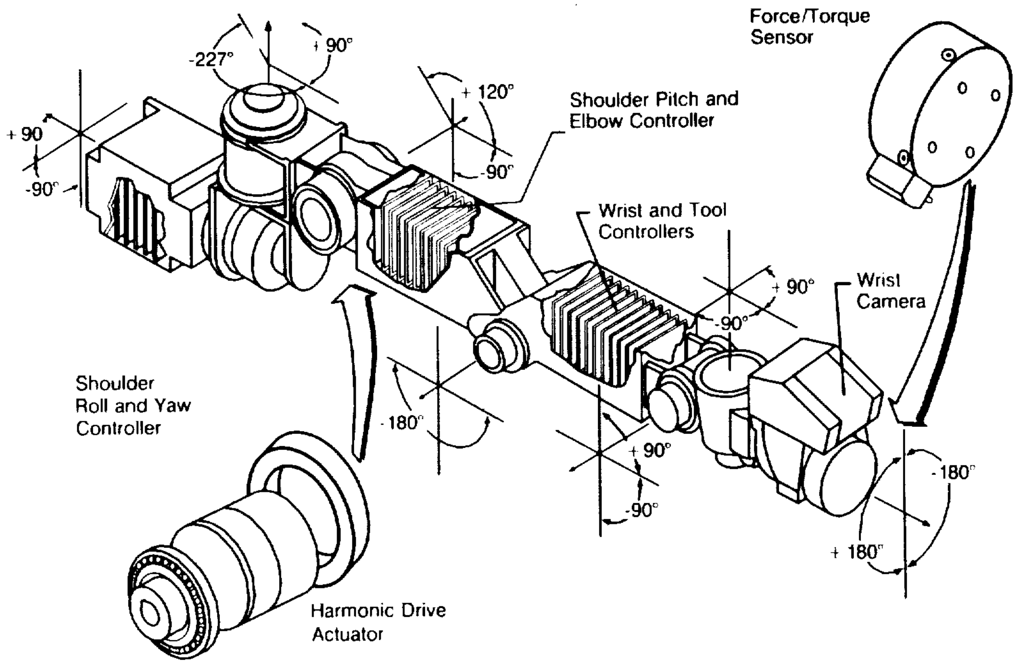


Figure B1. FTS Manipulator.

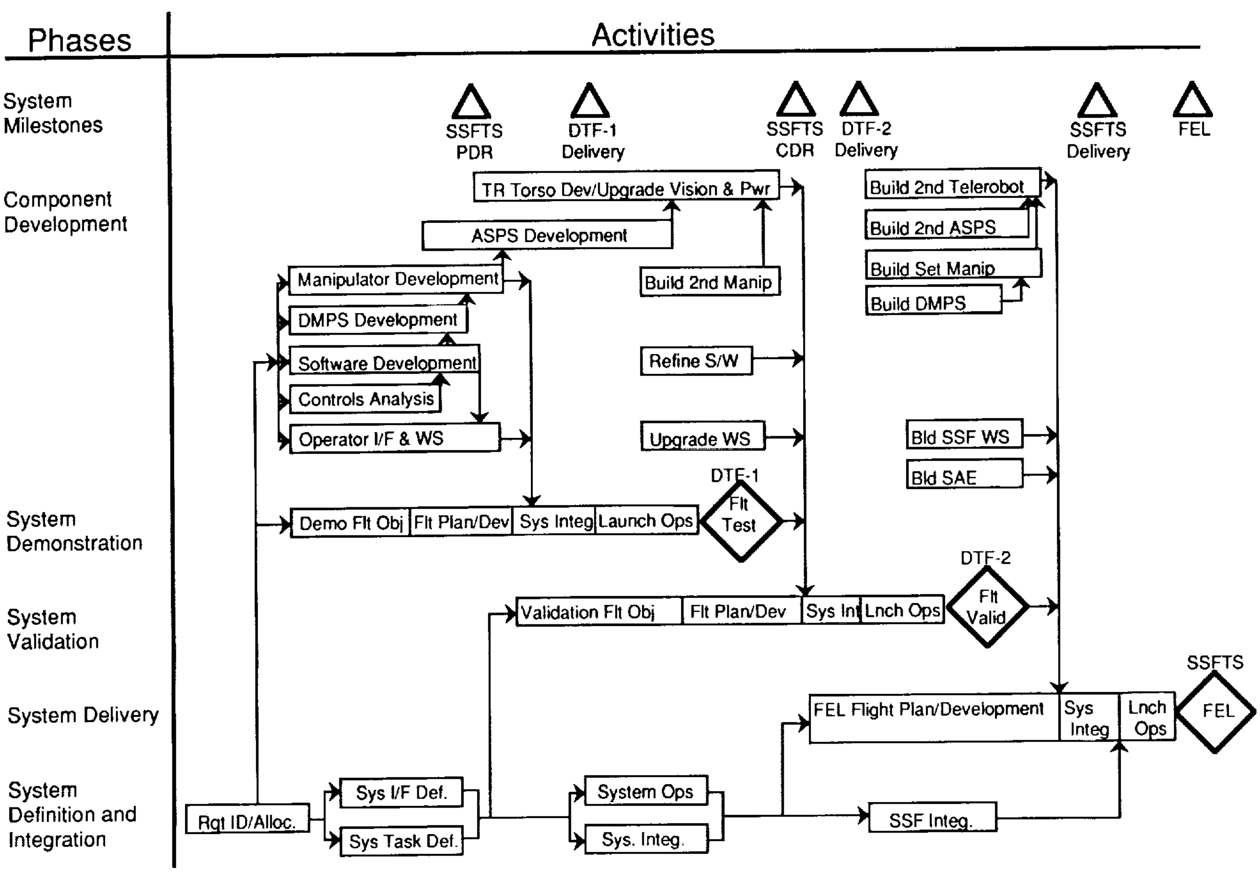


Figure B2. FTS Development Flow.

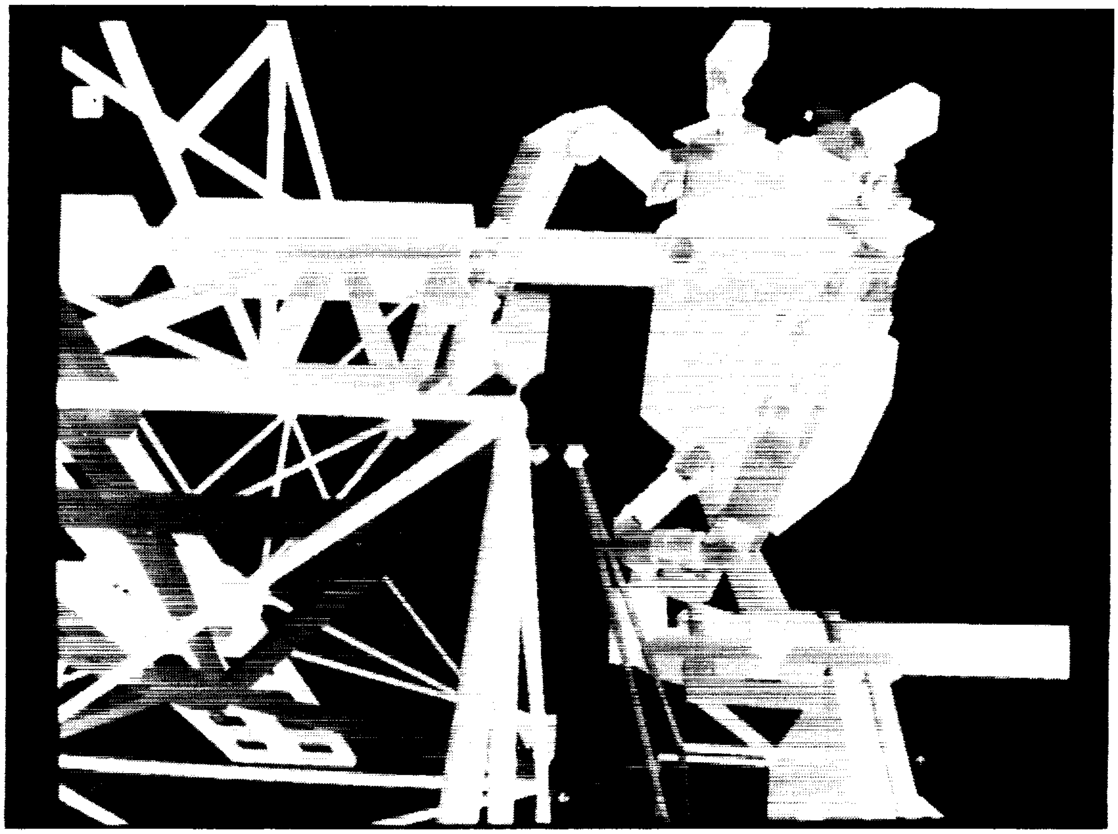

Figure B3. Kinematic Graphic Simulation Feasibility Analysis for Pallet Installation.


Figure B4. FTS Simulator.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

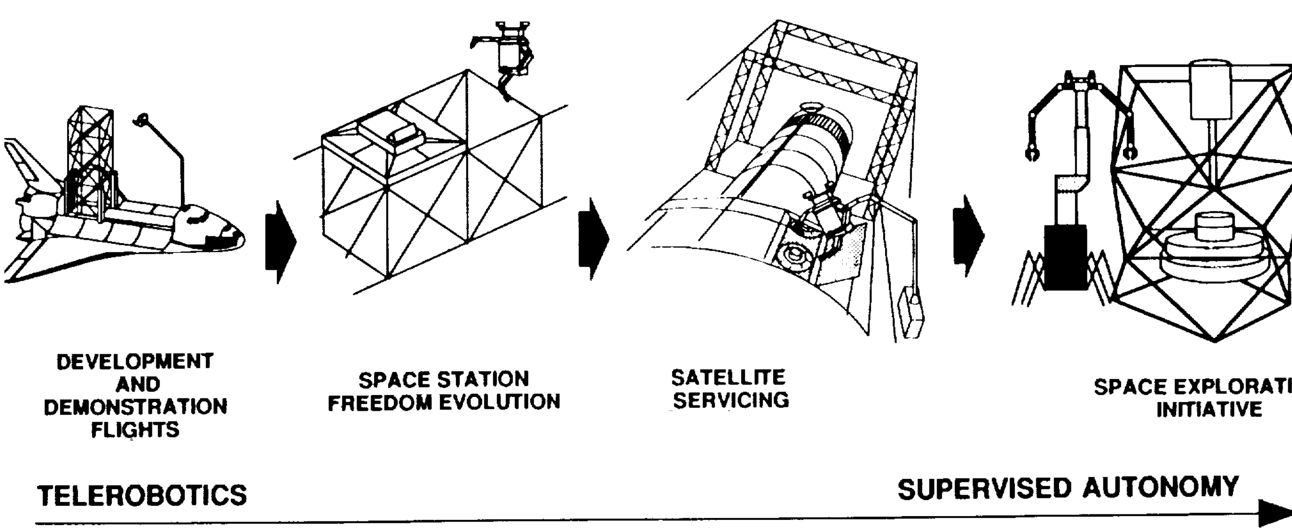


Figure B5. Telerobotic Flight System Reconfiguration and Growth Concept.

# APPENDIX C

## Office of Aeronautics, Exploration and Technology A&R Progress

NASA's research and technology development program in automation and robotics is focused in the Office of Aeronautics, Exploration and Technology (OAET). The OAET program has three major thrusts: Artificial Intelligence, Telerobotics, and Planetary Rovers. The objective of this program is to exploit the potential of artificial intelligence and telerobotics to increase the capability, flexibility, and safety of space and ground operations while decreasing associated costs. The goal of the artificial intelligence element is the use of artificial intelligence technology to effect the reduction of manpower involved in ground control; automation of control of subsystems aboard the Space Station, spacecraft and space transportation vehicles; and elimination of astronaut time spent performing housekeeping functions. The goal of the robotics element is to evolve the capability for remote space operations from the current level of teleoperation (direct human control) of a single crane-like arm, through the telerobotic operation (human task-level control) of multiple intelligent manipulators. The goal of the rover element is to develop and validate technology to enable the automated and piloted exploration of extensive areas of lunar and planetary surfaces. The Automation and Robotics Program is funded by the Information Sciences and Human Factors Division of OAET. Continuing progress for each of these technology development programs is described in this and in all previous ATAC progress reports.

**Artificial Intelligence Program**

The Artificial Intelligence research program is targeted toward the development, integration, and demonstration of the science and technology of AI that will lead to increasing the operational capability, safety, cost effectiveness, and probability of success of NASA missions. Major objectives include reduced mission operations cost by automating labor intensive tasks in ground mission control centers, increased productivity by automating routine onboard housekeeping functions, and increased mission success probability by automating real-time contingency replanning.

The program objectives are being accomplished by a core technology research program, which is closely coupled with several major demonstration projects. Two program elements have made these significant accomplishments recently:

Real Time Diagnostic System Demonstration (RTDS) Project:

The Space Shuttle Mission Control Center (MCC) is one of the most demanding decision environments within NASA. Flight Controllers must access information accurately and rapidly and apply their expertise to make consistent flight-critical decisions. Because of the demands of this environment, Mission Control has been an ideal place to implement knowledge-based systems (KBS) to gain immediate benefit for NASA and to determine the usefulness of KBS for a wide range of NASA ground and flight projects.

NASA is funding research in a number of areas in the field of artificial intelligence (AI) and knowledge-based systems (KBS). NASA is counting on the use of KBS and other automation techniques to reduce the cost of operations in the Space Station era. However, it was recognized by both OAET and the field centers that the benefits of KBS will only occur if the technology developed by OAET is transferred immediately into real NASA mission operations environments for proof-of-concept testing. KBS technology must prove itself in the field, so that it can be confidently included in the next generation of NASA facilities being built to support the Space Station. The RTDS Expert System Project was structured to provide this proof-of-concept testing by placing a KBS in a real NASA mission environment to solve real spacecraft monitoring problems.

In the RTDS Expert System Project, engineering workstations have been programmed with a mix of conventional algorithmic and KBS techniques to monitor Space Shuttle telemetry. Space Shuttle Flight Controllers defined an extensive set of fault detection algorithms and heuristics, which are be used to evaluate telemetry for detecting and diagnosing failures. The Masscomp 5600 engineering workstation, used in the project, executes these algorithms programmed in the "C" language and performs rule-based processing utilizing the CLIPS expert system tool. CLIPS is an expert system building tool, developed at JSC by the Mission Planning and Analysis Division.

One of the major aspects of the RTDS project was to implement a real-time interface between the Space Shuttle telemetry stream and the automated applications running in the engineering workstation. The RTDS project developed this interface by integrating off-the-shelf tools. A commercial off- the-shelf telemetry processor, the Loral Instrumentation ADS-100, acts as a "front-end" for the engineering workstation. The ADS-100 performs conventional telemetry processing tasks, such as frame synchronization, decommutation, and calibration. The ADS-100 passes this data to the engineering workstation over a Direct Memory Access (DMA) channel. The telemetry is structured in the shared memory segment of the workstation, so that a wide range of applications can access the data simultaneously.

The expert system workstation is located in the Flight Control Room, adjacent to the conventional operations consoles. This has allowed the validation of the performance of the expert system by comparing its results to those of the conventional system. This has also increased operator acceptance, because they can compare the results of the two systems.

RTDS began with the development of the INCO system, designed to provide intelligent assistance to the Mission Control Center communications console operator, began development in FY87, and received initial operational testing during STS-26 in September, 1988. Based on the success of the INCO expert system, the RTDS has been expanded to cover other subsystems on the Space Shuttle. Specifically, this has included the installation of automated expert assistants at the Space Shuttle Main Engine, Mechanical, Tire Pressure Automated Monitoring, Remote Manipulating System, Guidance and Navigation Control, Flight Instruments Emulation, Engineering, and Weather console operator stations. RTDS represents the first truly operational use of AI technology in a major NASA mission setting. It was an unqualified success for the OAET CSTI AI program, and is also well known as an innovative application in the Artificial Intelligence R&D community.

During STS-28, all of the data acquisition systems were certified for use in classified missions and installation was completed one week before flight. The Booster expert system performed extremely well and the Booster console operators continue to rely heavily on this system for making ascent system diagnoses. The Mechanical Expert System was used heavily when problems developed in the tire instrumentation. The instrumentation was giving strange pressure indications and it was not clear whether the tire was leaking or not. The Tire Pressure Automated Monitoring system was used heavily to monitor the tires, correcting tire pressures for variation in wheel well temperature and pressure and plotting the data on color graphic screens.

This work showed that simple automation activities can sometime have a big payoff. The Mechanical System utilized a simple real time tool to log and plot tire pressures. The system calibrated the tire pressures and corrected the pressures for temperature variation. It plotted the pressures against a preflight calculated reference. The Mechanical systems officers have been using this to monitor the tires and look for leaks. RTDS has been expanded to utilize rules to monitor these plots to automate the leak detection process. This significantly aided the Mechanical systems flight controllers in monitoring the tires.

While classified operations were in progress on the third floor of the Mission Control Center during STS-28, RTDS was supporting unclassified operations on the second floor as four simulations were conducted during the mission. Also during this mission, early versions of the Remote Manipulator System (RMS) automation were used for the first time.

During launch preparations for STS 29, one of the MPS helium tanks experienced a high pressure anomaly. The Booster console operators had trouble retrieving data from the MCC mainframe complex to resolve the problem in time to resume the countdown at T-3 hours. Instead they used the Rinstant replayS feature of the RTS telemetry acquisition system. This capability allows RTDS to log up to one hour of telemetry on the workstations and replay through all of the applications with features such as view in fast forward, freeze frame, and single frame advance. The Booster console operators used this capability to resolve the problem.

During the STS-29 flight, the RTDS expert systems were used to troubleshoot problems in the Ku-band and payload S-band communications systems and in the main propulsion system. When the expert systems detected the anomalies in real time, the flight controllers used the Rinstant replayS capability built into the systems to replay the anomalies several times. This was used to convince them that in two cases the problem was not serious and in one case that it was.

One area for RTDS expansion was recognized during the flight. Most of the existing RTDS work has focused on detecting configuration errors and fault conditions that can be identified by a discrete set of indicators. During the flight it became apparent that there is also a need for tools which detect failure signatures that have a time history. This was shown dramatically in the fuel cell area when the hydrogen tank anomaly was only observable by looking at a five-minute signature plot.

During STS-30, the RTDS Booster subsystem that monitors the main engines was used during ascent. During prelaunch it was used to troubleshoot a recirculation pump problem that had caused a launch scrub. The system did not have sufficient information to find the root cause of the failure, but the expert system and the Rinstant replayS capability were used extensively by flight controllers and mission managers to look at the problem approximately ten minutes after the scrub occurred. Eugene Kranz, head of mission operations at JSC said "The Booster Expert System paid for itself " in making this data available rapidly. Booster was also used in a training role during the scrub-turnaround. The

Booster console operators used the instant replay mode to replay many of their training simulations and conducted several hours of standalone training using the expert system workstation.

RTDS was utilized as a prime tool in both the front and back rooms of the Mission Control Center during the flight.In fact during the IUS/Magellan deploy, RTDS expert systems were the prime displays providing information to flight controllers on the communications between the orbiter and the payload.

During the STS-34 flight the RTDS Booster, INCO and MMACS expert systems were all fully operational, as well as part of the GNC expert system. While in ascent Auxiliary Power Unit #1 switched to hi-speed mode. The MMACS ascent entry monitor detected the change and showed it graphically.

Spacecraft Health Automated Reasoning Prototype (SHARP):

As a result of the CSTI AI program (RTDS in particular), JSC's manner of doing business in Mission Control for Shuttle has changed. AI is now a standard accepted part of Mission Control, and has been built into the upcoming JSC Mission Control Center for Space Station. The same thing is happening at JPL as a result of the SHARP element of the CSTI AI program.

The goal of SHARP is to develop and demonstrate multi-mission automation technologies for unmanned planetary exploration spacecraft and associated ground data systems operations. The technologies being developed are intended for initial use at the Space Flight Operations Center at JPL , but will be applicable to flight operations at GSFC. The initial focus is on the development of techniques for automated real time monitoring and diagnosis functions for system health and status, and the development of automated assistants for real-time mission operations to aid in the identification of spacecraft science data. The first actual application area is spacecraft "telecommunications link analysis", with a major deliverable being a system that operated in parallel with current Voyager operations ground systems during the encounter with Neptune on August 24, 1989.

The SHARP system helped identify and isolate a problem in Voyager science data. The problem originated when science personnel complained on July 26, 1989 that the correction count was too high. Correction count is a measure of the number of errors in the science data. Voyager Telecom personnel also felt that the count was abnormally high, but could not confirm the problem. Normally, Telecom personnel cannot confirm that the error rate is in fact higher than expected unless they perform a tedious manual process, which is generally inconclusive due to statistical scatter in the data. If there was a problem, no one knew how to quantify it, no one knew what the problem was, or how bad it was.

Telecom personnel used SHARP to construct a scatter plot of real-time data for BER (Bit Error Rate) versus SSNR (Symbol Signal-to-Noise Ratio). This plot identified an anomalous condition which was corrupting the science data at relatively high SSNR's where no errors are expected. The plot also defined the magnitude of the problem with the science data, and provided an ability to correlate errors and DSN stations. This helped isolate the location of the problem by showing that there was no correlation between errors and assigned DSN stations at the times at which the worst data was occurring. This confirmed that the location of the problem was at JPL, not at a station. Further investigation by Telecom personnel traced the problem to the wide band interface to the Data Acquisition and Capture System (DACS). The problem was corrected by replacing the failed unit. After the failed component in the Voyager ground system was replaced, SHARP's display verified nominal performance of the new component.

The SHARP system was instrumental in resolving the science data anomaly. Without the use of SHARP, Telecom personnel would have selected and examined only a few points manually. This would not produce an accurate result due to the statistical scatter in the data. There is no way to determine how long it would have taken to find the problem without SHARP. What is certain is that if Telecom had been using SHARP earlier, it would have avoided a few weeks worth of bad science data from the Voyager spacecraft. This goes directly to the benefits of SHARP for timely detection and resolution of problems, thereby improving the productivity of the operations team and the quality of the total science data return.

There were three anomalies in Telecom during the encounter itself, which SHARP detected simultaneously with the human operators. In each case, no action was required since the anomalies "fixed themselves" after a few minutes. All were on-board problems with no ready explanation (probably just age of the spacecraft), e.g., receiver automatic gain control, and S-band traveling wave tube base temperature. None of the three were serious problems. SHARP frequently detected "conscan errors", i.e., the DSS antennas were drifting and loss of contact with the s/c was possible. In each case, when the magnitude of the problem reached sufficient proportions for it to be manually detected and corrected at the stations (many, many minutes later), the alarm situations went away.

During the encounter itself, the operators constructed several plot displays and spent most of their time (that portion of their time where SHARP was attended to) looking at these plots as opposed to the other displays, which were looked at much less frequently.

SHARP analyzed and provided anomaly detection coverage on 50% more channels than Telecom operators currently have access to. As a result, it provided information that they did not have the training to deal with. This may be a problem for each case where it is attempted to layer an automated system on an existing operations process. Automation has the capability to fundamentally change the operations process itself. In the Voyager case, operators were not able to make use of SHARP's analyses on these channels. Finally, because nobody ever had access to all of this data before, SHARP did not have sufficient knowledge to really integrate its analysis over all the additional channels.

SHARP was extremely sensitive to quick trends, or noise, in the data, and reacted very conservatively in declaring alarm situations. This was not inaccurate behavior (i.e. not false alarms), the alarms were real and indicated by the data. However, the more experienced operators recognized these situations as not requiring any intervention, and in fact, the problems usually went away pretty quickly. SHARP in this case acted as a "naive" operator might, and took every alarm very seriously. While it is desirable to have an automated system react this way, it may be disconcerting to the operators.

Based on SHARP's success during the Voyager encounter, the JPL Office of Telecommunications and Data Acquisition (TDA), which develops and operates the Deep Space Network, has decided that AI and expert systems technology (as exemplified by and including SHARP) should be part of standard development and operations practice in the DSN within ten years. TDA has directed the Information Systems Division to plan and carry-out this technology insertion program, which includes the near-term application of SHARP and its derivatives to monitoring and control functions in the DSN stations world-wide as well as the Network Operations Control Center (NOCC). SHARP will be used by DSN engineers in order to develop requirements for the NOCC upgrade currently in progress. While an approved plan is still to come, this step is a "green light" from TDA management and represents a major, successful impact of SHARP and the Voyager demonstration on the DSN.

Automation has always been a significant part of NASA's missions. Pioneer, Viking, Voyager, Mariner, and Surveyor, for example, were unmanned autonomous spacecraft. The Shuttle, in traveling from Earth to orbit, is an autonomous system with the capability for human intervention only at certain fixed points. Without high degrees of automation, these missions would not have been possible. However, that automation, which can be termed "traditional automation," is preprogrammed, rigid, and inflexible. Future automation, for evolutionary Space Station, for a return to the Moon, and for planetary exploration, will benefit greatly from a new class of automation which is qualitatively different from the traditional. This new class will be able to: adapt to a changing and uncertain environment; decompose high-level commands into ones a machine can execute; develop plans to accomplish tasks, monitor the execution of those plans, and dynamically replan as necessary; and know when to report back to its human supervisor.

In short, the next generation of automation will be far more flexible than the current generation. This added power and flexibility will free scarce human resources from a myriad of tasks that are dangerous, repetitive, or simply non-interesting. It is important to note that the emphasis, however, is not on eliminating or minimizing the need for humans in space exploration, but rather to find the right cooperative mix of human and automated agents for any given set of mission goals.

**Telerobotics Program**

Research and development in sensing and manipulation for future automation is carried on under the Telerobotics element of the CSTI program. The program objectives are being accomplished by a core technology research program, which is coupled with demonstration projects. The technology core includes work in cognition (planning, problem solving, and learning), sensing, and manipulation. Several program elements have made significant accomplishments recently:

Laboratory Telerobotic Manipulator:

The operational requirements and physical characteristics of a space telerobotic system are considerably different from conventional teleoperator systems and from industrial robotic systems, but it must have features of both. A telerobotic system must have a high level of automation, using automated task primitives and sensor feedback to minimize the operator's workload. But it must have the capability to be directly controlled by the operator (or astronaut) in case of failure or unanticipated situation. To operate as a Rmaster/slaveS teleoperator the system should have low inertia and some compliance. But for automatic tasks the system must have high accuracy and minimum backlash.

A number of anticipated space robotics applications will require two hand/arm coordination. The current capability for addressing these problems is based on various master/slave dynamic control strategies, including one approach demonstrated at the Langley Research Center during 1988, featuring a constrained form of dual-arm cooperative control in which the left arm action is commanded in position control mode and the right arm is commanded in a hybrid (force/position) control mode. Another approach to coordinating dual arms is to employ a dual-arm master/slave teleoperator. The operator then controls the applied forces as well as the position of the two arms. Tests conducted by Langley Research Center using a dual arm system at Oak Ridge National Lab compared results of the ACCESS truss assembly task with the same task performed in the Shuttle Bay. The success of this experiment lead to the design and development of the Laboratory Telerobotic Manipulator, which is a dual-arm 7-degree of freedom (DOF) telerobotic system that can be used in either master/slave or telerobotic modes.

The LTM development was completed during 1989 and the system was delivered to Langley Research Center, where it has been incorporated into the Intelligent Systems Research Lab (ISRL). The LTM is used to support telerobotics guidance and control research at LaRC, and technology applicable to the Flight Telerobotic Servicer (FTS).

Future telerobotic manipulators for space applications will have redundant (more than six) degrees-of-freedom. In return for higher weight and increased complexity, these extra degrees-of-freedom provide the guidance controller with an infinite number of manipulator configurations to place the end-effector at any desired position in its workspace. This makes it possible to bypass obstacles, avoid singularities, and move along efficient trajectories. In addition, it provides a fail-operational capability should an axis of motion fail. The LTM has a system of redundant kinematics, which is used to develop guidance laws which effectively use the extra degrees-of-freedom and are still computationally efficient enough to allow real-time control. This will be an important research result from the LTM, as well as the development of techniques forcontrolling a 7-DOF manipulator as a teleoperator.

The LTM is an integrated telerobotic system, developed for laboratory research, but representative of a space system. The first telerobotic system studies done utilizing the LTM compare and evaluate the utility and effectiveness of various input control devices driving it to perform specific tasks. A test matrix has been assembled to include a set of input devices with essentially different configuration characteristics as well as additional ones which cooperating US government and industry research laboratories have requested to be included in the study. These controller options include:
1) replica dual-arm master/slave teleoperation, with and without force reflection, 2) reduced-size dual-arm master with full-size slaves, with and without force reflection; 3) 6-DOF side arm controllers; and 4) the JPL Force Reflecting Hand Controller (FRHC), a 6 DOF displacement and force type hand controller. Both generic tasks such as peg-in-the-hole and realistic in-space tasks such as truss assembly are performed and analyzed. These studies are expected to provide an ordering of controller characteristics which are desirable and undesirable for operating dual-arm redundant manipulator systems.

The differential traction drive system utilized by the LTM offers low backlash and minimal lubrication requirements, but it has not been used in telerobotic applications or in space. Therefore, LaRC, which developed the traction drive concept, has conducted additional analysis and tests in support of LTM, thus advancing this promising technology.

LTM incorporates extensive sensing both for controls and for engineering tests. In addition, it has a hierarchical, distributed microprocessor system similar to the NASREM architecture recom-mended by NIST and GSFC.

Neutral-BuoyancyTelerobotic Simulation:

The objective of this task is to develop and evaluate technologies and procedures for free-flying telerobotic systems through the use of high-fidelity neutral buoyancy simulation. Utilizing three underwater teleoperated vehicles, analysis is conducted in the areas of multi-vehicle interactions, vehicle/human interaction, telerobotic structural assembly, and generalized and special purpose manipulators for use with free-flying vehicles. The task is also intended to develop an understanding of the infrastructure required (workcells, special tooling and jigs, logistics, maintenance, training, development and validation of procedures and hardware and software, etc.) which must be developed for a teleoperator, robot or telerobot to be effective in NASA space and terrestrial applications.

The MIT Space Systems Laboratory has been actively involved in basic research on telerobotic operations in space. This research has focused on the development of the Beam Assembly Teleoperator (BAT), designed for free-flying manipulation tasks, and on the Multimode Proximity Operations Device, a telerobotic equivalent of the Orbital Maneuvering Vehicle. Each of these systems is self-contained and operates in the neutral buoyancy environment for maximum simulation of the weightless space environment. The BAT was originally designed to assemble the same structure used in the Experimental Assembly of Structures in EVA (EASE) flight experiment from the Space Shuttle mission STS 61-B. It has also been used to assemble a space station-type truss structure, both alone and in cooperation with crewmen. As an auxiliary investigation into further cooperative roles for a telerobotic device in the EVA worksite, BAT has been used to demonstrate the simulated rescue and retrieval of an incapacitated EVA test subject.

Near-term applications of BAT include further assemblies of EASE and Space Station structures, both alone and in assisting the EVA crew. Additional work conducted during 1989 included the simulated servicing of the Hubble Space Telescope, with efficiency comparisons of EVA-only, telerobotic-only, and EVA telerobotic cooperation performing the servicing tasks.

The Multimode Proximity Operations Device (MPOD) is designed for research into human and robotic control of free flying vehicles performing proximity operations at the Space Station. As such, MPOD has been used for basic identification of human control algorithms for remotely-piloted vehicles in weightlessness, as well as direct onboard control, utilizing the built-in cockpit in MPOD. The vehicle has also been used to investigate appropriate roles for an Astronaut Support Vehicle, as a direct parallel to the development of diver support vehicles in the undersea community. Research in advanced control systems and crew interfaces for MPOD is ongoing.

Further efforts in the MIT Space Systems Laboratory during 1989 include the deployment of the Apparatus for Space Telerobotic Operations (ASTRO), a second-generation telerobotic vehicle with advanced capabilities; research, using computer scene generation and motion carriage simulation, into the underlying fundamentals of space simulation methodologies; and advanced control systems development, including the application of neural network technologies as a learning control system for vehicles and manipulators.

Human Man-Machine Interface Iconic Interface:

The primary effort within this task is to develop a telerobotics control-communications interface to integrate the functions of a supervising human operator and remote robot system. Initial efforts have focussed on design of manual control interfaces to remote manipulators and graphic displays for workspace and task presentation. An electromechanical architecture for force-reflecting hand control has been developed; the hand controller has been integrated with the teleoperation control architecture. This teleoperation brassboard system has been developed and expanded for dual-arm, redundant capability, and applied to experimentation on generic and mission-specific task boards.

Work in graphic displays and task presentation includes research on graphics-based task animation and visual (TV-based) multi-camera displays. The graphics developments include design for several applications: 1) modeling and high-fidelity off-line simulation of tasks via operator-driven animation of a virtual robot; 2) on-line predictive simulation of task behavior under time delay; 3) displays of non-visual sensor/task information to aid operator cognition and improve operator perception of hard-to-see places; and 4) providing Ron-the-screenS cues to enhance depth and orientation perception. The work in visual RTVS display technology is concerned with human factors requirements, display design, and operator training and display accommodation. A multi-camera, computer controlled, dual-arm teleoperation facility has been developed and incorporates resources from both the above teleoperation control brassboard, graphics display, and multi-camera TV display developments. The effect of display configurations, resolution, stereo separation, graphic superpositions and others are being evaluated to minimize operator eye-head movement and improve operator depth perception.

Significant accomplishments during 1989 for this task include the development of a user-customizable iconic interface for telerobot configuration control. This system provides a software-based graphics RswitchboardS for telerobot system control, which reduces the need for advanced control station hardware, and incorporates a new communications protocol between the iconic interface and the brassboard which enables simplified operator interaction with the control system.

**Planetary Rover Program**

Through the Pathfinder program, OAET is developing a variety of high- leverage technologies that will support a wide range of potential future NASA missions. One of those missions is the Planetary Rover Program. The overall goal of the program is to develop and validate technology to enable the automated and piloted exploration of extensive areas of lunar and planetary surfaces. The key technologies identified by the program are navigation, mobility, power, operations autonomy, communi-cations, manipulation, thermal control, computation and advanced architectures. these technologies are being addressed within NASA and at universities, notably at Carnegie-Mellon University. There are related efforts at Rensselaer Polytechnic Institute and the California Institute of Technology.

CMU Ambler assembly completed:

The objective of this activity is to prototype an autonomous mobile robot for planetary exploration which includes mobility characteristics superseding those possible with wheeled designs. Utilizing an innovative approach, the Ambler incorporates six orthogonal legs arranged in two stacks to traverse extremely rugged terrain while maximizing payload potential and minimizing power consumption. This task is complimentary to the wheeled vehicle research being conducted by the rover program tasks at JPL. The Ambler includes development of perception, planning and real-time control in an integrated system.

The assembly of the Ambler hardware was completed in 1989, and the vehicle took it's first steps during the Planetary Rover Intercenter Working Group meeting on December 13, 1989. At that time, all controls and motion computation was performed with off-board computers which were connected to the AMBLER via an umbilical, and the vehicle was walking "blind" (the perception sensors were not yet installed). Formal roll-out of the vehicle will be conducted at the end of March, 1990.

By roll-out, the vehicle will be capable of receiving a global direction goal from a human operator, sensing it's environment, determining a local traverse path to obtain the goal, and walking along the determined path while recognizing and avoiding obstacles. Future work will include moving all computation and perception systems on-board and removing the umbilical, as well as the development of control algorithms and software for general-case gait control, advanced perception system develop-ment, terrain analysis for footfall placement, and integration of sample acquisition and preservation testbeds.

The legged design approach offers several advantages over conventional wheeled designs, including: 1) climbing slopes while maintaining level body motion, which enables simplified sensor and navigation system design; 2) traverse of extremely rugged terrain, including non-contiguous paths, which could not be traversed by a wheeled rover; 3) low sensitivity to soil slip during walking, as most forces between the vehicle and the soil are vertically oriented (i.e. the only side forces are when the body is pulled forward); and 4) increased sampling capabilities (i.e. mount sampler on leg, which can then be dropped into crevasse or elevated up to ten feet, and moved laterally up to ten feet).

Each leg of the AMBLER has three joints: a 360-degree rotation joint at the "hip", a prismatic "thigh" which allows 1.5 meter horizontal extension of the leg, and a prismatic "knee" joint which allows full translation of the 10-foot tall leg. The variable geometry of the vehicle allows the body to be raised to a full height of 6 meters, and the vehicle CG to be configured appropriately for the current terrain and walking gait.

Conclusions

During the past year the Code R A&R program has continued to be successful in developing new technology and in transferring that technology into operational use at the NASA centers. The RTDS and SHARP examples at JSC and at JPL in mission control for manned and unmanned missions, which are described above are prime examples. The Space Station has taken the RTDS technology generated by the Code R program and baselined it into the planned Mission Control Center for Station. The INCO (Integrated Communications Officer) workstation which the first of the successful implimentations of Artificial Intelligence in the RTDS system in the Shuttle Mission Control Center, was selected by the American Association of Artificial Intelligence (AAAI) as one of the 25 most innovative applications of artificial intelligence during the past year.

In the area of telerobotics, most of the work is aimed at improving and evolving remote manipulation in space operations. The LTM at LaRC, which is described above, is now being ready for emperical research. It's first use will be as part of a study on the capabilities and limiations of various types of hand controllers. Now that the FTS line item for evolutionary development has been deleted, the Code R telerobotics program is the only place where R&D is being done to develop the technology for the evolution of the FTS. The Rover work at JPL and at CMU is being fed into the NASA planning studies for the Space Exploration Intitiative. This provides an empirical background for the scenario developers to base their projections on. Also the fact that both wheeled and legged rovers are being developed simultaneously is allowing both groups of researchers to better understand their relative advantages and limitations.

# APPENDIX D

## FTS Assembly Tasks

| Category | Sanctioned by Assembly Planning Review (APR) | Reviewed by APR but Not Sanctioned |
|---|---|---|
| Set up Assembly Work Platform (AWP) and Mobile Tranporter (MP) for Build | Deploy MT<br>Attach canisters to AWP<br>Install SAE<br>Configure AWP worksite<br>Attach utility spool<br>Camera | |
| Attach smal items to ITA | None | Utility trays<br>CETA rails<br>Dampers<br>Utility ports<br>Lights |
| Pallet Installations | Port side pallets | Solar array beta joints<br>Alpha Joint<br>Fold out IEA support struts<br>Propulsion module platform<br>TCS pallet<br>C&T pallet<br>GN&C pallet |
| TCS Installation | Radiator panels | Subcooler/condenser/boom attachment to TCS pallet |
| Payload Bay Ops | Release canisters<br>Configure PLB FSE<br>Stow FSE in PLB<br>Release MTS<br>Payload Bay Cleanup | Attach/release grapple fixture to beta joint, IEA, SRMS<br>Retrieve tools & MFR<br>Release utility spool |
| Deployments | MTS | S Band antenna<br>Attach/deploy Ku Band antenna |
| Utility Connections Electrical & Fluid | Utility (power, data, fluid) connection of pallet to be named later | Install umbilicals to beta joints, IEA<br>Make utility tray connections<br>Make utility tray to utility port connections<br>Connect pallets to utility ports |
| Inspections | Numerous visual inspections | Other types of inspections |
| Truss Type Connections | None | Attach Alpha Joint support struts<br>Attach Utility Spool struts to AWP |

# APPENDIX E

## Fisher-Price Study Robotics Recommendations

**Robotics Recommendations**

1. Rely on SSF robots to accomplish a majority of the external maintenance workload by Assembly Complete.
2. Define, adopt, and enforce program-wide ORU/robot compatible design standards.
3. Define, adopt, and enforce program-wide ORU worksite accessbility standards.
4. Implement an onboard collision avoidance capability in the Mobile Service System.
5. Implement a ground-based SSF geometry electronic database ("world model") for uplink initialization of onboard local robot workspace geometries and collision-avoidance algorithms.
6. Implement ground-based remote control of SSF robots for monitoring and control of all robot functions.
7. Implement a vigorous verification program for all robotic functions with special emphasis on all robotic functions.
8. Implement a "robot repair of robots" policy to ensure that maximum utility of robots is achieved with a minimum of EVA expenditure.
9. Integrate the use of all SSF robots (the US Mobile Transporter, the US Flight Telerobotic Servicer, the Canadian Mobile Servicing Center and Special Purpose Dexterous Manipulator, and the Japanese Large Arm and Small Fine Arm) both as maintenance agents and as receivers of maintenance.
10. Begin analyses of SSF robots (as a group) performing multiple serial and multiple concurent tasks for the purpose of optimizing robot and crew efficiencies.
11. Begin analyses of the use of the teaming SSF individual robots and sets or robots with EVA astronauts for the performance of maintenance tasks to optimize the efficiencies of the combined set of human and machine maintenance agents.
12. Evaluate the benefits of the use of ground-controlled robots early in the assembly time period in between Shuttle flights to accomplish the maintenance tasks required.
13. Perform all inspections of exterior surfaces through an optimized combination of truss-mounted closed circuit television cameras, the SSF robot cameras, and the use of the SSF robots to position any additional inspection sensors identified in the future.
14. Design all EVA equipment to be robot-compatible ORUs to facilitate robotic assistance prior to, during to, and after periods of EVA.

**Robot- and EVA-Compatible ORU Recommendations**

1. Form an External Maintenance Task Force to develop, test and implement ORU design standards.
2. Provide EVA/EVR compatible tools and interfaces as Government Furnished Equipment (GFE) to each work package and international partner.
3. Refine the Box Type ORU Strawman Standards and develop standards for other types of ORU's.
4. Continue to develop and test ORU mock-ups as part of the process of establishing ORU design standards.
5. Determine the cost and benefits of different types of standardization.
6. Develop external maintenance procedures which minimize and optimize the roll of the on-orbit crew through the use of ground control and automated subroutines.
7. Develop a common EVA/EVR ORU exchange tool.
8. Investigate common ORU interfaces across the entire use cycle from ground storage to Space Station application and return.

# APPENDIX F

## 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 |
| CETA | Crew and Equipment Translation Aid |
| Code E | NASA HQ Code for the Office of Space Science and Applications |
| Code M | NASA HQ Code for the Office of Space Flight |
| Code R | NASA HQ Code for the Office of Aeronautics, Exploration and Technology |
| Code MT | NASA HQ Code for the Office of Space Flight, Office of Space Station Engineering |
| CR | Change Request |
| 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 |
| EVA | Extravehicular Activity |
| FDIR | Fault Detection, Isolation, and Recovery |
| FSE | Flight Support Equipment |
| FTS | Flight Telerobotic Servicer |
| GN&C | Guidance, Navigation, and Control |
| GSFC | Goddard Space Flight Center |
| 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 |
| MSFC | Marshall Space Flight Center |
| MUT | Mission Utilization Team |
| NASA | National Aeronautics and Space Administration |
| OAET | Office of Aeronautics, Exploration and Technology |
| OMS | Operations Management System |
| PDR | Preliminary Design Review |
| PMAD | Power Management and Distribution |
| PMC | Permanently Manned Capability |
| POP | Program Operating Plan |
| RSIS | Robotics Systems Integration Standards |
| RTDS | Real-Time Data System |
| SAE | Storage Accommodation Equipment |
| SDTM | Station Design Tradeoff Model |
| SSE | Software Support Environment |
| SSF | Space Station Freedom |
| SSFP | Space Station Freedom Program |
| TCS | Thermal Control System |
| WETF | Weightless Environmental Test Facility |
| WP | Work Package |

# APPENDIX G

## NASA Advanced Technology Advisory Committee

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# Report Documentation Page

| | | |
|---|---|---|
| 1. Report No. NASA TM-102872 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle Advancing Automation and Robotics Technology for the Space Station Freedom and for the U.S. Economy—Progress Report 11 | | 5. Report Date November 1990 |
| | | 6. Performing Organization Code |
| 7. Author(s) Advanced Technology Advisory Committee (ATAC) [ATAC Progress Report 11] Henry Lum, Jr., Chairman | | 8. Performing Organization Report No. A-90308 |
| | | 10. Work Unit No. 476-1401 |
| 9. Performing Organization Name and Address Advanced Technology Advisory Committee Chairman, Henry Lum, Jr./FI NASA ARC, Moffett Field, CA 94035-5000 | | 11. Contract or Grant No. |
| | | 13. Type of Report and Period Covered Technical Memorandum |
| 12. Sponsoring Agency Name and Address NASA Headquarters ATTN: Earle Huckins/MT Washington, DC 20546-0001 | | 14. Sponsoring Agency Code |

15. Supplementary Notes

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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 eleventh in a series of progress updates and covers the period February 14, 1990, through August 23, 1990. 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 10, the Flight Telerobotic Servicer, and the Advanced Development Program. Assessments are presented for these and other areas as they apply to the advancement of automation and robotics technology for the Space Station Freedom.

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|---|---|---|---|
| 17. Key Words (Suggested by Author(s)) Robotics, Space Station, Automation, Expert systems, Artificial intelligence, Freedom | | 18. Distribution Statement Unclassified-Unlimited<br>Subject Category - 59 | |
| 19. Security Classif. (of this report) Unclassified | 20. Security Classif. (of this page) Unclassified | 21. No. of Pages 50 | 22. Price A03 |

NASA FORM 1626 OCT 86

For sale by the National Technical Information Service, Springfield, Virginia 22161