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

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

Progress Report 7 — April 1988 Through September 1988

Advanced Technology Advisory Committee
National Aeronautics and Space Administration

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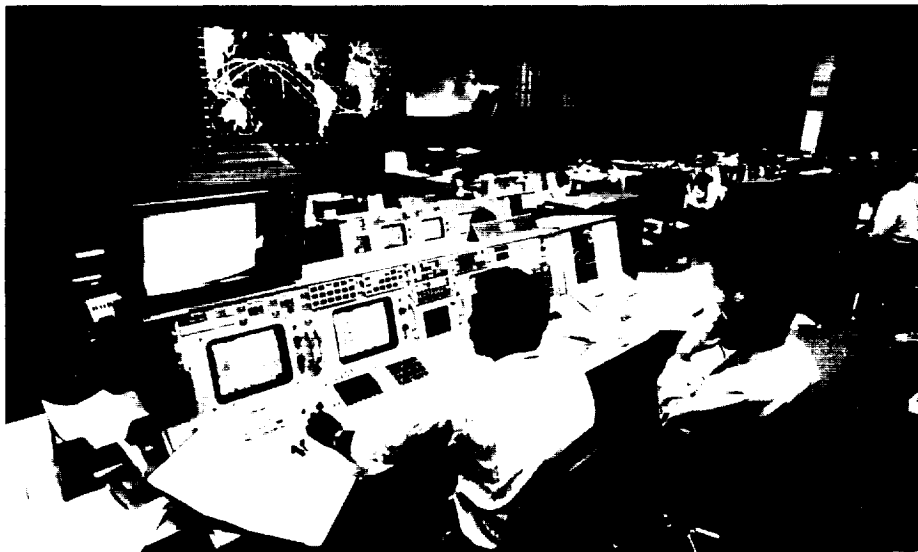
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Advanced automation technology is being evaluated for use as a key element in the Space Shuttle Mission Control Center (MCC). This technology will be evaluated, in parallel with previous technology, during the Space Shuttle mission STS-26, planned for launch on September 29, 1988. The MCC functions for which this technology is being evaluated are command and control of Space Shuttle communications, instrumentation, and data systems.

In the MCC, the Flight Controller charged with command and control of Space Shuttle communications, instrumentation, and data systems is the Integrated Communications Officer (INCO), shown in the top photograph. The INCO is responsible for real-time monitoriung, detecting faults, and performing reconfigurations in systems such as the space-to-ground S-band communications system, the Shuttle television and audio systems, the Shuttle data recorders, the Shuttle payload communications system, and the command and telemetry systems.

New technologies include a commercial off-the-shelf telemetry processor, a real-time operating system, a rule-based inference engine, high resolution full-color graphics, and networking. The system is being used in the MCC in parallel with conventional mission monitoring tools to evaluate the effectiveness of expert system technology in a real space mission operations environment. Side-by-side location of the conventional system and the expert system allows comparison of techniques and capabilities. The middle photograph shows the conventional system in the foreground and the expert system in the background.
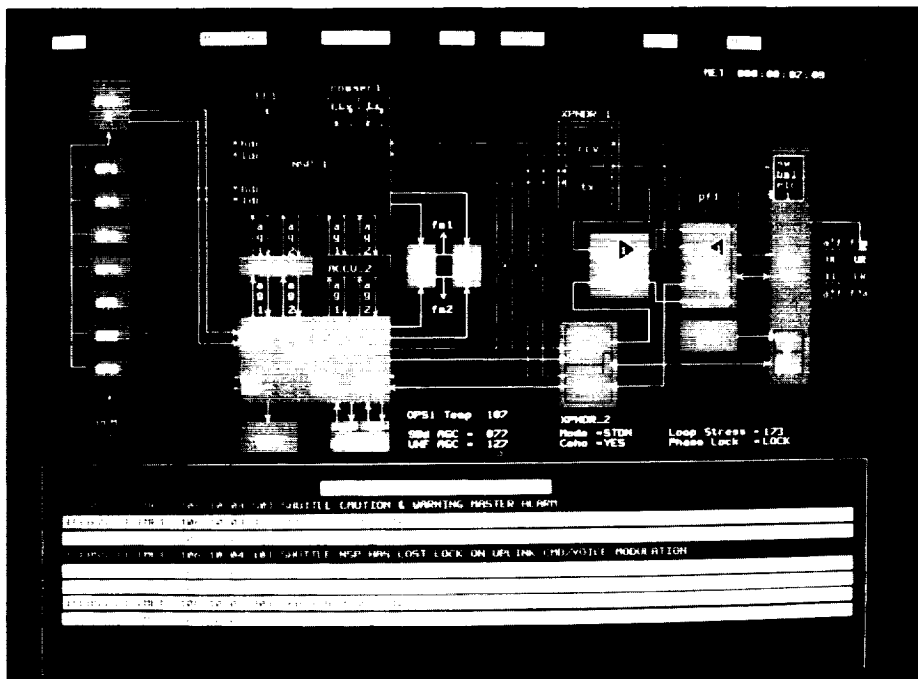
The INCO Expert System is a real-time expert system which monitors Space Shuttle telemetry and advises Flight Controllers on fault detection. The system was developed by NASA flight operations personnel to incorporate their knowledge of Space Shuttle communications performance. The system draws heavily on NASA artificial intelligence research and is based on the C Language Integrated Production System (CLIPS) expert system shell, developed at the Johnson Space Center.

The system uses color graphic schematic displays (bottom photograph) which are animated by Shuttle telemetry to identify the location of faults for the Flight Controller. Faults are annunciated by text messages that are color coded for severity. This approach focuses operator attention on critical areas better than the conventional monochrome displays. The rule-based expert system techniques allow the system to perform a true system-level evaluation.

Introduction

In response to the mandate of Congress, NASA established, in 1984, the Advanced Technology Advisory Committee (ATAC) to prepare a report identifying specific Space Station Freedom systems which advance automation and robotics (A & R) technologies. In April, 1985, as required by Public Law 98-371, ATAC reported to Congress the results of its studies (ref. 1). The initial ATAC report proposed **goals** for automation and robotics applications for the **initial** and **evolutionary** Space Station. Additionally, ATAC provided **recommendations** to facilitate the implementation of automation and robotics in the Space Station Program.

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:

> **Independently review the conduct of the Space Station program and assess the integration of A & R technology. Based on assessments, develop recommendations, review the recommendations with NASA management, and discuss their implementation with consideration for safety, reliability, and cost effectiveness. Report assessments and recommendations twice annually to Congress.**

The Space Station Program will develop a baseline station configuration which can be readily 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.

ATAC has continued to monitor and to report semiannually NASA's progress in automation and robotics for the Space Station. To a lesser extent, ATAC has reported other NASA program-sponsored activities in A & R related to the Space Station and transfer to the U.S. economy. The reports are documented in ATAC Progress Reports 1 through 6 (refs. 2 - 7). Progress Reports 1 through 5 covered the definition and preliminary design phase (phase B) of the Space Station Program. Progress Report 6 covered a period of time during the startup of the design and development phase (phase C/D) of the Space Station Program.

Phase C/D leads to a permanently inhabited station, to be operational in the mid-1990's.

This report is the seventh in the series of progress updates and covers the period of April 1, 1988, through September 30, 1988. **However, progress and program changes occurring after August 15, 1988, are not reflected in this document.**

A new approach has been adopted for this ATAC Progress Report. All of the committee's assessments have been included in only one section, "ATAC ASSESSMENTS."

ATAC also solicited and was provided with summaries of progress in A & R from the NASA Office of Space Station (OSS), the Office of Aeronautics and Space Technology (OAST), and the Office of Space Flight (OSF). These are included as Appendixes A through D (OSS), Appendix E (OAST) and Appendix F (OSF). In addition, these offices supported an ATAC Review which was held on July 18-20, 1988, for purposes of additional dialogue and understanding of the progress. This ATAC Progress Report is the first one which has included a specific section of the A & R activities of the Office of Space Flight.

New ATAC members are David C. Moja, Kennedy Space Center, and Gabriel R. Wallace, Marshall Space Flight Center.

ATAC Assessment

The ATAC assessments for this reporting period are based upon the committee members' appraisals of progress in advanced automation and robotics for Space Station Freedom, as described in oral presentations and written summaries to ATAC by various NASA organizations. These summaries are included as appendixes to this report.

Progress With Respect to the Original ATAC Recommendations

Progress with respect to ATAC's original recommendations, first reported in 1985 (ref. 1), and previously adopted as Space Station policy, has been summarized by the Office of Space Station and is included as Appendix A. ATAC concludes that NASA has completed or made significant progress on all of the recommendations, even those recommended for an augmented A & R program, which was never budgeted by Congress. ATAC applauds NASA for this progress, made during very difficult times of changing Space Station configurations and management arrangements, and of uncertain funding in the Space Station Program.

A new Space Station policy has been adopted to replace the previous set of statements. The policy of the Office of Space Station (OSS) is to fully utilize A & R technologies in the design and development of the baseline Space Station where they are found to: (1) be technically appropriate within the context of overall system design, (2) have favorable cost-to-benefit considerations, and (3) have sufficiently mature enabling technologies.

To better provide for the growth and evolution of the Space Station, more basic and applied research is needed. The Space Station will also be a proving ground for many of these A & R technologies as they mature. Level I of the Space Station Program and the Office of Aeronautics and Space Technology (OAST), in addition to other NASA organizations, have ongoing efforts, but not of the level necessary to aggressively advance NASA's position in A & R technology.

Technology transfer from NASA to U.S. industries is a related concern of ATAC. Although a program with some provisions for technology transfer exists within NASA's Office of Commercial Programs, the technology transfer mechanisms need to be strengthened and expanded to include other opportunities, such as the use of proposed regional manufacturing centers, to be established under the auspices of the National Industrial Standards Institute (formerly the National Bureau of Standards). NASA's systems engineering and integration activities, required to incorporate each expert system, each vision system, each robot arm, etc. into the Space Station, will develop solutions to technical issues which would otherwise likely deter many potential industry users.

Overall Plan for Applying A & R to the Space Station and for Advancing A & R Technology

Both Space Station Level I and Level II expect their A & R implementaion plan documentation to be ready for review by October 1988. NASA has made progress in this area, as alluded to in the discussion above and described in more detail in Appendix B. Briefly, the progress includes the following:

- A Level I (Code ST) funded Advanced Automation Study (ref. 8) was conducted, led by Dr. Peter Friedland of Ames Research Center and comprised of leading members of the artificial intelligence (AI) industrial community. This study identified promising applications of AI that could be incorporated during the development phase of the Space Station using existing technology, and it determined hooks and scars required to accommodate the increased future use of advanced automation in both on-orbit and ground systems. The Study team will be working directly with Level II and with the Level III system and subsystem managers in the upcoming months to refine the requirements and specifications necessary to incorporate selected advanced automation applications and the requisite hooks and scars into the Space Station Program documentation, and thus influence the efforts of the work package contractors.
- A tutorial on artificial intelligence technology and Space Station advanced automation efforts was presented to the senior management of the Office

of Space Station and the Office of Aeronautics and Space Technology. The presentations were structured to provide an increased understanding of the current status of AI and its relevance to Space Station applications. The presentations generated considerable interest in knowledge-based systems (KBS) technology and provided numerous examples of KBS applications that are relevant to the Space Station Program.

- The Program Requirements Document (ref. 9), which contains a section on A & R characteristics of the Space Station, was baselined.
- Plans were made for establishing a Level I A & R Review Group to provide implementation advice for the Space Station Advanced Development Program.
- A Level II A & R Steering Group was established to give advice on A & R issues and progress.
- Change requests were prepared for potential inclusion in the Program Definition and Requirements Document (ref. 10) to increase the A & R content of the Space Station development program.
- The FY 89 Space Station Advanced Development Program is focused on A & R. The principal emphasis is on knowledge-based systems and on hooks and scars, including the computer environment required to support their implementation.
- Transfer of A & R technology from OAST programs to Space Station programs has continued. During this report period, interaction between the OAST research teams at JPL and the Flight Telerobotic Servicer (FTS) project team at GSFC resulted in recommendations in such areas as telerobotic architecture, teleoperation data rate requirements, and testbed requirements. Transfer of two hand controllers to the FTS project will be completed as soon as they are modified to be compatible with the FTS architecture. Other hardware and software items (including sensors, vision algorithms, and robot control language) have been transferred for evaluation and will also require modification, as planned, before they can be operated as a system.

The Advanced Automation Study has had a significant beneficial influence on the activities within OSS and OAST. This study has helped narrow the gap between expectations and reality for systems autonomy. ATAC sees a convergence of understanding about current state-of-the-art and future directions which appears focused and cohesive. Coordination between OAST and OSS is occurring in this area, as well as coordination with the Office of Space Flight (OSF).

The Office of Space Station is to be commended for making A & R the exclusive focus of the Space Station Advanced Development Program for FY 89. This program is correctly addressing three critical issues of advanced development of A & R:

- Advanced development of the more mature and beneficial A & R applications for potential inclusion in the baseline Space Station.
- Identification and specification of hooks and scars that will enable the baseline Space Station to capitalize on future A & R advances during the growth and evolution of the Space Station.
- Advanced development aimed at maturing and transitioning A & R technology for increased application of A & R during the growth and evolution of the Space Station.

It is appropriate that the Space Station Advanced Development Program resources are more weighted toward automation than toward robotics. This weighting takes into consideration the already existing FTS initiative and is consistent with the long-standing view of ATAC that automation will be of greater long-term benefit. Level I is also working with the Office of Exploration (OE) to define requirements for future missions. This work is planned to continue.

Definition and Integration of A & R in the Baseline and Evolutionary Space Station

Level II plans to pursue development of A & R technology by funding the prototyping of technologies which could be developed enough to be included in the baseline Space Station. The candidates for such prototyping are to be recommended by three Level II A & R-related working groups. The actual development activities could be performed by the Level III offices, the NASA Field Centers, and the work package contractors. ATAC anticipates that these activities will be closely coordinated with those of the Level I Advanced Development Program, particularly those dealing with telerobotics, which require greater coordination across the program offices at NASA Headquarters.

ATAC cannot, at this point of the Space Station Program, make rigorous assessments of the inclusion of specific instances of advanced automation or robotics. However, we can make the following related assessments:

(1) Levels I and II are becoming well organized and staffed and are making significant progress in the process of identification, evaluation, and selection of A & R candidates.
(2) The Space Station Program is beginning to identify specific candidates for both advanced automation and robotics.

Progress on the FTS for the Space Station

The Space Station Program FTS Requirements Document for phase C/D has been updated. The FTS phase C/D request for proposals (RFP) will be released after a cost review has been conducted. In recognition of the wide interest in the FTS, the draft of the technical portion of the RFP was released to interested parties in the aerospace industry, as well as to NASA Centers, for their review and comments. The FTS draft describes rather clearly what the FTS will do. It appears quite reasonable and not outside of what may, in fact, be achieved. Currently, the FTS project plans to conduct a 1991 and a 1993 flight test. The FTS phase B contractors are currently studying various options for the 1991 flight test, so that little definitive information about that flight test is available for ATAC to assess.

The FTS Project Office at Goddard Space Flight Center finished, in July, an in-house phase B FTS study, in which it developed its reference version of the FTS, called the "Tinman". The results of this study are being used as a basis for the RFP requirements and as a reference to evaluate the phase C/D proposals.

ATAC encourages the FTS project to continue its efforts. However, ATAC questioned whether or not the FTS project was being adequately coordinated with the other robotic elements of the Space Station and with other space telerobotic developmental projects at NASA. NASA recognizes the need for coordination across the various NASA organizations dealing with space teleoperations and is in the process of addressing this issue at a high policy level, with a Steering Group being formed between OSS, OSF, OAST, and OSSA for this purpose. Pending completion of final negotiations with the International Partners of Space Station, ATAC stresses the importance of addressing issues of compatibility among all Space Station robotic elements during the development stage of the Space Station.

Research and Technology Base Building to Support A & R Applications

OAST has the major responsibility in this area and has described the status of its program in Appendix E. The OAST program is divided into two areas: Telerobotics and Systems Autonomy, both with core technology and integration testbed activities. Also, both areas are planning application demonstrations.

ATAC notes that OAST has recently made considerable progress in its ability to highlight its technology research achievements in A & R to more rapidly allow advanced automation development by other NASA organizations for specific applications. This is especially true in Systems

Autonomy, where OAST has established a solid organizational infrastructure with highly visible, scheduled applications-oriented demonstrations.

OAST and OSF have jointly funded the development of an entirely new system to assist the communications officer at the Mission Control Center (MCC) at Johnson Space Center (JSC). This system includes an expert system which acts as an integrated communications officer, monitoring telemetry data and assisting the communications officer in making decisions. The system also includes new display hardware and other technologies. The system is being tested during Space Shuttle mission STS-26 and, if successful, will be adopted for operational use. Additional funding by the Space Station Advanced Development Program will support the development of additional MCC console positions to develop a better understanding of the hardware and software architectural requirements necessary to support systems of this type in the Space Station control center.

The development test flights (DTF) of the FTS will provide a comparable opportunity for the same type of system integration and demonstration of operations for telerobotics. OAST recognizes the need for more research in the "use" of telerobotics, and important steps are being taken to accelerate the progress in telerobotics applications. Since the first laboratory integration demonstration, described in ATAC Progress Report 6, technical information derived from the telerobotics testbed and core elements has been transferred to the FTS project and its phase B industrial contractors. In addition to the ongoing transfer to space-based applications through the FTS, three ground-based applications have been identified for initiation in fiscal year 1989. These are: (1) the automated connect/disconnect of Space Shuttle external GH_2 vent umbilicals, being studied at KSC, (2) the Space Shuttle RMS advanced force/torque control study being conducted at JSC, and (3) the study of application of telerobotics leading to pre-launch inspection of the Space Shuttle payload bay at KSC.

The Associate Administrators of OSS and OAST were briefed on the Civil Space Technology Initiative (CSTI) A & R program and the Space Station A & R program. In addition to covering the programmatic and technical aspects of both programs, the briefings emphasized ongoing cooperation between OAST and OSS and the transfer of OAST-sponsored technology to the Space Station. It was recognized that OAST's investment in A & R provided the Space Station with an excellent set of opportunities for A & R applications.

In the discussions of the need for improved coordination in telerobotics, ATAC concluded that part of this need could be attributed to the existence of conflicting technology definitions. NASA needs to decide upon

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common definitions among all its organizations for the concepts of robotics, telerobotics, advanced automation, autonomy, expert systems, artificial intelligence, and knowledge-based systems. Some of these terms mean different things to different people, which is the cause of some of the miscommunication and lack of coordination between the various organizations.

Office of Space Flight Activities in A & R Related to the Space Station

A description of A & R work which is being conducted by the Office of Space Flight is in Appendix F. This office has developmental programs which include the following:

- Operations automation
- Shuttle Remote Manipulator System (RMS) enhancements
- The EVA Retriever (a free-flying robot for retrieval of objects in the Space Station EVA environment)
- The Satellite Servicing System and the Tumbling Satellite Retrieval Kit

ATAC encourages the coordination of these programs with similar ones elsewhere in NASA by the Intercode A & R Working Group. Such coordination would benefit all of NASA and would avoid undesirable duplication of effort.

APPENDIX A

Progress With Respect to ATAC Recommendations/ NASA A & R Policy

Several significant activities in the area of advanced automation and robotics have been completed or initiated subsequent to the February 15, 1988 cutoff date of ATAC Progress Report 6.

An Advanced Automation Study, funded and managed by Level I, was conducted to identify promising Space Station applications that could be incorporated during the development phase of the program, using existing technology, and to determine the "hooks and scars" required to accommodate the increased future use of advanced automation in both on-orbit and ground systems. The Advanced Automation Study Team was comprised of leading members of the artificial intelligence (AI) industrial community, whose selection was based upon their experience in delivering successful AI-based systems to commercial and Department of Defense customers. The resultant report was briefed to Level I and Level II on February 18, 1988 and has been distributed to ATAC and to appropriate Level III and contractor personnel. The report was also forwarded with the transmittal of ATAC Progress Report 6 to the Congress. The Advanced Automation Study Team will be working directly with Level II and III system and subsystem managers in the upcoming months to refine the requirements and specifications necessary to incorporate selected advanced automation applications and the requisite hooks and scars into the Space Station Program documentation and thus influence the efforts of the work package contractors.

The Space Station Level I Program Requirements Document (PRD) was formally baselined on February 25, 1988. The PRD is a description of the requirements that Levels II and III and the work package contractors must meet in the development of the Space Station. The document is formally controlled by Level I, and any characteristics that must be provided to meet external commitments (e.g., Congressional, international, other NASA Offices) are covered therein. The PRD contains a section on A & R that addresses the concerns voiced by ATAC in its reviews of the Space Station Program's utilization of these technologies in the design, development, and eventual operation of the Space Station. The A & R requirements contained in the PRD will influence the detailed requirements and specifications contained in the Level II Program Definition and Requirements Document (PDRD), to which Level III and the work package contractors must respond. The A & R section of the PRD has had a positive impact in the Space Station Level II Program Requirements Review (PRR) process and will continue to influence the Space Station development program in the A & R areas.

Separate working groups for advanced automation and robotics have been established at Level II to effect the advocacy and coordination of A & R activities across the development program. An A & R Review Group is being established at Level I to provide advice on the implementation of A & R efforts funded by the Level I Advanced Development Program. The Review Group is comprised of representatives from Levels I, II, and III, OAST, OSF, the astronaut crew, and mission operations. Additionally, Level II has established an A & R Steering Group to advise the Associate Program Director on A & R issues and progress within the development program. This Steering Group is comprised of the

chairmen of three Level II Working Groups (the Advanced Automation Working Group; the Robotics Working Group; and the Artificial Intelligence, Expert Systems, and Technology Working Group), Level II personnel from Utilization & Operations and Program Requirements & Assessment, and technical representatives from OAST and the Level I A & R Advanced Development Program. The charters of these A & R Working Groups cover the spectrum from development through the evolutionary Space Station, and they address baseline applications of A & R as well as the hooks and scars necessary to permit increased future use of A & R. The Level II Working Groups have been very active during the PRR process and have proposed numerous change requests to the PDRD that have the potential to significantly increase the A & R content of the Space Station development program.

A tutorial on artificial intelligence (AI) technology and Space Station advanced automation efforts was held June 17, 1988, and was attended by senior management from OSS and OAST as well as technical staff from OSS, OAST, OSF, and OSSA. The presentations were structured to provide an understanding of the current status of AI and its relevance to Space Station applications. The keynote speaker was Dr. Edward Feigenbaum, Professor, Stanford University, widely known as one of the founders of the AI field. Following Dr. Feigenbaum's overview of the history of AI and its present role in the industrial sector, Dr. Peter Friedland of Ames Research Center provided an overview of AI programming techniques and tools, with an emphasis on how AI applications are developed and deployed. Dr. Friedland also presented the results of the recently completed Advanced Automation Study that he chaired. At the conclusion of the briefings, a video tape that demonstrated a knowledge-based

system (KBS) for the Integrated Communications Officer (INCO) console position in the Mission Control Center was presented by Mr. John Muratore, Head INCO, JSC. Additionally, Dr. Larry Young, MIT, discussed and demonstrated a prototype KBS for on-board reactive science in the area of vestibular physiology. The presentations generated considerable interest in KBS technology and provided numerous examples of KBS applications that are relevant to the Space Station Program.

The formulation of the Space Station Level I Advanced Development Program for FY89 is nearing completion and will focus entirely on A & R. The selection of individual development efforts has been based upon their relevance to the baseline Space Station development program, and each has been structured to identify the technical requirements necessary to either incorporate these technologies during the design and development of the Space Station or to provide for their inclusion during the evolution of the Space Station. Application areas range from fault detection, isolation, and reconfiguration for the Thermal, Power, Life Support, and Reaction Control systems to KBS advisory support for Mission Control Center console positions, needed for the sustained operation of the Space Station. The development of the enabling technology to support these and other applications, such as Design Knowledge Capture (DKC), is also a major component of the Advanced Development Program. Technology development efforts will focus on the Space Station Information System (SSIS), particularly the Operations Management System (OMS), the Data Management System (DMS), the Technical and Management Information System (TMIS), and the Software Support Environment (SSE) as targets for enhancement to better support advanced automation and robotics applications during the

development and evolution of the Space Station.

Level I, with the cooperation and participation of Levels II and III, has recently initiated a very aggressive approach to strengthen the technology transfer mechanisms from OAST and other Government agencies to the Space Station Project Offices at the Work Package Centers, with particular emphasis on the involvement of the work package contractors. This will help to ensure maximum consideration of advanced A & R concepts in the baseline design and the provision of the hooks and scars for the evolutionary Space Station. The relationship in A & R between OSS and OAST is formally specified in Memorandums of Understanding (MOU's) covering telerobotics and advanced automation technologies (signed December 1986 and January 1988, respectively). Memorandums of Agreement (MOA's) addressing deliverables, schedules, and joint funding responsibilities accompany each MOU. The telerobotics MOU/ MOA addressed the early requirements of the Flight Telerobotic Servicer (FTS) project and the transfer of OAST technology and expertise. As the FTS project is nearing the end of phase B and the OAST Telerobotics Program has matured since the initial MOU and MOA were drafted, OSS and OAST have taken action to revise the documents to better address Space Station Program requirements in robotics.

On July 26, 1988, the Associate Administrators for OSS and OAST were briefed on the Civil Space Technology Initiative (CSTI) A & R Program and the Space Station A & R Program. In addition to covering the programmatic and technical aspects of both programs, the briefings emphasized ongoing cooperation between OAST and OSS and the transfer of OAST-sponsored technology to the Space Station. The Space Station A & R

briefing also contained material covering A & R policy, infrastructure, internal and external coordination, A & R in the Space Station development program, and the Advanced Development Program A & R tasks. It was recognized that OAST's investment in A & R has provided the Space Station with an excellent set of opportunities for A & R applications. Furthermore, given the importance of A & R in the growth and evolution phases of the Space Station, OAST's continued investment in A & R was emphasized as vital to the Space Station's future.

During the last reporting period, Level II has made considerable progress in implementing ATAC's recommendations and ensuring strong advocacy for automation and robotics in the baseline and evolutionary Space Station. At the top level, an A & R steering group advises level II on A & R technology. Two consultants in particular to this group are Dr. Henry Lum from Ames Research Center, and Mr. Dick Frisbee from Ocean Systems Engineering. The former brings a wealth of knowledge on artificial intelligence and expert systems, being the OAST Center manager for this effort and thus ensuring continuity and coordination between the OAST and OSS programs. Ocean Systems Engineering is engaged in the underwater inspection, maintenance, repair, and replacement of oil drilling platforms throughout the world, using robotics, telerobotics, and human-EVA. Their practical experience in a field very akin to the space application has already provided excellent insights as to what is feasible and how to achieve it.

Within the Space Station organization, three working groups in particular are to be singled out. The Advanced Automation Working Group (AAWG) under Mr. Paul Neumann, is responsible for the applications of advanced automated systems across the board; the

Robotics Working Group (RWG), under Mr. Ben Barker, is responsible for the applications of telerobots and robots throughout the Space Station; and the Artificial Intelligence, Expert Systems, and Technology Working Group (AIESTWG), under Mr. Larry Webster, is responsible for the utilization of those technologies throughout the baseline Space Station. The composition of each of these groups consists of Level I and Level II personnel, representatives from each of the Space Station work package project offices, and consultants from each of the work package contractors. In addition, Canada is represented on the RWG. These groups have had several meetings each, have read the PRD and PDRD, have initiated changes in the latter, and are active in the requirements change process. Among the most important systems/subsystems they are concerned with are the Thermal System, the Power System, the Life Support System, the Flight Tele-robotic Servicer, the Mobile Servicing System, the Remote Manipulator System, the Orbital Maneuvering Vehicle, the Japanese Remote Manipulators, the Polar Orbiter Servicer, the EVA Management System aboard the Space Station, and the Ground Support and Mission Control Systems on the ground. This is by no means a complete list, but typifies the range of activities these groups are involved with.

While these groups have shown good initiative and come up with several excellent ideas, the ultimate effect they will have is still an unknown, since the funding levels for the baseline Space Station have not yet been established, negotiations with the work packages is just being initiated, and at the top-most levels the responsibilities, domains of activity, and interfaces for all the robotic systems under consideration are yet to be determined and agreed upon.

It is obvious that the activities undertaken to address the thirteen original ATAC recommendations are receiving constantly increasing attention as evidenced by:

- The emphasis on A & R in the Level I and Level II A & R Plans (draft form)
- The formation and activities of the Level I and Level II working groups that are addressing A & R issues
- The FY 1988 and 1989 Advanced Development Programs generated and implemented by Level I
- The development of plans for the four work package contractor negotiations for the inclusion of A & R in the baseline and evolutionary Space Station, including appropriate hooks and scars, by both Levels II and III

- The phase B studies on the Flight Telerobotic Servicer (FTS) which are nearing completion, and the upcoming issuance of the RFP for the FTS phase C/D activity
- The increased emphasis in the research program of the Office of Aeronautics and Space Technology (OAST) in A & R of relevance to the Space Station Program
- The initiation of coordinating activities between the FTS, the Orbital Maneuvering Vehicle (OMV), the Mobile Servicing System (MSS), the Remote Manipulator System (RMS), and other robotic systems under consideration for Space Station applications.

There are increasing activities at Level I to study and implement technology transfer both to and from NASA and the commercial sector of the economy, and finally there is a large activity in industry to focus independent research and development (IRAD) on advanced automation and robotics for both the Space Station and long-range applications by companies directly and tangentially associated with the Space Station Program.

APPENDIX B

Overall Plan for Applying A & R to the Space Station and for Advancing A & R Technology

Scope

The Space Station Freedom A & R Plan encompasses all facets of the Office of Space Station's efforts to apply A & R technology in the development, operation, and evolution of the Space Station and, in time, will also include similar activities conducted by the International Partners. The plan covers three distinct yet overlapping and complementary areas of interest. These are: (1) the identification and development of A & R applications to be implemented on the baseline Space Station; (2) the A & R component of the Space Station Advanced Development Program; and (3) the development of candidate A & R applications, with appropriate phasing, for the evolutionary Space Station.

Space Station A & R activities are occasionally described as two separate components, internal and external. Internal activities refer to those conducted, funded, and/or managed under the auspices of the Office of Space Station. These consist of all the A & R activities within the Evolution Studies and Advanced Development Programs managed by the Strategic Plans and Programs Division (Code ST), as well as those conducted in the development of the baseline Space Station which are managed by the the Space Station Program Office (Code SS) and the Work Package Centers. Similarly, the International Partners, as participants in the development of the Space Station, are covered under internal A & R activities. External activities refer

to interface, interaction, and coordination efforts with all other organizations, both within and outside NASA, that are germane to the Space Station A & R Program.

Space Station Automation & Robotics Policy

Encourage Broad Application of Automation & Robotics

It is the policy of the Office of Space Station (OSS) to fully utilize advanced automation and robotic technologies in the design and development of the baseline Space Station where: (1) the technologies are found to be technically appropriate within the context of overall system design; (2) the technologies are favorable, given cost-to-benefit considerations; and (3) the enabling technology selected is sufficiently mature. This policy is clearly stated in the Program Requirements Document (PRD) and is reflected in the corresponding Program Definition and Requirements Document (PDRD).

Provide for Increased Use of Automation & Robotics

The OSS fully understands that both areas of technology are undergoing rapid change as new techniques and capabilities are discovered and brought to maturity. Consequently, the provision of accommodations that will enable the baseline Space Station to fully capitalize on future A & R advances during its growth and evolution is an important facet of Space Station A & R policy and is thus reflected in both the PRD and PDRD. The identification and specification of these A & R accommodations (hooks and scars), are heavily emphasized in the A & R efforts conducted under the Space Station Advanced Development Program. Additionally, the Advanced Development Program efforts are aimed at maturing and transitioning the technology required to enable

greater use of A & R during the growth and evolution phases of the Space Station.

Capitalize on Existing Momentum

The OSS intends to take full and complete advantage of the tremendous momentum in A & R research, technology development, and applications that exist within the academic, Government, and commercial sectors. Within NASA, the Office of Aeronautics and Space Technology (OAST) has made a substantial commitment to A & R research and technology development through the Systems Autonomy and Telerobotics Technology Programs. Memorandums of Understanding (MOU's) and corresponding Memorandums of Agreement (MOA's) have been signed by OSS and OAST to ensure that the Space Station Program avails itself of the technology products that are forthcoming from OAST's investment. Similarly, the MOU's and MOA's provide a forum for OSS to state technology requirements and to potentially influence the OAST decision process as it pertains to A & R (see below: "External A & R Coordination").

In addition to OAST, other Government agencies provide substantial funding for A & R research and technology development. Foremost is the Defense Advanced Research Projects Agency (DARPA) whose combined investment in the Strategic Computing Program (SCP) and associated supporting research exceeds $100M per year. Much of the SCP investment in A & R is of direct relevance to long-term Space Station technology needs or application domains. The OSS has established an interface with appropriate DARPA Strategic Computing Program management to more effectively leverage its investment in these technologies. Additionally, the Air Force has a strong program in the advanced

development and application of
A & R technology. The formal
structure for the coordination of
NASA and Air Force programs is
the Space Technology Inter-
dependency Group (STIG). A STIG
subcommitee is chartered to address
joint interests in A & R.

Terrestrial Spinoffs of Automation & Robotics Technology

To the maximum extent practicable,
OSS intends to disseminate informa-
tion concerning the development
of A & R technology for use by the
Space Station Program and the
application of these technologies
to the Space Station systems. The
extent to which the OSS investment
in A & R advances the state-of-the-
art or the state-of-the-practice in
specific domains will largely
determine the rate and degree of
technology transfer to the terrestrial
economy. As with past NASA
programs, the length of time required
for design, development, and testing,
as well as the stringency of the
space-qualification process, will
serve to inhibit advancement of the
state-of-the-art and the state-of-
the-practice in A & R applications
undertaken by the Space Station
Program. However, the Advanced
Development Program's A & R efforts
will have a higher likelihood of early
terrrestrial application due to the
selection of technologies and
applications which have a higher
degree of risk and a correspondingly
higher potential payoff.

Space Station Transition Definition Program

The Space Station Program,
recognizing the importance of
growing and evolving the baseline
station and its dedicated ground
support facilities during the projected
thirty-year life of the Space Station,
established the Transition Definition
Program to define, develop, and
implement a program to enable

Space Station evolution in keeping
with the needs of users and the long
term goals of the United States. The
primary thrusts of the Transition
Definition Program are to define
reference evolution configurations
which are consistent with projected
user requirements, national space
policy, and Space Station Program
constraints; to define and incorporate
baseline design accommodations
(hooks and scars) which satisfy the
requirements associated with the
reference evolution configurations;
and to develop advanced technology
that ensures technology readiness
to enhance the Space Station's
capabilities and to enable evolution.
The Transition Definition Program
is divided into two separate, but
nonetheless interconnected, com-
ponents: Evolution Studies and
Evolution Advanced Development.
The Transition Definition Program
is managed by the OSS Strategic
Plans and Programs Division and
involves all of the NASA Centers
and each of the Space Station
Program work packages.

Evolution Studies

Active planning for Space Station
evolution was ongoing during the
phase B activity and directly in-
fluenced many aspects of the
baseline station. Workshops to
survey and discuss potential Space
Station growth and evolution modes
were held in September 1985 and
July 1986. At each workshop,
emphasis was placed on looking
beyond the ten-year mission data
set for the Space Station , and con-
sideration was given to the potential
impacts of expanded commercial
requirements as well as the recom-
mendations made by the National
Commission on Space (NCOS).

Presentations based on the material
produced in these workshops were
provided to senior NASA manage-
ment and served to lay the founda-
tion for the Transition Definition
Program and to establish the primary

thrusts of the evolution studies.
These thrusts are: (1) to identify
and understand the evolution options
for the growth of the Space Station
into a mature research and
development platform and the
evolution, or "branching" of the
Space Station to support one or more
of the "New Initiative Missions"
discussed in the NCOS Report and
presently being defined by the NASA
Office of Exploration (Code Z); (2) to
identify and understand the forces
and constraints that impact the
growth and evolution of the Space
Station, particularly in the areas of
mission requirements, external
factors (budget, policy, etc.),
infrastructure planning (transporta-
tion, servicing, etc.), and techno-
logical limitations and opportunities;
and (3) to provide for Space Station
evolution by keeping the options
open and facilitating changes
through definition of specific growth
and evolution requirements for the
baseline station, and by developing
requirements for the technologies
necessary to enable the Space
Station to support the New Initiative
Missions.

The Evolution Studies efforts
conducted in FY 1988 have focused
on Space Station support of
projected increases in multidiscipline
research and development and the
support of New Initiative Missions
(e.g., the Manned Lunar Base,
Humans to Mars, etc.). The individual
studies are managed by personnel
from various NASA Centers, and
the results are integrated by the
Langley Research Center (LaRC)
Space Station Office. One of the
studies, the Advanced Automation
Study (ref. 8), has had a major impact
in the baseline Space Station
Program and in the formulation of
an expanded Advanced
Development Program in FY 1989.
The study was initiated in October
1987 at Ames Research Center
(ARC) and had three major
objectives: (1) to develop a refined
list of baseline Space Station
candidates for advanced automation,

specifically knowledge-based systems; (2) to analyze the evolution of KBS applications in the Space Station's on-orbit and ground support systems; and (3) to identify critical technology areas required to enable the evolution of KBS applications for the Space Station.

Several evolution studies to be initiated in FY 1989 will examine the impact of A & R technology in meeting evolution requirements and will identify A & R technology needs that enable Space Station evolution. The topics include Advanced Robotics for In-Space Vehicle Processing, Advanced Automation for In-Space Vehicle Processing, and Data Systems Evolution. These studies will be used to directly influence the Space Station Advanced Development Program and will also provide long-range technology requirements which will be provided to the Office of Aeronautics and Space Technology to support long-range planning for its Systems Autonomy and Telerobotics programs.

Evolution Advanced Development Program

The primary goals of the Space Station Advanced Development Program are to enhance baseline station capabilities with an emphasis on increasing productivity and reliability while reducing operations costs, and to enable Space Station evolution by providing mature technology in areas required to support advanced missions. The products of the Evolution Advanced Development Program range from demonstrations and evaluations of technology at a near-operational level of readiness to detailed requirements, performance specifications, and mature technology components suitable for transition to NASA and contractor organizations for implementation during the growth and evolution phases of the Space Station.

During phase B, a number of A & R studies were conducted that clearly demonstrated A & R's high potential to address concerns about productivity, reliability, and long-term operations costs. Subsequently, with the establishment of the Transition Definition Program, as described above, and following an Evolution Advanced Development Task Force, which met at LaRC in February 1988 with Level I, II, III, OAST, and Center participation, the initial Advanced Development Program has been totally focused on A & R applications and technology development. Heavy emphasis has been placed on advanced automation, particularly KBS, due largely to the demonstrated ability of KBS to provide improvements in productivity and reliability and to reduce operations costs. This disproportionate funding of advanced automation is more than balanced at present by the substantial investment in the development of the Flight Telerobotic Servicer as part of the baseline Space Station. As the evolution studies begin to assess technology requirements for support in New Initiative Missions, additional technology disciplines will be added to the Advanced Development Program.

Presently, the Advanced Development Program has two major categories: Application Development and Demonstration; and Technology Development and Evaluation. Sub-categories under Applications Development and Demonstration include On-Orbit Systems Control, Ground Operations Support, and the Space Station Information System. Under Technology Development and Evaluation, the sub-categories are Advanced Automation Software Development, Computational Hardware, Human Factors, and Robotic Systems Integration and Accommodation. The individual tasks are managed by personnel at NASA Centers who have appropriate expertise and involvement with the baseline Space Station Program.

The investment rationale guiding the advanced automation tasks in the On-Orbit Systems and Ground Operations Support sub-categories is aimed at understanding the hooks and scars associated with the utilization of advanced automation techniques, particularly KBS, and their unique requirements for instrumentation, control redundancy, software-controlled switches, etc. Identification and documentation of the implementation and system engineering issues are central to each of the advanced automation tasks. The issues include: integration with conventional automation techniques; requirements for processing, data storage, and communications; software development, testing, and maintenance; and identification of the boundaries of advanced automation performance in terms of speed, application complexity, ability to scale-up to large applications, and "brittleness" of advanced automation software. ("Brittleness" is the tendency for the software to make a bad recommendation to the user while assigning a high degree of confidence to the recommendation). An attempt has been made to cover as many systems and subsystems as funding permitted to identify any unique or unexpected requirements, to build credibility within the design and engineering groups associated with the particular systems and subsystems, and to improve (within the design and engineering groups) the understanding of advanced automation benefits and current limitations.

For the Space Station Information System (SSIS), the driving rationale has been to enable the growth and evolution of the Operations Management System (OMS) and the Data Management System (DMS). The OMS provides the command and control capability for the Space Station and is comprised of on-orbit and ground components, respectively known as the Operations Management Application (OMA) and the

Operations Management Ground Application (OMGA). The DMS provides the computational and communications capability and interconnections necessary for the OMA and OMGA to function. Key issues to be examined and understood include extensible software, hardware, and communication network architectures and adequate processing, memory, data storage, and network bandwidth for the baseline Space Station to permit early post-IOC growth without requiring major upgrades. Additional areas of emphasis are: the improvement of the software development, testing, and maintenance process for both conventional and advanced automation software through the use of KBS tools; the development and integration with the Software Support Environment (SSE) of tools needed to develop, test, and integrate KBS applications; and the development of software tools to support the acquisition and manipulation of design knowledge for both the SSE and the Technical and Management Information System (TMIS).

Advanced Development Program A & R Coordination

To ensure the success of the A & R efforts funded by the Advanced Development Program, the Space Station Level I Automation & Robotics Working Group (SSARWG) has been established. The purpose of this group is to provide the Director, Strategic Plans and Programs Division (Code ST), Office of Space Station, with periodic evaluations of the A & R tasks funded by the Evolution Advanced Development Program. In particular, this group's responsibilities will include:

- Assessment of the consistency of the A & R Advanced Development Program with the Space Station A & R Plan and the Space Station A & R Implementation Plan.

- Evaluation of the ongoing and planned A & R advanced development efforts in the context of technical appropriateness, maturity of the selected technologies, and the operational and programmatic requirements imposed by Space Station development, growth, and evolution.
- Development and maintenance of criteria to be used in the identification, evaluation, and prioritization of A & R advanced development efforts and recommendation of new technology and application directions, as appropriate.
- Recommendation of technical and programmatic approaches for A & R advanced development efforts to ensure the relevance of A & R applications and technology products to the baseline and evolutionary Space Station.
- Provision of semiannual technology progress reports, including briefing charts and photos of significant accomplishments, to be used by Level I and to support the ATAC process.
- Provision of advocacy support for the A & R Advanced Development Program as appropriate.

The SSARWG is comprised of representatives from OSS (Levels I, II, and III), the crew, Mission Control (JSC & KSC), OAST, OSF, OSSA, OSO, and OE and will meet semiannually (more frequently, as required).

External A & R Coordination

The Information Sciences and Human Factors Division (Code RC) of the Office of Aeronautics and Space Technology has had an aggressive research program in Systems Autonomy (advanced automation) and Telerobotics since

1985. Because the research program preceded the establishment of a well-defined Space Station Program, especially in the fields of A & R, the OAST unilaterally, and fortuitously, decided that a significant portion of its program should be devoted to a sequence of increasingly difficult technological demonstrations in both Systems Autonomy and Telerobotics, with near-term emphasis on Space Station applications. Its program objectives were to stimulate the development of advanced technology, perceived to be essential to the implementation of advanced autonomy and robotics applications. As was appropriate for a research and development program, its objective was to demonstrate technological feasibility. The Systems Autonomy Program Plan (ref. 11) provides a detailed description of OAST's investment in advanced automation.

With the advent of the Space Station and its Advanced Development Program's investment in A & R, it was natural for the Office of Space Station to take advantage of this research and to leverage the OAST activities by jointly funding relevant efforts supported by the Systems Autonomy and Telerobotics programs. The intent is to extend the efforts beyond proof of feasibility, to a stage that demonstrates applicability to Space Station needs, and requires only minor modifications and flight qualification testing to be fully adoptable by the Space Station.

Level I initially adopted this approach on an informal basis, but it was ultimately followed with a Memorandum of Understanding and a Memorandum of Agreement between OAST and OSS for telerobotics, in December 1986. The MOU is a general document of long term duration, agreeing to a formal partnership, while the MOA is a living document that deals with specific items, schedules, and resources. In January 1988 a similar pair of documents was signed for systems

autonomy between the same two principals. As one of the many benefits of this formal relationship, OAST has modified its program to accommodate Space Station needs and schedules, both in telerobotics and in systems autonomy.

The natural relationship between these two Offices has been strengthened to the mutual benefit of both. Level I has also participated as an active member of several groups established by OAST, including the Systems Autonomy Intercenter Working Group (SAIWG), the Telerobotics Intercenter Working Group (TRIWG), and the Automation and Robotics Steering Group (ARSG). Similarly, OAST personnel have participated in several similar groups established within the Space Station Program at both Levels I and II. Through constant interaction with these various groups, each Office has beneficially affected the program of the other and has greatly enhanced the potential for truly implementing a technology transfer program from one Office to the other. Level I intends to continue and to vigorously augment this relationship as part of its ongoing A & R plan.

While OAST is the most natural and immediate external organization with which to coordinate the A & R advanced development activities, it is not the only one. Increasingly, OSS is developing, and will continue to develop, relationships with other relevant Offices within NASA on a similar basis. This includes especially the Office of Space Flight (OSF), which has funded several important KBS application and technology development efforts as well as the Office of Space Science and Applications (OSSA), the Office of Exploration (OE), and the Office of Commercial Programs (OCP). Presently, MOU's and MOA's are being drafted, several of which address joint activities.

Additionally, for the mutual benefit of both parties, Level I is developing joint programs with several Government agencies outside of NASA, such as DARPA and the USAF, and with others that have vested interests and extensive investments in automation and robotics.

APPENDIX C

Progress on Definition and Integration of A & R in the Baseline and Evolutionary Space Station

During this report period, the Space Station Freedom program achieved its first major milestone for the development phase, the conduct of the Program Requirements Review (PRR). The preparation and conduct of this review involved all levels of the program and represented a major area of emphasis throughout the spring of 1988. The objectives of the Program Requirements Review were to assure that the extensive set of Level II requirements documents was appropriately responsive to all of the known program requirements, as stated in the Program Requirements Document, the Program Approval Document, the intercode memorandums of understanding, and the international agreements. In addition, the PRR was intended to assure that the many documents containing the Level II requirements were self-consistent.

In preparation for the PRR, an effort was made to update the Level II requirements to conform to the program baseline. This update was established at a Space Station Control Board meeting held on April 26. Review documentation was issued in early May, and Review Item Discrepancies (RID's) were submitted by program participants and other interested parties throughout that month. An automated RID tracking system was established, which tallied in excess of 6600 RID's. These were reviewed by 11 teams and dispositioned by PRR pre-board and board actions in mid and late June, respectively. Several actions and studies resulting from these dispositions will be worked off over the next several months. The next major links in this chain of events are the Project Requirements Reviews, intended to review the Level III documentation. These will be held in late summer and into the fall of 1988.

A second area of program-wide emphasis during this reporting period was the preparation for the negotiation of the work package contracts. After the work package contractor selections and the award of letter contracts in December 1987, each Work Package Center and its respective contractor participated in detailed fact-finding concerning their respective proposals. Results of the fact-finding necessitated adjustments to the proposals in preparation for negotiations of the definitive contracts, which are currently underway. A team headed by Level II, and with program-wide participation, reviewed each Center's pre-negotiation position and assigned appropriate actions prior to recommending approval to the Associate Administrator for Space Station.

The topic of automation and robotics received considerable attention in both of the above activities. The increased understanding thusly obtained has helped the program mature its approach to this subject. It is recognized that the responses from the work package contractors were not as aggressive on the subject of advanced automation as was anticipated. On the other hand, the contractors proposed ideas in the area of robotics which had not been previously baselined in the program, but which merit further examination. The Advanced Automation Study commissioned by Level I also contributed significantly to the developing plan for the use of A & R technologies in the program. This developing plan distributes work done on the application of A & R technologies into three domains of attention, as depicted in Table C-1.

The first domain is that of accommodations and standards. It has been demonstrated that for these technologies to be effective, the environment in which they operate must be somewhat structured. In addition, since development of the application of these technologies will be conducted by many organizations, there is a need to provide design standards to facilitate how each will be integrated into the system and to minimize the unique training for their operation. Within this domain, two categories have been established, one pertaining to the development of design guidelines and standards for the phase I Space Station, and the second pertaining to the definition of hooks and scars for evolution.

TABLE C-1. - A & R DOMAINS OF ATTENTION

Accommodations and Standards	Applications	Development Environment
● Design guidelines for phase I Space Station	● Baseline content	● Testbeds
	● Targeted additions	● Software support
● Hooks and scars for evolution	● High-leverage prototyping	
	● Evolution	

The second domain addresses the actual application of these technologies. Categories within this domain include applications already incorporated into the baseline content of the program, and targeted additions to that content. This second category acknowledges that there are areas in which a more aggressive approach, particularly in advanced automation applications, is not only desirable but is well within the readiness of the technology, and creates an advocacy and a mechanism for its insertion into the program baseline. The third category takes into account the fact that these technologies are rapidly emerging and that the Space Station is still 6 1/2 years from launch. A decision on some applications today may not be valid at the time of launch. In an effort to allow the program to remain technologically current in critical areas at launch, the program has established a high-leverage prototyping effort. This effort is designed to allow the prototyping of applications thought to be not yet ready for development but anticipated to yield high pay-offs. These prototypes will serve as demonstrations of the proposed applications, thus enabling an informed decision at a later time. The ease with which insertion of these applications will be made late in the development phase will be dependent on how thoroughly the design guidelines and standards are adopted by the program. The last category in this domain is assigned to those applications for which technological readiness is foreseen to be beyond the time of the Space Station launch and assembly. These are candidates for the Space Station evolution phase.

The third domain of attention pertains to providing the necessary environment in which to develop and test the applications. It requires access to appropriate system and multi-system testbeds and to the rules, tools, processors, operating systems,

and compilers to facilitate software development. All of the domains are applicable to both the flight and ground segments of the Space Station endeavor.

The process for managing activities in all three domains and their respective categories will be documented in the Space Station Program Automation and Robotics Implementation Plan. A first draft of this plan is currently in preparation, and a review draft will be circulated to program participants in late summer 1988. The current target is to seek approval of the plan in the fall of 1988.

The plan is being prepared under the guidance of the Level II A & R Steering Group. The group is chaired by the Associate Director, Space Station Program Office and has membership from each Level II Group and Office as well as consulting support from the Ames Research Center and from Ocean Systems Engineering. It is responsible for developing program policies on the subject of these technologies, for coordinating the related activities of all Level II Groups and Offices, and for providing advocacy for the use of these technologies. Three integrating working groups work closely with the Level II A & R Steering Group. These working groups, whose chairmen are members of the Steering Group, provide the primary technical integration of program activities in their areas of responsibility.

The Robotics Working Group (RWG) was formed in February 1988. It is responsible for performing the technical integration of activities pertaining to the development and utilization of robotic devices on the Space Station and for advocating the utility of such devices. One of the major activities in process is the development of a document titled "Space Station Design Criteria and Practices for Accommodation of

Robotic Systems." Review drafts of this document will be released in late summer 1988. It is anticipated that the final document will be incorporated into the Space Station's baseline documentation system by the end of calendar year 1988.

The Advanced Automation Working Group (AAWG) was also formed in February 1988. It has a similar responsibility for the technical integration and advocacy for the development and utilization of advanced automation applications on the Space Station. Among the working group's current tasks are the development of an implementation plan for the recommendations made in the Advanced Automation Study, the identification of potential candidates for high-leverage prototyping, and the development of design standards and guidelines for the incorporation of automated systems.

The Artificial Intelligence, Expert Systems, and Technology Working Group (AIESTWG) was formed in October 1987. Its primary role is to enhance the capability of the Space Station's information system, with a focus on the development of a technology-compatible environment and infrastructure for the development and utilization of advanced automation techniques. Current activities are addressing topics such as shells and higher order languages for knowledge-based systems applications, software support infrastructure, operating system services, and standards for information transfer. As is the case for all of the working groups, the AIESTWG is also developing candidate prototyping activities and testbed and software support requirements.

APPENDIX D

Progress on the Flight Telerobotic Servicer for the Space Station

During this ATAC report period, the scope of the Flight Telerobotic Servicer (FTS) test flight program was expanded. Instead of a single flight, it was decided to conduct two flights: a development flight in 1991, and a demonstration of the initial flight system capabilities approxi-mately two years prior to the first element launch (FEL) of Space Station Freedom. It was also decided that the FTS prime contractor should be more involved in the concept development and the implementation of these flights than was originally envisioned. A modification of the FTS phase B contracts was issued to each of the phase B contractors, Martin Marietta Astronautics Group and Grumman Space Systems, for them to develop mission concepts for the Development Test Flight (DTF) and initiate the purchase of long-lead items for the 1991 flight.

As stated in previous ATAC reports, the contractor phase B studies are being conducted under Source Evaluation Board (SEB) control. This means both teams can develop their concepts and discuss them as they evolve with the SEB, knowing and being confident there will be no synthesis of design concepts.

The phase B study contract included the clause that specific trade studies—in particular, the trade studies which address the interface between the FTS and the Space Station itself— would be open to support the Space Station Program Requirements Review (PRR) activity. The Space Station's interface and resource requirements from these trade studies were combined
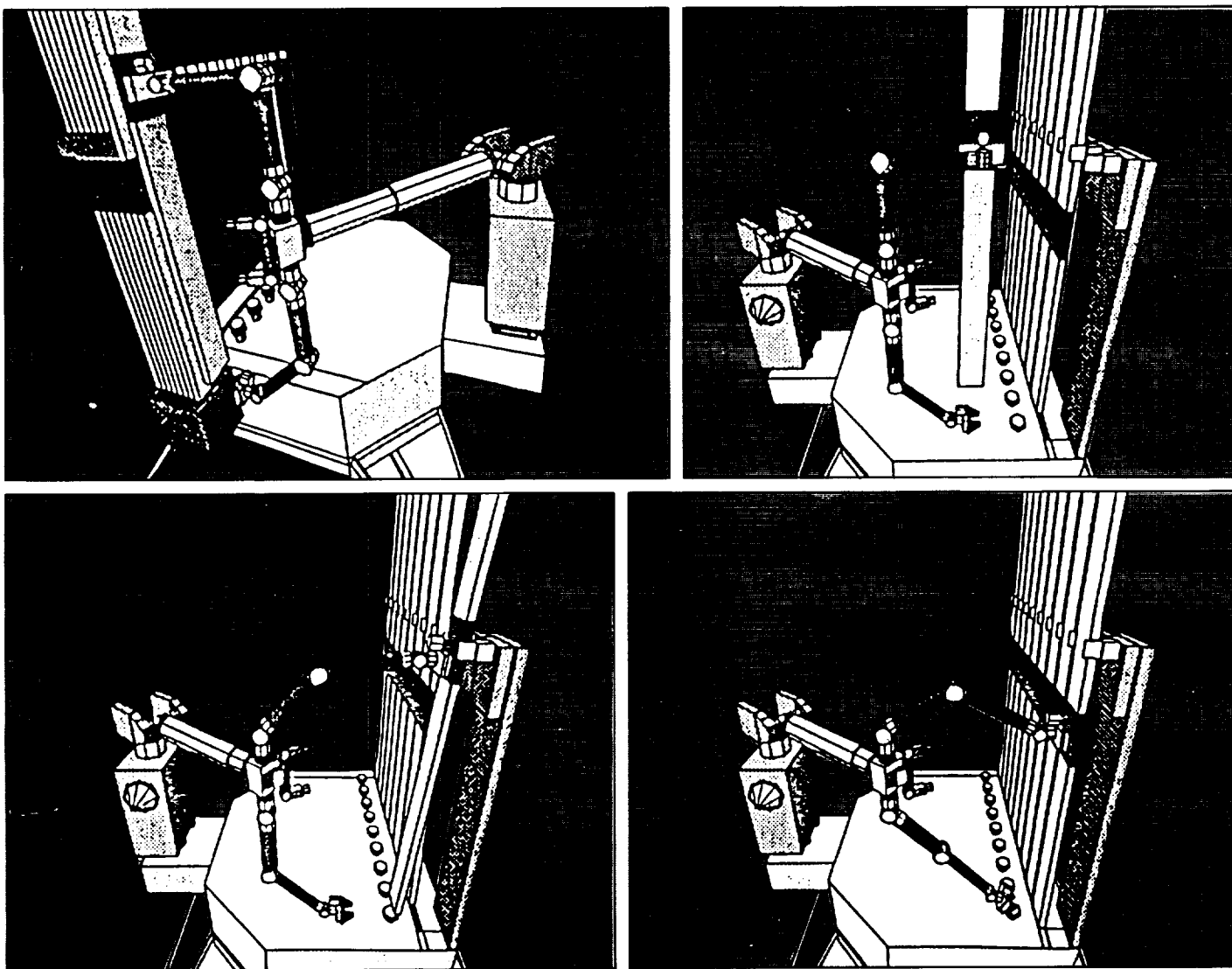

Figure D-1.— A NASA in-house concept of a method to remove thermal radiator panels from a carrier magazine and install them in the Space Station Electrical Power System (EPS) pallet.

with the results from the NASA in-house study to develop the inputs to the Program Definition and Requirements Document (PDRD). The requirements developed by all three studies—the NASA in-house study and the two contractor studies—were in sufficient agreement that the FTS project could establish the scope of the interfaces with the Space Station.

The NASA in-house phase B study was completed during this reporting period, and the contractors were briefed on the results. In meeting the study objective of developing an approach that would help NASA be an intelligent buyer, this study team followed the same requirements as the phase B contractors. The in-house team developed a telerobotic concept that could accomplish the five tasks (truss assembly, orbital replaceable unit (ORU) changeout, structure interface adapter (SIA) installation, thermal utility connector mate/demate, and inspection) defined in the FTS phase B request for proposals. This in-house conceptual design is being used to establish criteria and parameters for the phase C/D specifications, to help establish the interfaces between the FTS, the Space Station, and the Space Shuttle, and to determine the technical and cost drivers in the in-house cost studies.

In parallel with the phase B studies, a separate group, the Mission Utilization Team at GSFC, has been involved in determining tasks the FTS could be asked to assume during assembly of the Space Station. The Work Package 2 prime contractor, McDonnell Douglas, suggested as part of its winning proposal, that the FTS be used to assemble the Electrical Power System (EPS) radiator. This assembly task involves the manipulation of 1-inch by 1-foot by 50-foot heat-pipe panels and the insertion/attachment of the panels into the EPS pallet. The Mission Utilization Team developed a fixture concept that would allow an FTS to accomplish the task. They also developed a script, detailing each required activity. The in-house concept was then evaluated to see if it could accomplish the EPS radiator assembly task. Figure D-1 is an artist's concept of the in-house design accomplishing the installation of the thermal radiator (i.e., ORU exchange) in the Goddard Space Flight Center (GSFC) Robotics Laboratory and performing the sequences, using a FTS operational simulator.

APPENDIX E

Progress in Research and Technology Base Building to Support A & R Applications

NASA's research and technology development program in automation and robotics is focused in the Office of Aeronautics and Space Technology (OAST). The OAST has two major thrusts: Systems Autonomy and Telerobotics. Continuing progress for each of these two technology development programs is described in this and in all previous ATAC progress reports.

Systems Autonomy Program

The overall goal of the Systems Autonomy Program is the development and validation of intelligent autonomous systems technology for NASA aerospace missions. Major objectives are: 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 (one demonstration and one core research) have made these significant accomplishments recently:

1. Integrated Communications Officer (INCO) Expert System Demonstration

2. Automatic Classification (AutoClass) Research

The Systems Autonomy Program is funded by the Information Sciences and Human Factors Division of OAST.

INCO Expert System Demonstration 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 is 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.

In the Integrated Communications Officer (INCO) Real Time Expert System, NASA has developed an "intelligent associate" to assist the Flight Controller charged with command and control of the Space Shuttle's communication and data systems. This system is now placed in the Flight Control Room (FCR) of Mission Control and is being used daily to assist flight controllers during mission simulations. The system will be flight-tested during the STS-26 mission of the Space Shuttle.

The INCO Real Time Expert System Project is a joint effort between the Mission Operations Directorate at the Johnson Space Center (JSC) and the Artificial Intelligence Research Branch at Ames Research Center (ARC). JSC operations personnel have programmed the system, with ARC personnel providing expertise on techniques and methodologies. Because the operations personnel have programmed the system, user acceptance has been accelerated. The basic system capabilities developed by the INCO project are now being expanded into seven

additional discipline areas, such as electrical power and life support.

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 OAST and the field centers that the benefits of KBS will only occur if the technology developed by OAST 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 INCO 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 INCO Expert System Project, an engineering workstation has 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 (350) and heuristics (130), which can 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 INCO project was to implement a real-time interface between the Space Shuttle telemetry stream and the automated applications running

in the engineering workstation. The INCO 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 INCO console. 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.

The expert system has several distinct advantages over the conventional console. For example, the expert system makes heavy use of color graphic displays to communicate information to the operator. This is in sharp contrast to the black and white text displays of the current MCC. Operators have expressed a strong preference for the color graphic displays, and simulations have shown that the color graphics displays can reduce the time required by Flight Controllers to identify malfunctions on the Space Shuttle. The workstation and telemetry processor combination has also shown itself to be approximately 3 seconds faster than the conventional mainframe computer-complex display console.

Perhaps the most important advantage of the expert system is that it captures corporate knowledge

about spacecraft monitoring. The expert system contains the knowledge and expertise of specialists in many discipline and subsystem areas. It utilizes this knowledge to provide a second-by-second evaluation of the Space Shuttle's communication systems. This allows a junior operator to evaluate problems and make recommendations with the consistency and depth of more experienced personnel.

Based on the success of the INCO Expert System Project, the system is being expanded to cover other subsystems on the Space Shuttle. Specifically, seven black and white consoles are being removed and replaced with the expert systems. This will provide an immediate and significant benefit to NASA's ability to safely operate the Space Shuttle. The system will also provide some small manpower savings, as at least one Flight Controller monitoring position is expected to be completely automated by late 1989. Many of the concepts from the project are being utilized in other JSC projects which involve real-time monitoring of spacecraft systems.

AutoClass Research

The Bayesian learning group within the Artificial Intelligence Research Branch at ARC has developed the general theory for discovery of patterns in noisy data. This theory is being tested in the relatively simple but important domain of automatic classification. Here the goal is to find natural classes within a set of objects (examples, cases etc.) that reflect some underlying cause. A program (AutoClass) for auto-matically finding such classes has been developed and tested on many data bases. It has found classes that were unsuspected by workers in the field, and these classes have since been confirmed by further investigation.

AutoClass is being extended to become a general purpose tool for use by researchers for exploratory data analysis. The Bayesian theory on which AutoClass is based is sufficiently general that it can be applied to many other problems of interest to NASA. In particular, it can help provide solutions to problems in weather prediction, fault diagnosis, medical pattern discovery, satellite data analysis, visual processing, and so on. Many of these applications require further work before useful tools are available.

In the area of automatic classification of data, AutoClass has several important advantages over most previous work:

- AutoClass automatically determines the most probable number of classes. The discovered classes represent actual structure in the data. Given random data, AutoClass discovers a single class.
- Bayes theorem is all that is required to perform classification. No ad hoc similarity measure, stopping rule, or clustering quality criterion is needed. Decision theory applies directly to the probability distributions calculated by AutoClass.
- Classification is probabilistic. Class descriptions and assignments of objects to classes are given as probability distributions. The resulting "fuzzy" classes capture the common sense notion of class membership better than a categorical classification.
- Real-valued and discrete attributes may be freely mixed, and any attribute values may be missing.
- Classifications are invariant to changes of the scale or origin of the data.

Autoclass has classified data supplied by researchers active in various domains and has yielded

some new and intriguing results. The following is a sample:

- Infrared Astronomy Database: The Infrared Astronomical Satellite (IRAS) tabulation of stellar spectra is not only the largest database AutoClass has assayed (5425 cases, 94 attributes) but the least thoroughly understood by domain experts. AutoClass results differed significantly from previous analyses. Evaluation of the new classes by infrared astronomers indicates that the hitherto unknown classes found by AutoClass have important physical meaning. The AutoClass infrared source classification is the basis of a new star catalog, which is scheduled to appear shortly.

- Clouds Database: When applied to examples of 2-D cloud data (in both visual and infrared), AutoClass rediscovered the known cloud types as well as finding finer structure within some of these types.

Other databases are being collected and analyzed which seem appropriate for classification, such as a second infrared spectral database and weather data.

AutoClass is potentially applicable wherever large amounts of data need to be structured before more detailed (and often partial) models can be tested. The IRAS results illustrate AutoClass's use in an astronomical survey. It will be equally useful in planetary survey applications, such as Landsat, Seasat, and the Mars Orbiter. AutoClass-type programs may well be essential for organizing the very large data flow expected from the Space Station.

AutoClass can be applied to histories of complex systems to identify the evidential patterns associated with underlying states and transitions. Given these patterns, the current

state of a particular system can be identified and its future states predicted to some probability. This is the field of Diagnostics, traditionally associated with biological systems, but equally applicable to complex mechanical, electrical, and software systems. Such a diagnostic system would be of great utility for such complex systems as the Space Shuttle and the Space Station.

Telerobotics Program

Progress has continued briskly in telerobotics - the complex technologies being developed to improve the efficiency and safety of remote manipulation in space. The activities are managed in two main elements:

- A research core aimed at advancing the state of the art in the areas of Sensing and Perception, Planning and Reasoning, Control Execution, Operator Interface, and Systems Architecture and Integration
- An integration testbed project to demonstrate the integration of key technologies in an operating system

Plans are being formulated for initiating a third activity: Application Demonstrations. These will be focused toward the application of telerobotic technology to ongoing NASA operations.

Core Research

Planning and Reasoning

Research in artificial intelligence has focused on developing an architecture concept to facilitate interaction and feedback among high-level task planning systems and robotic systems. An AI task planner is being implemented which plans high-level manipulation of 3-D convex polyhedral objects for unstructured tasks and incorporates

information at logical, topological, and metric abstractions. The planner automatically generates the assembly-disassembly sequence for compositions of objects, including reasoning about spatial obstructions and spatial interference.

A geometric modeling system and a geometric reasoning engine have been implemented. These modules allow realistic verification and feasibility of task planning actions and constraints. Modifications are being made to this planner to make it applicable to experimental telerobot and simulated space scenarios. Work is also under way to integrate the planner and the geometric reasoning engine. Interfaces are also being implemented to close the integration gap of the task planning system with trajectory and grasp planning functions. This work is being conducted with leading university collaborators.

Control Execution

The Aerospace Robotics Laboratory (ARL) at Stanford University has made significant developments on several fronts in the dynamic control of robotic manipulators.

The ARL multiple-flexible-arm research facility is nearing operational status and will soon allow study of the role of flexibility in multi-arm cooperation. Experiments with the smaller rigid-arm cooperation facility are successfully achieving object insertion tasks requiring cooperative action by two arms to achieve object impedance control.

In the flexible-manipulator regime, very successful experiments have been concluded, demonstrating load-adaptive control of the single-link continuously-flexible manipulator, for tip loads varying by up to 250 grams. The single-link flexible manipulator possesses a multitude of characteristics, making it a very difficult target for adaptive control,

which makes these results particularly exciting. Experiments continue in control of mini-manipulators combined with the single-link and multi-link flexible manipulators. The research is intended to produce control techniques applicable to the many manipulators, both on Earth and in space, whose flexibility must be recognized in order to achieve high-performance control.

The new Space Robot Simulator Vehicle facility is nearing operation as well. Onboard and laboratory computer facilities are being completed, and experiments in floating-base multi-arm cooperation and satellite motion planning and execution will soon be possible. The goal of this research is the development of cooperating, free-flying space robots for extravehicular construction, repair, and service operations that are controllable at a high level by their human operators or by autonomous planning systems. Research has been concluded with the existing single-arm facility, with which successful manipulator dynamic control was demonstrated and the groundwork laid for the ongoing multi-arm control and navigation research.

Operator Interface

At the Jet Propulsion Laboratory, experiments have been conducted to evaluate enhanced 6-axis force reflection and graphics perception for advanced teleoperation. The enhanced force-reflecting capabilities have been built into an experimental dual-arm teleoperated system with a 1500 Hz bandwidth and the ability to sense joint and task-space velocities at servo rate. The system allows the operator to feel the instantaneous rates and forces due to contact between the end-effector and the task environment. The computing architecture of the system has been designed to be flight-qualifiable by

appropriate selection of processors and by using a single compact electronics package. The system provides at least an order of magnitude improvement in bandwidth over existing systems. In addition, by concentrating all of the computations in one place, it reduces the weight, power, and cabling requirements that would be necessary for a space application.

Enhanced graphics perception capabilities provide, in real-time, an overlay of computer-generated and real images of the robot and the task. This can be used to compensate for inevitable time delays, due to the physical separation between the operator and the robot. These advanced teleoperation experiments, performed in collaboration with several university researchers, are developing an experimental database on the trades between force-reflection fidelity and system stability, compensation for time delays, and strategies to optimize operator actions in the execution of simulated space tasks.

Sensing and Perception

A complementary set of experiments has been conducted at the Jet Propulsion Laboratory with an advanced robot control architecture which allows a robot to exhibit a certain level of intelligence and autonomy by acquisition and perception of sensory data and operation in partially unknown and unstructured environments. The robot is controlled by the operator by means of a built-in database with geometric computer models of objects, such as satellite panels, electronic modules, and fixtures, which are typical of space operations. The system has embedded in it, newly developed AI-based planning and control algorithms and software for automated design of spatial trajectories and for compliant grasp,

manipulation, and handling of objects in the robot environment. It can also respond by localized sensor-based reflex action to small changes in the position and force interaction between the robot and these objects. The autonomous system aims at liberating the human operator from having to specify in excruciating detail the actions that the robot should take, thereby freeing the operator to control and monitor the performance of a given task at a higher, simpler, and more abstract level of human-machine interaction.

Sensing and perception research has resulted in the development of new machine vision algorithms, software, and computer architectures. It has also led to experimental evaluation with a realistic satellite mockup. Enhanced vertex detection, tracking, camera calibration, and multi-resolution algorithms have been developed. A multi-resolution pyramid machine has also been configured from commercial data cube modules. The multi-resolution algorithms and computing architecture will allow performance of such computationally intensive vision tasks as rapid stereo matching and 3-D perception of dynes. These tasks are not feasible with current computational approaches. A satellite mock-up has been tracked using only natural features at 9.7 r/min, a typical spin rate for satellites in space. Tracking at the higher spin rate of 14 r/min has been achieved with visual labels as tracking targets. Labels would be used for the night portion of each orbit in which natural features would not be detected easily. Experiments have also been conducted on operator-assisted satellite acquisition using a joystick-controlled overlay.

Systems Architecture and Integration

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, as well as investigating applications to satellite servicing tasks, starting with the Hubble Space Telescope. 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 include the development 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.

Testbed

In January 1988, JPL began a series of core technology demonstrations, integrating several subsystems to perform a satellite servicing task. These demonstrations were carried out over several weeks, lasting until March 14, 1988. A mockup of a spinning Solar Maximum Mission (SMM) satellite was captured and docked with supervised autonomy and with dual-arm cooperative control, as reported in ATAC Progress Report 6.

More extensive tasks were performed to demonstrate the full integration of the subsystems. The arms were positioned randomly with respect to the worksite. The tele-robot, by knowing its joint coordinates and with a Cartesian model of the task space, was able to automatically compute the motions to open a door. Before opening the door, however, the telerobot correctly recognized a crank inhibiting the free motion of the door. The telerobot interrupted its intended task to first move the crank to a non-interfering position. Dual arms opened the door, cooperating to avoid joint singular-ities. One arm assisted the other by holding the door partly open, while the original arm repositioned itself to avoid the pose flip (to avoid exceeding the maximum excursion of the arm's joints).

The top level, NASREM level 4, of the telerobot architecture was shown for the first time. This subsystem is the basic high-level planning function of the telerobot. By coupling it with a powerful simulation tool, a real-time replanning capability was demonstrated, where one arm took over the tasks being performed by the other arm when the latter encountered a reach limitation. It is planned that in 1989 this capability will be integrated into an operator control station, being built by RCA. Also demonstrated was the wireframe, voice controlled part of the operator station, which can designate objects that are modeled, but are not located in the data base.

Many of the results derived from this integration work were reported to the FTS project at the Goddard Space Flight Center (GFSC) for the phase B studies. An example of the nature and significance of such results is the determination that real force reflection, where the control loop is closed at the operator site, requires a communication link operating at least at 200 Hz. The researchers and testbed integrators at JPL, however, formulated an alternate control scheme that, while limited to kinesthetic force reflection, is adequate for several tasks and can be implemented at only 30 Hz, thus significantly lessening the requirements for the data system.

Members of the JPL telerobotics research and testbed teams participated in reviews and working groups sponsored by the FTS project at GSFC. Significant contributions were made in the strawman design of the FTS and in areas such as FTS testbed functional requirements, FTS testbed interface specifications, computer architecture for the FTS development test flight, and FTS data rate requirements.

A smart end-effector, driven from a PC, was delivered to the FTS laboratory and may be operated later for evaluation and demonstration. Two force-reflecting hand controllers, consisting of

hardware and embedded software were built by JPL for the FTS laboratory testbed, and are now being modified at JPL to be compatible with the FTS (NASREM) architecture. In addition to these hardware items, several developmental software packages were delivered to GSFC for evaluation, related to functions such as machine vision, run-time control, and AI planning. The evaluation was successful and it is expected that the items will now be modified and adapted to operate with the FTS laboratory systems.

APPENDIX F

Summary of the Advanced Development Efforts of the Office of Space Flight in A & R Technology

There has been a recent surge of interest in the application of technology to space flight operations and processes. The objective is "to reduce the cost of access to space by identifying, advocating, and demonstrating key technologies and approaches to improve operations efficiency, reduce the operations costs, and improve the reliability of space transportation systems operations while continuing to meet flight safety and performance requirements and supporting overall agency and Office of Space Flight (OSF) goals." To achieve this objective, high leverage operations technologies which have the potential to reduce operations costs and to improve reliability must be identified. Such technologies must be important considerations in the design of future transportation systems and in the early definition of operations concepts.

To effectively support a high flight rate and to support Space Station operations in terms of cost, manpower, reliability, and facility requirements, it is necessary to determine new ways of doing business, rather than to simply streamline current operations, procedures, and techniques. Potential areas for the development and application of technology, including payload requirements definition and integration, flight design, operations planning, crew activity planning, ground crew and flight crew training, flight reconfiguration, on-orbit operations and spacecraft servicing, data management, and control center operations are being pursued at the Johnson Space Center.

NASA began the development of an advanced automation capability at Kennedy Space Center (KSC) in 1984. This effort included the development of three artificial intelligence development laboratories: one in the Shuttle Launch Processing Directorate, one in the Cargo Processing Directorate, and one in the Design Engineering Directorate. The goal of the KSC automation development effort has been to implement automation systems that will improve the efficiency, reliability, quality, and safety of the Space Shuttle and of cargo processing operations.

For several years, Marshall Space Flight Center (MSFC) has conducted studies of the design of teleoperated on-orbit servicing techniques and hardware. Center roles have not yet been finalized in the further development of the Satellite Servicer System (SSS); however, it is expected that MSFC, JSC, and GSFC will be involved.

These programs are providing both near and longer term developments in automation and robotics, whose benefits will apply across space transportation, Space Station, and all other NASA programs. It is important that these efforts continue.

Automation

Operations automation, the application of systems automation to the operation of manned spacecraft, has been under study at JSC. Currently, there are several significant technology applications, initiated as either Research and Technology Operating Plan (RTOP) activities or included in the Operations Effectiveness Initiative, sponsored by the Advanced Program
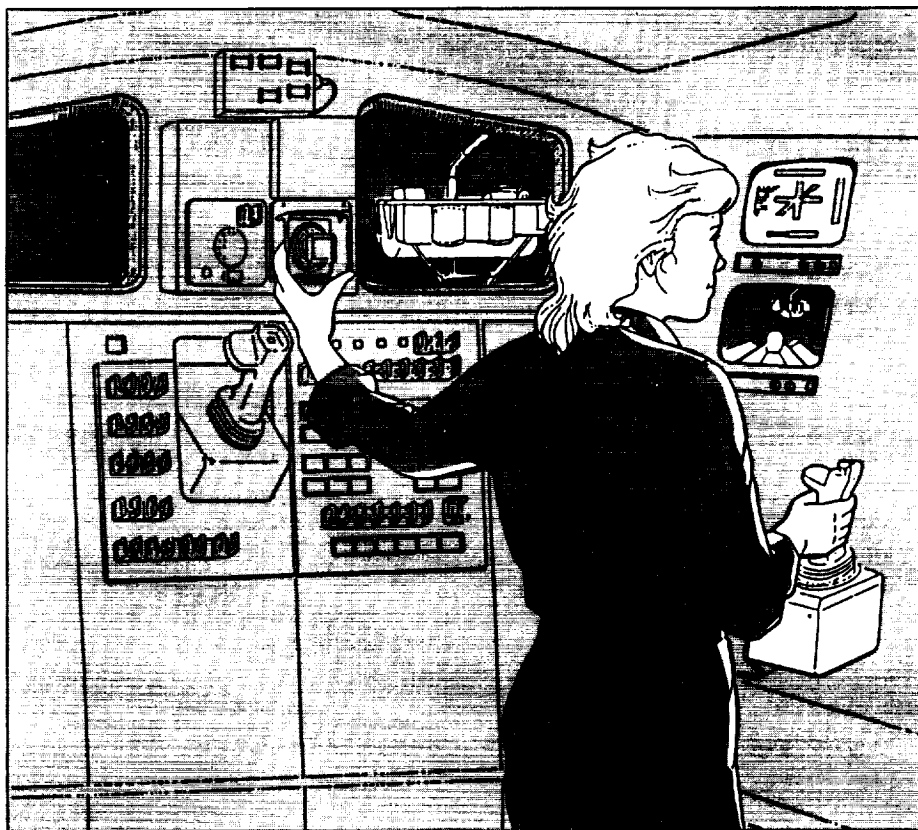

Figure F-1.— Force/torque sensing system enhancing the Space Shuttle Remote Manipulator System (RMS) capability.
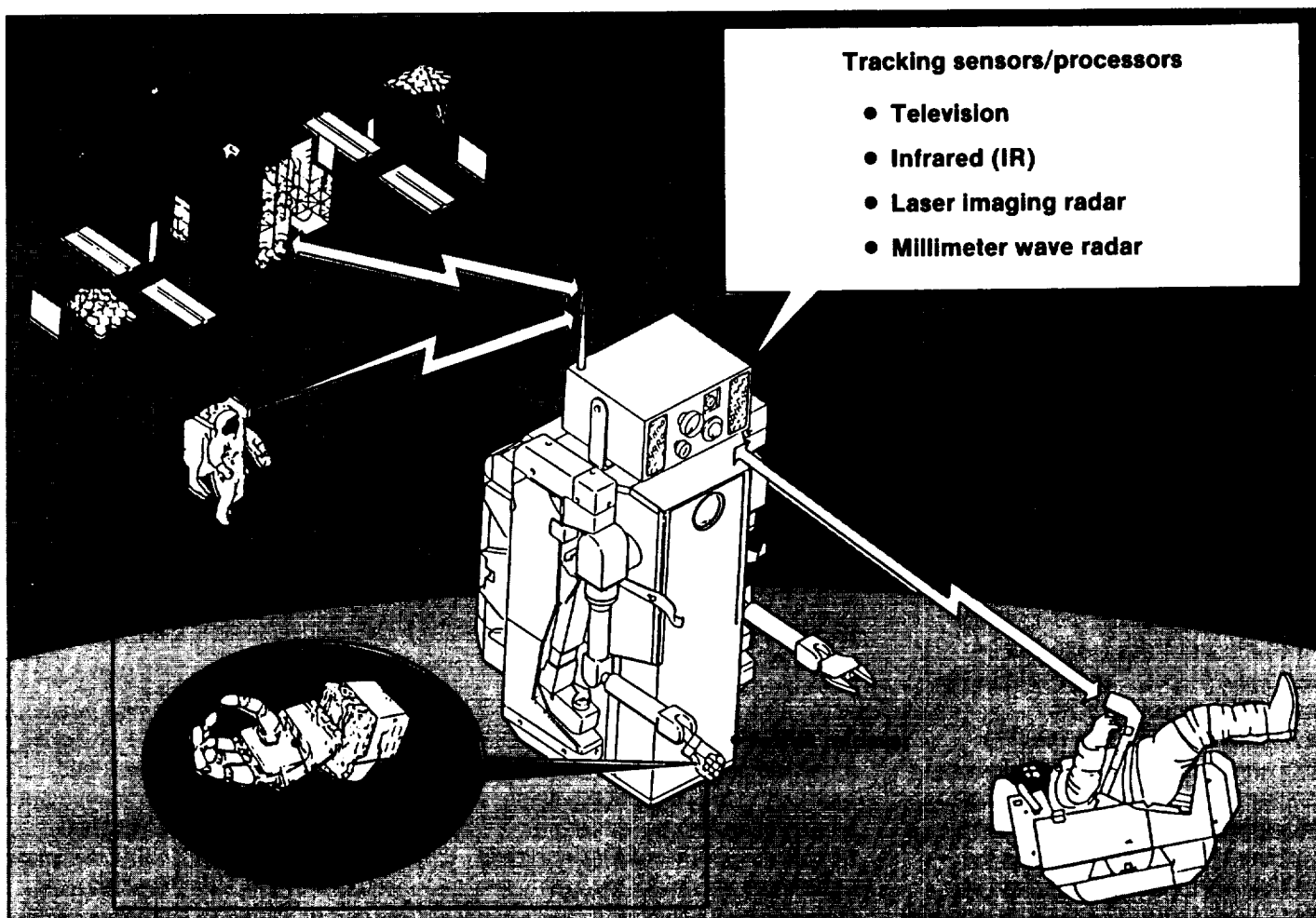
Figure F-2.— EVA Retriever conceptual design.

Development Office, OSF. The goal of the Operations Effectiveness Initiative is to identify and demonstrate new or enhanced processes or technologies, to be applied to ground and flight operations by selective applications of expert systems, robotics automation, and other technologies and processes whose applications during the design and development of future vehicles and systems will yield reduced life cycle costs. Ongoing significant technology applications include:

- Integrated autonomous operations testbed
- Automated software development workstation
- Knowledge-based system tool in Ada

- Intelligent computer-aided training
- Mission Control Center onboard navigation expert system
- Application of expert systems to onboard system management
- On-orbit ground tracking scheduling (TRACKEX)

At KSC, an automated diagnostics system for the liquid oxygen loading system for the Space Shuttle has been developed and used in five previous launches. The knowledge gained in this development will be applicable to the development of on-orbit refueling operations in the future. The Knowledge-based Autonomous Test Engineer (KATE) has begun as a quantitative diagnostics and control shell for the

Space Shuttle Environmental Control System (Shuttle hangar air conditioner). Its development will continue to encompass all Space Shuttle launch processing systems to achieve complete autonomous operations for the Space Station through a proposed project with OSS, to start in FY 89.

Robotics

The assembly of the Space Station and the subsequent implementation of the satellite service and transportation node functions of the Space Station depend heavily on the ability to effectively use telerobotics. The force/torque sensor, magnetic

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attachment tool, and the target and reflective alignment concept are enhancements to the Space Shuttle Remote Manipulator System (RMS), as illustrated in figure F-1. The knowledge and experience gained from these programs prior to the Space Station Remote Manipulator System and FTS operations are vitally important to realizing an effective A & R concept for the Space Station.

The EVA Retriever concept, being developed at JSC, is focused on the development of the technologies for a system which would be permanently employed aboard the Space Station and would be in a hot-standby mode during EVA or intravehicular activity (IVA) activity. The unit could also evolve as an astronaut helper. The EVA Retriever concept (figure F-2) is an autonomous free-flying robot for retrieving equipment or for retrieving a spacewalking astronaut drifting in separated flight near the Space Station. The device combines the proven Manned Maneuvering Unit (MMU) with a robot latched-in where an astronaut would normally be. Television tracking and laser ranging signals are used by "intelligent" software in an onboard computer system for pattern recognition, perception, and path planning to command search and rendezvous maneuvers. Robotic arms and hands are used to grapple the target when in range. An important milestone in its development was reached this year when a simplified-vocabulary model was tested on a two-dimensional air-bearing floor simulation. The model carried out commands and acknowledged them with a synthesized voice.

A robotics development project is under way at KSC to perform automated connect/disconnect of STS External Tank GH2 vent umbilicals. This technology will be useful in designing on-orbit fluid transfer systems and in understanding the applications of robotics
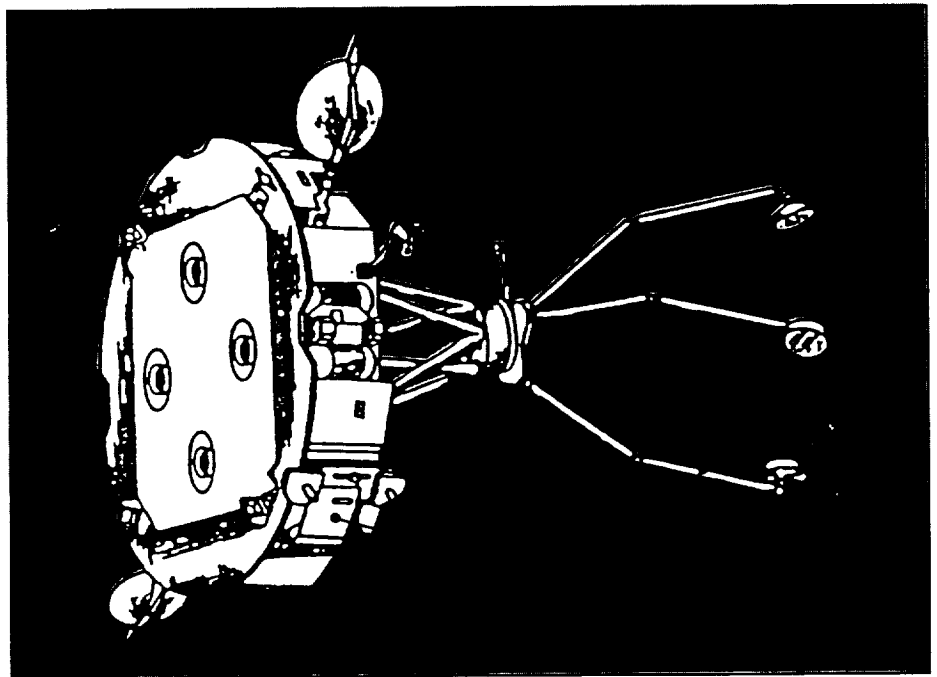

Figure F-3.— Tumbling Satellite Retrieval (TSR) kit.

in vehicle safing and launch processing in space. At the same time, KSC is also developing a Robotics Applications Development Laboratory, a state-of-the-art laboratory containing a large-capacity industrial robot, sophisticated computer and software systems, and several mockup testbeds. Remote operation of automated servicing and checkout robots, to be demonstrated in the laboratory, will be similar to the same scenarios for remote operations on the Space Station.

Two important developments closely related to the Flight Telerobotic Servicer project are underway at MSFC. These include the Tumbling Satellite Retrieval (TSR) kit and the Satellite Servicer System (SSS). The TSR kit (figure F-3) has been under study at MSFC for several years. When outfitted on an Orbital Maneuvering Vehicle, it will be used to recover prematurely-failed satellites for repair and reuse or to retrieve one that has completed its design life and has ceased operation. Also, removal and disposal of "junk" satellites, spent upper stages, motor

casings, and other space debris will make it possible to preserve the operational integrity of high-traffic zones in space. The first of two study phases for the TSR are scheduled to be completed in August of 1988, with the definition of a system concept. Ground testing and simulation will be conducted in the next phase.

During 1988, a concentrated effort was initiated to define a new project initiative, leading to the development of a Satellite Servicing System. This system draws on many years of analytical studies and robotic simulation activities, conducted at MSFC, in the maintenance of free-flying spacecraft at the module level. These studies have clearly shown that spacecraft programs may derive considerable economic benefits by combining modular maintenance and expendable resupply. Further demonstrations at MSFC have shown that technology exists to build a supervised automated system. Current NASA planning calls for the establishment of system requirements by October 1988 to support preliminary design initiation in early 1989.

R&D activities related to A & R

Table F-1 summarizes current research and development (R&D) activities in automation and robotics, which are funded by the OSF. Listed are the topics of work, brief descriptions, and the cognizant Center performing the developments.

TABLE F-1.— OSF RESEARCH AND DEVELOPMENT IN A & R

Title	Institution	Objective
Knowledge-based/expert systems		
Knowledge-Based Autonomous Test Engineer (KATE)	KSC	Continuing development to cover all Shuttle launch processing systems for complete autonomous checkout operations
LOX Expert System	KSC	Automated diagnostic system for the Shuttle liquid oxygen loading system
Automatic Test Expert (ATE) Air System Environment	KSC	Expert system designed to facilitate the development of automated test equipment and programs used for testing Shuttle firing room hardware boards
Electric Field Mill Network Analyst (EFMN)	KSC	Expert sytems software which mimics the reasoning of the experienced field mill network data analyst
Communications Trouble Desk	KSC	Development of an expert system to assist the operator of the trouble desk for the KSC communications system
Automated Software Development Workstation	JSC	Develop a knowledge-based environment for the construction of special purpose systems for the generation of applications software
On-board Ground Tracking Scheduling (Trackex)	JSC	Develop an expert system to automate and optimize Shuttle radar tracker selection. S-band & C-band trackers are scheduled in conjunction with TDRSS coverage
Application of Expert Systems to Onboard System Management	JSC	Develop an expert system which is capable of managing multiple subsystems
Intelligent Computer Aided Training	JSC	Integrate expert system technology with training methodologies to develop autonomous intelligent systems
Knowledge-based/expert system		
Knowledge Based System Tool in Ada	JSC	Use Ada to develop a state-of-the-art tool for constructing expert systems
Mission Control Center Onboard Navigation (ONAV) Expert System	JSC	Develop an ONAV console expert system to automate the monitoring in real-time of onboard hardware and software
Sensing/diagnostic		
Force/Torque Sensor for the Remote Manipulator System (RMS)	JSC/JPL	Development of a force/torque sensor to add feedback through the Shuttle RMS
Remote Maintenance Monitoring System (RMMS)	KSC	Develop automated real-time diagnostics system for Shuttle firing room computer systems
Operational Analyst (OPERA)	KSC	Develop automated real-time software diagnostics and configuration control system for Shuttle firing room software systems
Thunderstorm Weather Forecasting Expert System (TWFES)	KSC	Scenario-based reasoning system to assist USAF in predicting timing and location of thunderstorms during critical Shuttle operations

TABLE F-1.— OSF RESEARCH AND DEVELOPMENT IN A & R (continued)

Title	Institution	Objective
Manipulation/robotic systems		
Magnetic Attachment Tool (MAT)	JSC	Development of the MAT to temporarily hold objects at the end of the RMS, as an alternative to the standard end-effector
Target and Reflective Alignment Concept (TRAC)	JSC	To provide direct manipulator-to-object alignment and targeting
EVA Retriever Concept	JSC	Utilize a free-flying robot for retrieval of equipment drifting near Freedom Station, using voice command control
Automated Connect/Disconnect of Shuttle ET GH2 Vent Umbilicals	KSC	Demonstrate the use of advanced robotics to perform the connecting/disconnecting of the "T-O" umbilicals
Remote Shuttle Payload Bay Inspection and Closeout	KSC/JPL	Develop the capability for remotely controlled closeout functions and payload bay inspections
Tumbling Satellite Recovery	MSFC	Development of an OMV kit for retrieval of free-flying spacecraft in a stable control mode. Can be extended to unstable spacecraft or certain classes of debris
Satellite Servicer System (SSS)	HQS*	Supervised automated maintenance of remote free-flying spacecraft at the module level
Integrated Autonomous Operations Testbed	JSC	Define a system architecture and develop a testbed which supports the integration of technologies for autonomous on-orbit operations
Human/machine interface		
Intelligent Launch Decision Support System (ILDSS)	KSC	Scenario based reasoning system to assist NASA launch director and flow director personnel during critical launch operations
Expert Mission Planning & Replanning System (EMPRESS)	KSC	Interactive planning system with some auto-replanning capabilities. Based on USAF CAMPS architecture
Intelligent Computer Aided Training (ICAT)	KSC	Development of a computer aided training system for firing room and systems engineering operations personnel

*Lead center for this activity has not been determined.

APPENDIX G

Expenditures for Advanced Automation and Robotics

ATAC has not attempted to obtain refinements to the estimated expenditures reported in ATAC Progress Report 6. Deviations in funding from the previous report are believed to be minimal.

TABLE G-1.— NASA FUNDING FOR AUTOMATION AND ROBOTICS

[Fiscal year funding, millions of dollars]

Office and activities	FY 85	FY 86	FY 87	FY 88
Space Station	5.8	18.1	24.9	40.6
Definition phase	(5.8)	(8.1)	(4.9)	—
Advanced development	—	—	—	(20.6)
Flight Telerobotic Servicer augmentation	—	(10.0)	(20.0)	(20.0)
Aeronautics and Space Technology	N/R	10.2	18.0	25.4
Ground demonstrations				
Telerobotics				
Systems autonomy				
Core technologies, such as				
Sensing and perception				
Task planning and execution				
Control execution				
Operator interface				
System architecture and integration				
Definition of user needs				
Space Flight	N/R	4.6	4.5	9.7
Robotics				
OMV servicing and refueling				
Automation				
Space Science and Applications	N/R	0.7	0.8	2.5
Information system and telescience				
Servicing				
Payload carriers and pointing systems				
Space Operations	N/R	1.0	1.2	4.0
Space Tracking and Data Systems				
Commercial Programs	N/R	N/R	N/R	3.8
Commercial use of space				
Technology utilization				
Small business innovation research				
Total NASA funding, approximately	—	34.6	49.4	86.0

N/R — Data was not requested by ATAC

APPENDIX H

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APPENDIX I

Acronyms

A & R	automation and robotics
AAWG	Advanced Automation Working Group
AI	artificial intelligence
AIESTWG	Artificial Intelligence, Expert Systems, and Technology Working Group
ARC	Ames Research Center
ATAC	Advanced Technology Advisory Committee
CLIPS	C Language Integrated Production System
CSTI	Civil Space Technology Initiative
DARPA	Defense Advanced Research Projects Agency
DMS	Data Management System
DTF	Development Test Flight
EPS	Electrical Power System
EVA	extravehicular activity
FDIR	fault detection, isolation, and recovery
FTS	Flight Telerobotic Servicer
FY	Fiscal year
GSFC	Goddard Space Flight Center
INCO	Integrated Communications Officer
IOC	initial operating configuration
IVA	intravehicular activity
JPL	Jet Propulsion Laboratory
KBS	knowledge-based system (s)
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LeRC	Lewis Research Center
LOX	liquid oxygen
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASREM	NASA/NBS Standard Reference Model
OAST	Office of Aeronautics and Space Technology
OCP	Office of Commercial Programs
OE	Office of Exploration
OMS	Operations Management System
OMV	Orbital Maneuvering Vehicle
ORU	orbital replaceable unit
OSF	Office of Space Flight
OSS	Office of Space Station
OSSA	Office of Space Sciences and Applications
PDR	Preliminary Design Review

PDRD	Program Definition and Requirements Document
PRD	Program Requirements Document
PRR	Program Requirements Review
R&D	research and development
RFP	request for proposal (s)
RMS	Remote Manipulator System
RWG	Robotics Working Group
SSE	Software Support Environment
SSIS	Space Station Information System
STS	Space Transportation System
TDRSS	Tracking and Data Relay Satellite System
TMIS	Technical and Management Information System
USAF	United States Air Force
WP	work package

APPENDIX J

NASA Advanced Technology Advisory Committee

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16. Abstract

In April 1985, as required by Public Law 98-371, the NASA Advanced Technology Advisory Committee (ATAC) reported to Congress the results of its studies on advanced automation and robotics technology for use on the Freedom space station. This material was documented in the initial report (NASA Technical Memorandum 87566).

A further requirement of the law was that ATAC follow NASA's progress in this area and report to Congress semiannually. This report is the seventh in a series of progress updates and covers the period between April 1, 1988 and September 30, 1988.

NASA has accepted the basic recommendations of ATAC for its Space Station Freedom efforts. ATAC and NASA agree that the thrust of Congress is to build an advanced automation and robotics technology base that will support an evolutionary Space Station Freedom program and serve as a highly visible stimulator, affecting the U. S. long-term economy.

The progress report identifies the work of NASA and the Freedom study contractors. It also describes research in progress, and it makes assesments of the advancement of automation and robotics technology on the Freedom space station.

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