NASA Technical Memorandum 89190

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

Progress Report 3 — April Through September 1986

Advanced Technology Advisory Committee
National Aeronautics and Space Administration

Submitted to the
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NASA
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Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

Synopsis

Congress recognized, in 1984, the merit of developing a new generation of general purpose automation and robotics technology using the Space Station as a stimulus. This technology would be efficient and flexible enough to meet not only the needs of the Space Station but also needs, as yet only partly specified, in the terrestrial economy of the United States.

NASA, the work package contractors, and the international partners in the Space Station have continued their efforts to incorporate automation and robotics (A & R) in the preliminary design of the Space Station and their support of research that will improve the technology base. During the past 6 months, studies have focused on the conceptual design of a few high priority A & R candidates for the initial station.

Although critical issues remain, substantial progress has been made in the development of a U.S. telerobotic capability for the initial Space Station. ***But key steps need to be taken to accommodate the knowledge-based systems required for an autonomous Space Station.*** These knowledge-based systems would increase reliability and performance while saving crew time and reducing the need for ground operations support. The key steps include establishing in the design process a balanced view of initial and life cycle costs, "capturing knowledge" of Space Station design as it evolves, emphasizing automation and robotics in the requests for proposals (RFPs) issued for the design and fabrication phase (phase C/D), elevating automation and robotics in the program management structure, and increasing the funding priority for advanced development of automation.

The Advanced Technology Advisory Committee (ATAC) has continued to monitor the efforts in automation and robotics made by the Space Station Program and related groups. A summary of the committee's assessment of progress thus far is as follows.

1. Major progress has been made by NASA and the study contractors in the definition and preliminary design of applications and technologies for automation and robotics on the Space Station. ***The findings of the studies conducted are sufficient to merit the extensive inclusion of automation and robotics in the initial operating capability (IOC) and growth stations.***

2. ATAC is concerned that planning for operations and system autonomy is not progressing quickly enough to influence design in a major way and that consequently ***the benefit in life cycle cost offered by advanced automation is not being appreciated or balanced against initial cost.*** This lack of appreciation can have an adverse effect on the inclusion of design accommodations and on the capture of critical design knowledge required for future incorporation of automation and robotics in an evolutionary Space Station.

3. ***A & R considerations must be given high priority and weight in the process of procuring integration and hardware contractors for the design and fabrication phase (phase C/D) of the Space Station.*** The requests for proposals and proposal evaluation criteria must be oriented to selection of contractors who are innovative and comprehensive in their inclusion of automation and robotics in station design, who propose architectural concepts for the Space Station which will allow the incorporation of extensive automation and robotics in an evolutionary station, who are committed to capturing the design knowledge and to including the data bases required for robot-friendly design and evolution to an autonomous station, who include automation and robotics in the initial station to the extent possible within cost priorities, and who propose designs that give a balanced consideration to operational as well as initial costs.

4. ***NASA is perceived by some agency elements and study contractors as not committed to the inclusion of A & R recommendations.*** This perception is reinforced by program deficiencies such as no designated A & R systems engineer, no formal A & R technical integration panel, no A & R representation on station control boards, and no A & R advanced development program. If the Space Station is to have significant automation and robotics (besides the telerobot), the highest levels of NASA program management must give explicit direction, in word and in image, to the program elements and contractors

that the Space Station is not just acquiescing to automation and robotics, but is deeply committed to it. Evaluation criteria with major weight must be explicitly stated in the RFPs for phase C/D so that bidders know their proposals will be evaluated in terms of the quantity and quality of their A & R content. And, rather than allowing each element of the program to decide which A & R options to pursue and implement, the Space Station Program must conduct the systems engineering analysis necessary to set priorities on the A & R options, so that program managers can make informed tradeoffs and choices.

5. ATAC believes that the benefits of manipulators and robots are being recognized by Space Station Program elements as they study assembly and servicing requirements. The committee is concerned, however, that ***use of the telerobot for Space Station assembly and for station maintenance, as considered important by ATAC and intended by Congress, has not yet been planned.***

In Public Law 98-371 and related reports, Congress put forward an "affirmative action" program for automation and robotics which would make the Space Station a showcase user and driver of A & R technology for the benefit of the station and the U.S. economy.

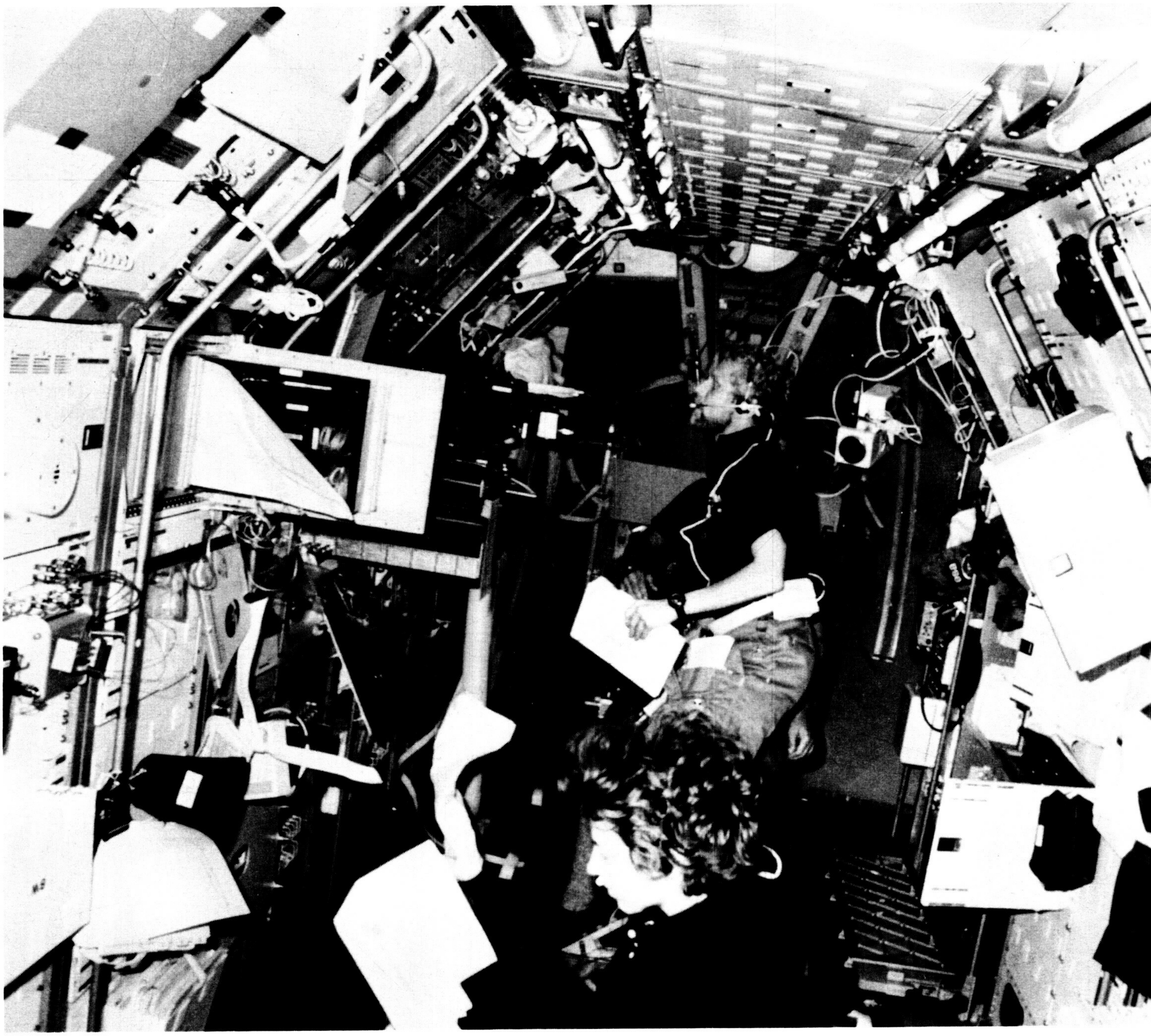
The approach taken by NASA has been to evaluate automation and robotics on its own merits, on the basis of trade studies within the Space Station Program. And, within the context of an unbalanced weight toward design-to-initial-cost for the Space Station initial operating capability, ***automation and robotics is not receiving sufficient priority.*** Although the costs of design, development, test, and evaluation (DDT&E) for automation and robotics are significant, the benefits, distributed over time, will greatly exceed the costs.

Congress has responded by setting aside funds to ensure an important national initiative in robotics. But an even larger payoff is projected in automation, which appears to offer a 2-4 year payback of its costs to the Space Station and has potentially greater benefits for the U.S. economy. Without an incentive comparable to that for robotics, automation may not receive adequate emphasis.

Because achievement of adequate system-level automation is primarily a top-down or systems integration activity and because the required bottom-up or subsystem studies are largely completed, ***ATAC has recommended that a strong management organization, with authority at level B and an identified target for automation expenditures, be established by NASA before the final drafting of the phase C/D RFPs.*** Otherwise, the retrofit of automation to the Space Station will be both prohibitively expensive and impractical.

ATAC has recommended to NASA that it provide greater management support for automation and robotics, especially automation. This support includes a balanced view of operational costs, a commitment to capture of design knowledge, and additional priority for advanced development and basic research in automation and robotics.

The NASA Administrator has asked the Program Manager to provide a written overview of the role of automation and robotics in the Space Station Program. This document should bring welcome clarification.



As intelligent machines earn trust by being reliable, they will amplify people's productivity and increase the scientific proportion of their work in future space laboratories.

Preface

In April 1985, as required by Public Law 98-371, the NASA Advanced Technology Advisory Committee (ATAC) reported to Congress the results of its study of automation and robotics technology for use on the Space Station. A further requirement of the law is that ATAC follow NASA's progress in this area and report to Congress semiannually. This report is the third in a series of progress updates and covers the period between April 1 and September 30, 1986. (However, progress and program changes occurring after August 12, 1986, are not reflected in this document.)

ATAC expects to get fewer details from the contractors during the period beginning October 1986, because they will be refining their current implementation plans for automation and robotics (A & R) and competing for the design and construction phases of the Space Station. A critical assessment period will be the one beginning April 1987, which will reveal the specific A & R designs included in the proposals of the winning contractors. ATAC plans to review Space Station configuration and assembly plans and operations plans from an A & R perspective in future progress reports.*

The drafts of this document were prepared by the Artificial Intelligence and Information Sciences Office at NASA's Johnson Space Center.

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*ATAC has not assessed, and neither expresses nor implies any opinion of, the advantages of one contractor over another. Any imbalance of material included in this report perceived by the reader should be considered insignificant.

A generic robot can assist the crew in assembly, maintenance, servicing, deployment, retrieval, and transportation. This illustration depicts a robot changing out an orbital replaceable unit. (Courtesy of McDonnell Douglas.)

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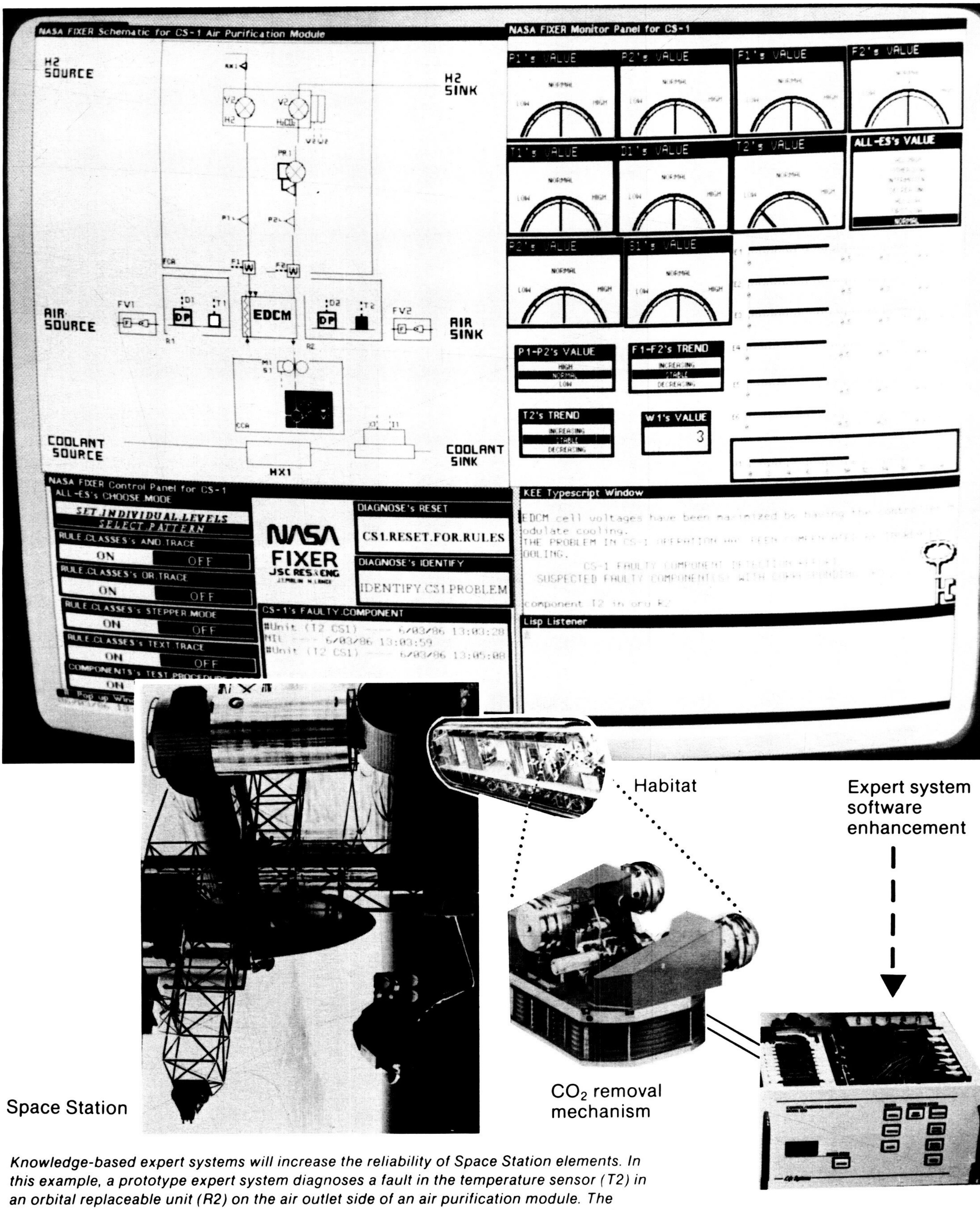

Knowledge-based expert systems will increase the reliability of Space Station elements. In this example, a prototype expert system diagnoses a fault in the temperature sensor (T2) in an orbital replaceable unit (R2) on the air outlet side of an air purification module. The expert system, after diagnosis, has commanded a controller to modify the operation of the coolant valve (W1, V1) in the electrochemical depolarized CO_2 concentration module (EDCM) to maintain safe operation until the fault can be corrected. (Courtesy of Johnson Space Center.)

Introduction

In a study mandated by Congress, recommendations were made and an approach to the implementation of advanced automation and robotics (A & R) on the Space Station was outlined. This work was documented in the initial report of NASA's Advanced Technology Advisory Committee (ATAC), submitted April 1, 1985 (ref. 1). The first year's progress toward implementing the recommendations was assessed in ATAC Progress Reports 1 (Oct. 1, 1985—ref. 2) and 2 (Apr. 1, 1986—ref. 3).

The NASA Space Station Program has continued to make progress in the definition and preliminary design of automation and robotics for the Space Station. The progress reported in this document has been assessed from Space Station Program reviews, from reviews of the implementation plans of phase B study contractors, from reviews of workshop documentation, and from an ATAC review held to address selected topics of concern to ATAC.

This report of progress occurs at a critical time in the Space Station Program. The management structure of the Space Station Program is being reorganized and NASA has new leadership of both the program and the agency. Phase B preliminary definition and design studies are nearing completion, a baseline configuration of the station is being established, and the requests for proposals for the design and fabrication phase (phase C/D) of the program are being prepared and will soon be issued.

An assessment of progress with respect to the ATAC recommendations is given in the following section. This assessment, along with the synopsis and conclusions, provides a top-level view of progress for this reporting period.

The submission during this period of the report (ref. 4) of the National Commission on Space, chaired by Thomas Paine, is noteworthy. In its discussion of building the technology base for piloted spacecraft, the commission advocated an approach similar to that espoused by ATAC. The commission report says,

"We need an integration of humans and machines, each augmenting the other's capabilities, to meet future transportation needs. Enabling technologies include tools, life support and health maintenance, and astronaut selection and training.

"Robotics is an extremely powerful tool, especially for extravehicular activity (EVA). The goal of our technology base in this area should be to replace EVA with robotics for routine satellite servicing and fueling operations. This is a repeatable and predictable activity and should take full advantage of robotics. For lunar distances, sensory-motor coordination of a space-situated robot's hands and eyes can be entirely within the brain of a human operator; for more remote operations, the robot itself must have this capability. NASA's robotic technology program should not follow U.S. industry, but should lead it, as industry thrusts will not produce the sensitive robotics needed for space operations."

In a subsequent paragraph, the report says,

"A third class of tools is expert systems. We propose a goal of providing sufficient on-board capability for semi-autonomous spacecraft repair, maintenance, and replanning for those conditions with communication delays. Current systems are too inflexible and rule-based: they need to evolve into self-diagnosed model-based systems. We recommend that: NASA **explore the limits of expert systems, and tele-presence or tele-science for remote operations, including ties to spacecraft and ground laboratories. In working toward these goals, a broad examination of the non-space applications of tele-science should be included."**

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

As in the previous reports, this section provides a summary assessment of the progress NASA has made toward fulfilling the recommendations originally made by the committee and adopted as policy by NASA. For convenience, each recommendation is stated before the assessment of progress.

1. Automation and robotics should be a significant element of the Space Station Program.

NASA, the contractors, and the international partners, in their definition studies, have identified a broad range of candidate A & R applications for all Space Station systems and subsystems (app. D). Preliminary design studies focusing on the most critical needs of the initial station are underway. Significant NASA and contractor activities in research and development have been pointed toward prototype expert systems for Space Station applications. Plans include the evaluation of selected candidates in demonstration test-beds. Work package contractors have issued updated versions of A & R implementation plans (refs. 5-11).

Congress has ensured an aggressive program in telerobotics for the station through its set-aside funding initiative. A lead center (Goddard Space Flight Center) has been selected, participation by other centers has been defined, and development and integration planning is proceeding at a vigorous pace.

The congressionally supported telerobotic servicer (TRS), a Canadian-provided mobile servicing system (MSS), and the Technical and Management Information System (TMIS) have been built into the Space Station Program Definition and Requirements Document (PDRD) (ref. 12). The configuration and assembly panel has addressed station assembly and the role of robotic elements.

Those responsible for A & R studies have clearly paid serious attention to the inclusion of automation and robotics in the Space Station. However, not all of those responsible for system and subsystem design have given this same level of consideration to including automation and robotics in the station. The role provided for automation and robotics in the management structure of the Space Station Program has not proved adequate for proper consideration of automation and robotics. Automation and robotics is not represented on the control boards governing station design decisions and does not have an equal voice in critical decisions. And no technical discipline or funding for automation and robotics as an entity has been established within the advanced development project of the Space Station Program.

Although teleoperation and telerobotics have been ensured, ATAC is concerned that advanced automation will not be the significant element desired. ***For automation to be a significant element of the Space Station Program, either greater weight must be given to life cycle costs or funds must be set aside for this area of technology.***

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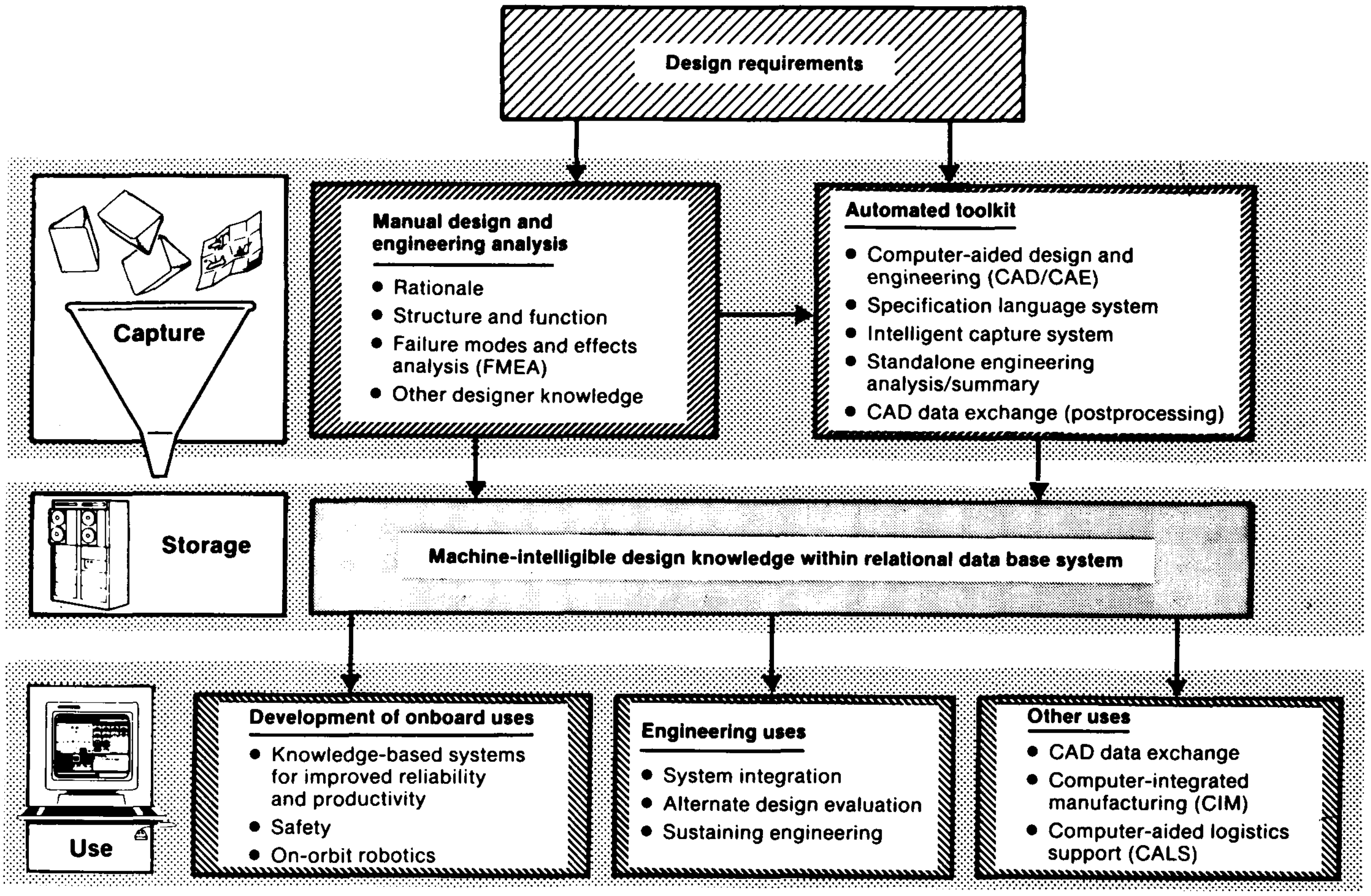
2. The initial Space Station should be designed to accommodate evolution and growth in automation and robotics.

Although A & R advocates within NASA and among the work package contractors have addressed this top priority issue in a serious way, their ***results have not yet been incorporated into the Space Station design control documents to be used in the phase C/D RFPs.***

The principal exception to this deficiency is the architectural control document (ACD) for the Space Station data management system (DMS). The DMS architectural control document delineates multiple, significant hooks and scars for accommodation of the future growth of the station and embraces many of the concepts that were put forth in the initial ATAC report (ref. 1). A further evaluation will be obtained when the DMS test-bed is used to evaluate expert system interfaces, as described later in this report.

ACDs for other Space Station distributed systems and baseline configuration documents (BCDs) for Space Station flight elements generally make scant, if any, mention of the evolution and growth considerations identified in previous ATAC reports. And the Program Definition and Requirements Document, which provides the functional requirements for the ACDs and BCDs, does not include functional requirements for "friendliness" to robots or knowledge-based systems. Although these documents are not yet final, ***ATAC is concerned that this deficiency in the control documentation process may reflect deficiencies in the design.***

In the plans for the Technical and Management Information System and the Space Station data management system, the committee sees evidence of provisions for the



The design process transforms design requirements into design solutions. The design knowledge created in this process is either captured by automated design tools or produced by conversion from manual methods. Both the design solution and the designer's knowledge that led to the solution are retained in an integrated data base. Opportunities for computer integration are extended to problems that require reasoning about the design, because the designer's knowledge is computer-intelligible.

storage and communication of design knowledge data bases. There appears to be an intent to capture the physical measurements and specifications of the engineering design of the Space Station. But ***adequate priority does not appear to be given to the capture of the "whys" or rationale used in the design process—knowledge needed to support later operation of expert systems.*** Without this design knowledge capture, ground operations personnel will be employed to become the experts in operations and diagnosis of less reliable systems.

The committee has recommended to NASA that the A & R requirements for design knowledge capture be included in the phase C/D requests for proposals and that the proposal selection criteria include contractor awareness of the critical issues of this ATAC recommendation. There is serious concern that, if this recommendation is not acted on, then automation will never become a significant part of the evolutionary Space Station and would have to be added on to the completed design at major cost.

3. The initial Space Station should utilize significant elements of automation and robotics technology.

A clear path has been established for the incorporation of telerobotic capabilities to support station assembly, maintenance, and servicing and to serve as a smart front end for the orbital maneuvering vehicle (OMV). Goddard Space Flight Center has been selected as lead center for the Space Station telerobotic servicer, and an active planning effort is underway, including technology development and demonstration plans detailed later in this report.

The list of possible applications of automation and robotics given in previous reports has been refined, with relatively few additions and deletions. The preliminary design phase has concentrated on a few of the most promising of these candidates because resource priorities are expected to severely limit their implementation for the initial operating capability. The Space Station Program Office has constructed a data base as an element of a plan to track the progress of candidate A & R applications and to record the rationale for decisions on inclusion or exclusion.

Progress continues to be made in planning the type of demonstrations suggested by ATAC. Noteworthy are those planned within the telerobotics initiative, the demonstrations in robotics and system autonomy planned by the Office of Aeronautics and Space Technology (OAST), and plans for use of the Space Station advanced development test-beds.

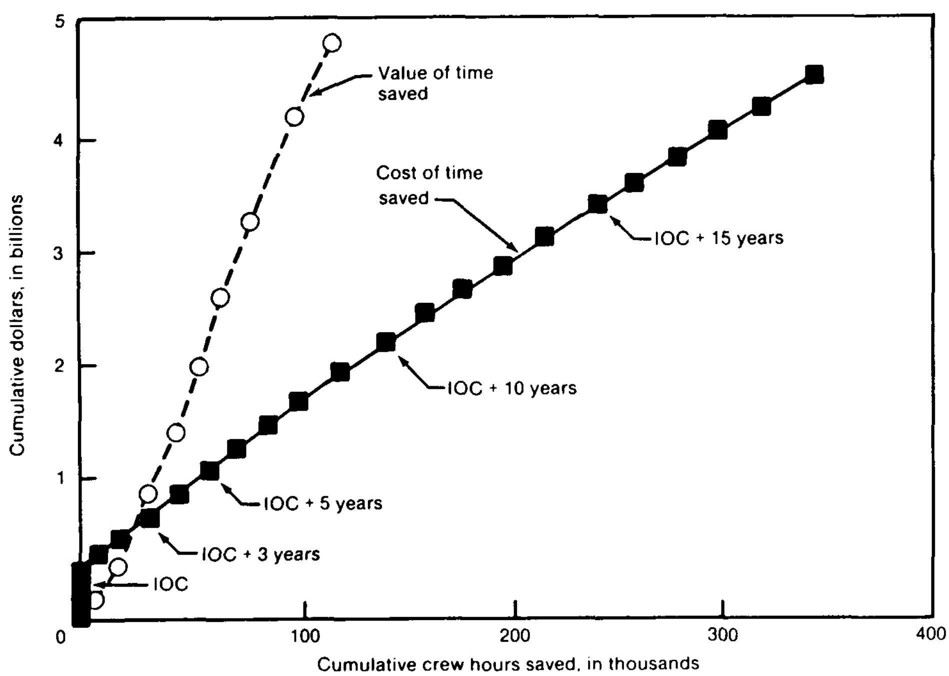
With the exception of the telerobotics initiative, however, ***actual inclusion of A & R technology may be inhibited by the stringent priorities within fiscal limitations unless proper account is taken of the benefits that A & R technologies can provide, such as reductions in operation costs and in demands on crew time.***

Crew participation in A & R studies has been very limited to date, and this lack of participation is considered a program deficiency. Close association, over a relatively long period, is required for crew confidence in automation and robotics to be established.

4. Criteria for the incorporation of A & R technology should be developed and promulgated.

Assessments of the candidate A & R applications have been carried out to varying degrees. Such assessments must start with a characterization of the application (cost, weight, power needed, etc.). NASA wants to select applications for automation on the basis of such criteria as crew safety, design performance, crew productivity, growth and evolvability, technology risk, and benefits to the U.S. economy, as well as the criterion of life cycle cost.

While there is a desire to use automation and robotics to minimize life cycle costs, A & R designs that rate high on the other criteria must also be given serious consideration. However, the Space Station Program has not implemented a method for balancing the various costs and benefits of automation and robotics and for guiding decisions regarding adoption of A & R candidates. At this point in the conceptual design of the station, the contractor A & R studies have implemented comprehensive selection criteria to varying degrees. Generally, there has been a tendency to simply rank A & R candidates (either analytically or judgmentally) rather than to attempt a life cycle cost minimization. Current plans would not implement uniform across-the-station evaluation before phase C/D.



The life cycle benefits of advanced automation and robotics will greatly exceed its initial costs. A time-phased A & R plan for station operations and maintenance would provide a financial benefit (in terms of the additional crew time available for science in space) within 3 years of initial operating capability. (Plan and analysis by Boeing.)

5. Verification of the performance of automated equipment should be stressed, including terrestrial and space demonstrations to validate technology for Space Station use.

It is still too early to assess the program for test and verification of specific Space Station equipment. ***There is a need to require demonstration results and further test plans in the phase C/D proposals.*** As noted in ATAC Progress Report 2, concern over lack of an integrated plan for demonstrations was somewhat allayed by the existence of plans for demonstration experiments by the Space Station Program and other NASA elements.

The plan to have an early test of the telerobotic servicer on the Space Shuttle is considered a good one. It will push the technology as well as demonstrate an operational capability. In addition, the Space Station advanced development project has provided for establishment of 14 test-beds for individual systems of the station. Automation and robotics systems can be embedded in the test-beds to provide realistic demonstrations of their usefulness. A test-bed of particular note is that for the data management system. Since the DMS, along with its operations management system (OMS), provides the data storage, management, processing, and communication for distributed elements of the station, it is a critical element for supporting knowledge-based and expert systems. Plans are underway to demonstrate an automated subsystem in the DMS test-bed in 1988, as part of the OAST system autonomy program.

6. Maximum use should be made of technology developed for industry and Government.

During previous report periods, formal reviews were held of all study contractor work in automation and robotics. Indepth presentations by study contractors and NASA centers were given. In addition, the phase B study contractors made surveys of off-the-shelf A & R technologies. Periodic meetings on Space Station subjects have continued; these have brought program elements in contact with other Government and industry representatives.

Much of the A & R technology currently being used by industry and Government requires significant additional research and development to meet Space Station requirements. Most of the available funds in this area are in research and development by OAST. Plans have been developed by OAST and the Office of Space Station (OSS) for transfer of OAST technology to the Space Station Program.

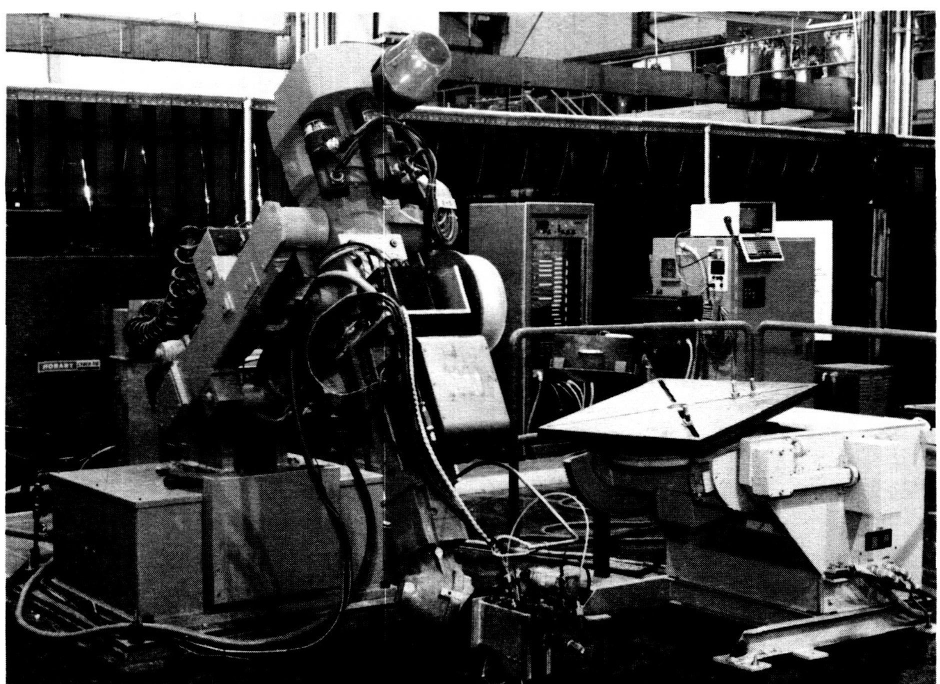
We believe the technology available is well understood and that it is being used as leverage to develop further technology. A good example of this leverage is the work by the Oak Ridge National Laboratory and the National Bureau of Standards which supports development of the telerobotic servicer.

7. The techniques of automation should be used to enhance NASA's management capability.

NASA has completed specifications and has received administrative approval for the development and implementation of the Technical and Management Information System. TMIS is a computer-based information network which will link NASA and contractor facilities and will provide engineering services, such as computer-aided design, as well as management support for such things as schedules, budgets, staffing, and facilities. It will significantly benefit the Space Station Program and should continue to receive support. However, the TMIS specifications do not include the requirements critical to design knowledge capture. Although it provides the communication mechanisms, TMIS leaves data capture, format standardization, data translation, and costing in the domain of the design organizations.

8. NASA should provide the measures and assessments to verify the inclusion of automation and robotics in the Space Station.

No quantified plan exists to provide the recommended measures and assessments. It is still too early to attempt to verify the inclusion of automation and robotics in the Space Station, except for the telerobotic servicer. Some issues remain over the definition of what constitutes advanced A & R technology. However, the A & R



Testing of robotic welding systems with coordinated parts positioning is being conducted for potential welding of Space Station modules and other large aluminum structures. (Courtesy of Marshall Space Flight Center.)

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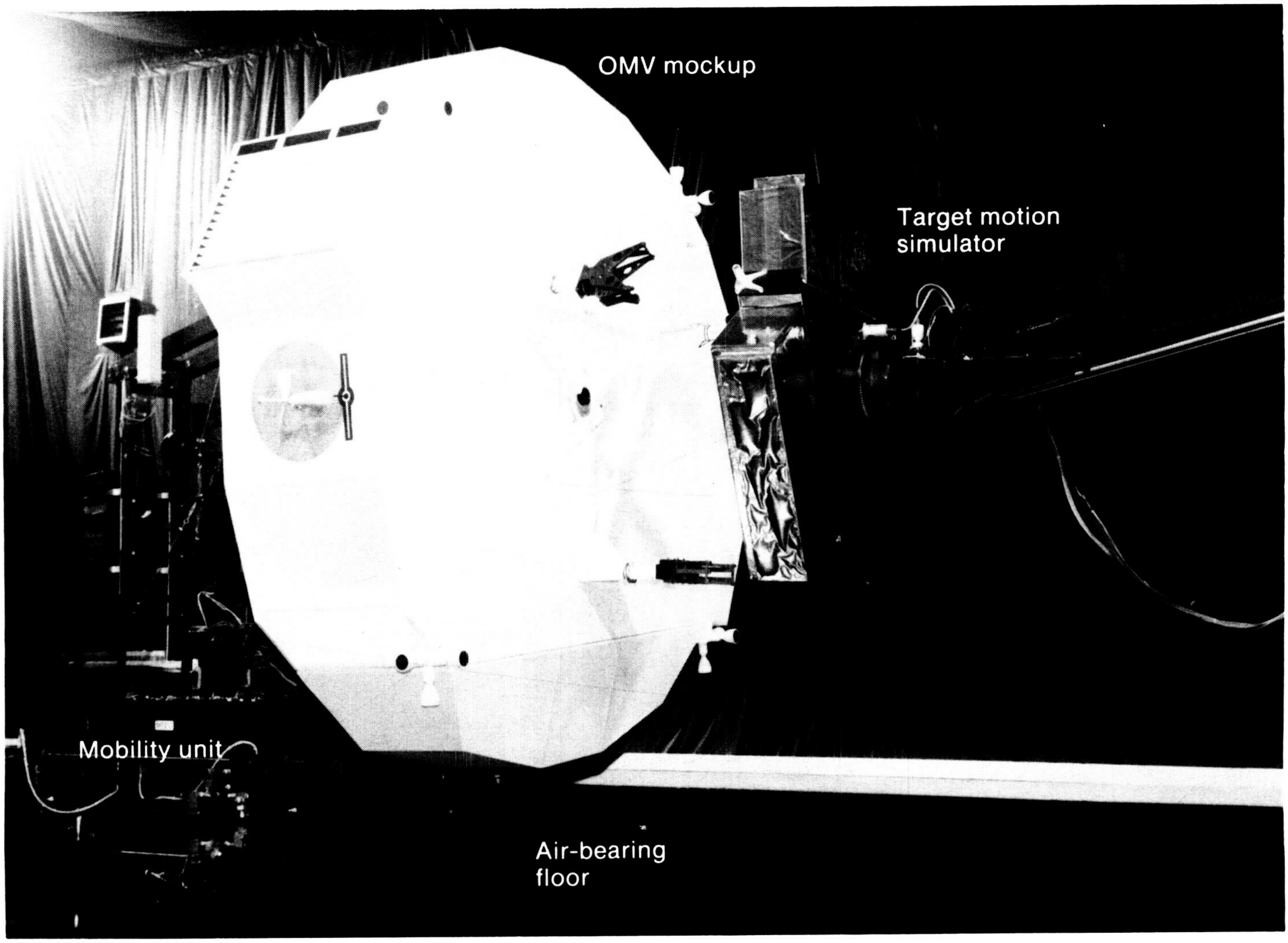
applications compiled in appendix D represent a first approximation. If A & R technologies are explicitly identified, described in detail, and costed in the phase C/D proposals, then a first assessment should be possible.

Recommendations for an augmented program

Recommendations 9 through 13 were made contingent on an augmented program that would enhance the technology base. In view of the inability to provide this augmentation, no discussion of these recommendations is included in this report.

Simulations of rendezvous and docking are being conducted under conditions simulating zero gravity. Automation of position sensing, rate sensing, and feedback to a mobility unit supports tests of automated docking of the orbital maneuvering vehicle (OMV) with a 6-DOF target motion simulator. (Courtesy of Marshall Space Flight Center.)



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

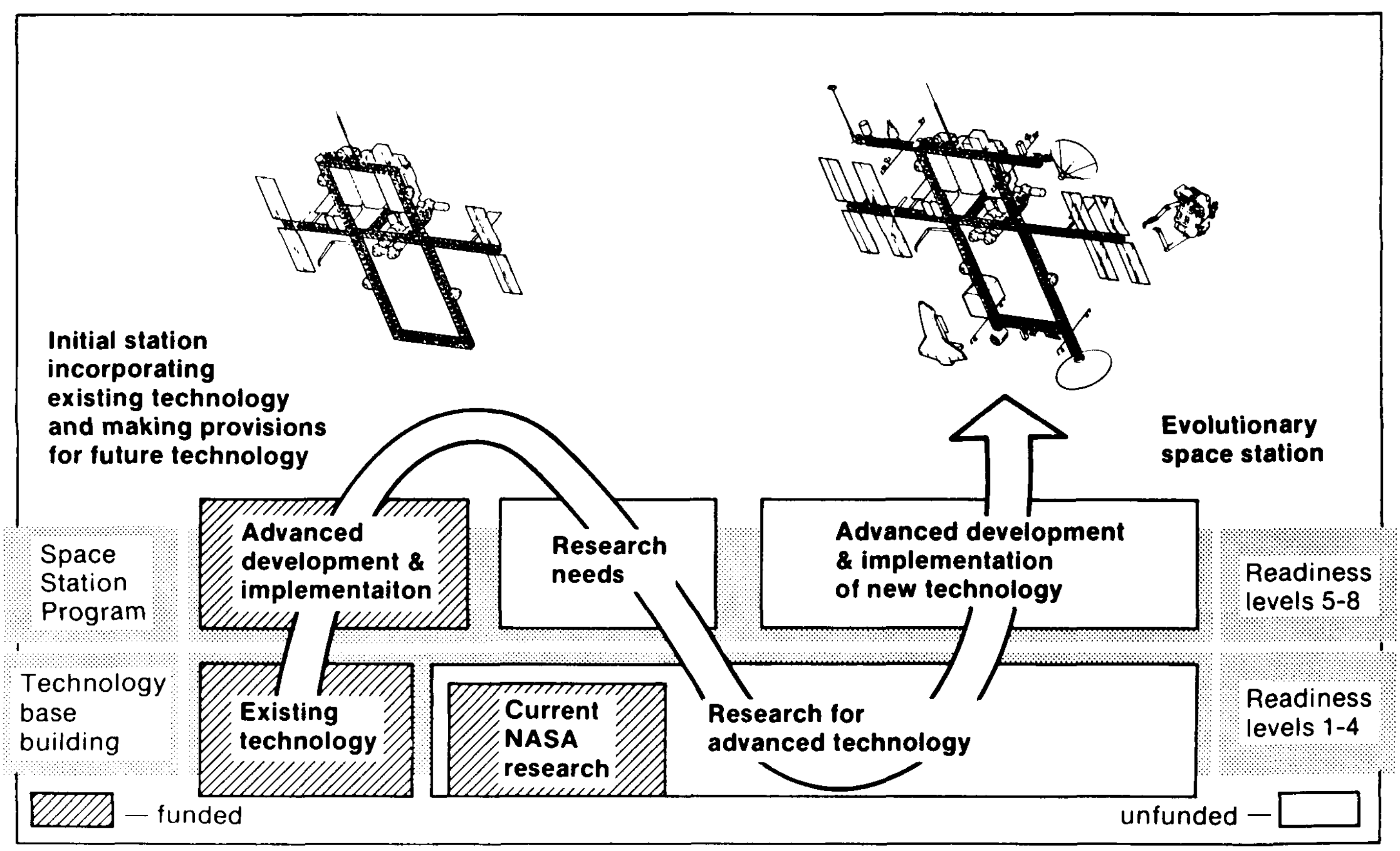
The plan for implementing A & R technology involves two major elements—the work on the Space Station proper and the building of a technology base. This plan has been described in full in ATAC Progress Report 2 and is summarized in the accompanying illustration and table 1.

TABLE 1.- LEVELS OF TECHNOLOGICAL READINESS

Readiness level	Definition
1	Basic principles observed and reported
2	Conceptual design formulated
3	Conceptual design tested analytically or experimentally
4	Critical function/characteristic demonstration
5	Component/breadboard tested in relevant environment
6	Prototype/engineering model tested in relevant environment
7	Engineering model tested in space
8	Full operational capability (incorporated in production design)

The approach to development of the telerobotic servicer is a prime example of the strength of the overall plan for applying A & R technology to the Space Station and for advancing the technology of automation and robotics. This approach involves interaction between the component of NASA concerned with the technology base (the Office of Aeronautics and Space Technology) and the Space Station Program. The status of the telerobotic servicer plan is presented in a later section.

A programmatic approach to the development of automation and robotics will lead to full implementation in the evolutionary space station.



Progress on Space Station Design for Applications of Automation and Robotics

During the definition and preliminary design phase (phase B), ATAC has continued to monitor progress on Space Station design for applications of automation and robotics. This ATAC report of progress occurs at a critical time in the Space Station Program. Requests for proposals for the design and fabrication phase (phase C/D) of the Space Station and formal design reference documentation are being put in final form.

In this section of the report, we will describe progress in A & R definition by the study contractors, we will present the preferred implementation sequences for automation and robotics, and we will discuss the integration and evaluation of A & R studies and the costs and benefits of A & R technology. The A & R events by which progress has been previously assessed are those listed in the Engineering Master Schedule. There are no A & R events identified in the Engineering Master Schedule beyond the previous ATAC report period. The A & R events have all been addressed by the study contractors and level B of the Space Station Program and are completed or near completion.

Subsystems Definition and Preliminary Design

The Space Station contractors at the work package centers continue to make progress in their A & R studies and have reported this progress in their interim A & R implementation plans (refs. 5-11). Since the contract start date, the study contractors have identified candidate applications of automation and robotics, proposed selection criteria, conducted technology assessments and cost analyses, and investigated growth considerations.

ATAC Progress Report 2 identified candidate applications and listed preliminary recommendations of automation and robotics for the initial operating capability (IOC) of the Space Station. These applications and recommendations have been updated with relatively few revisions and are included as appendixes D and E.

The study contractor process generally results in the convergence of several A & R application candidates into one A & R design element. For example, four or five robotic applications may be accomplished by one generic robot. And two or three automation candidates may merge into one expert system.

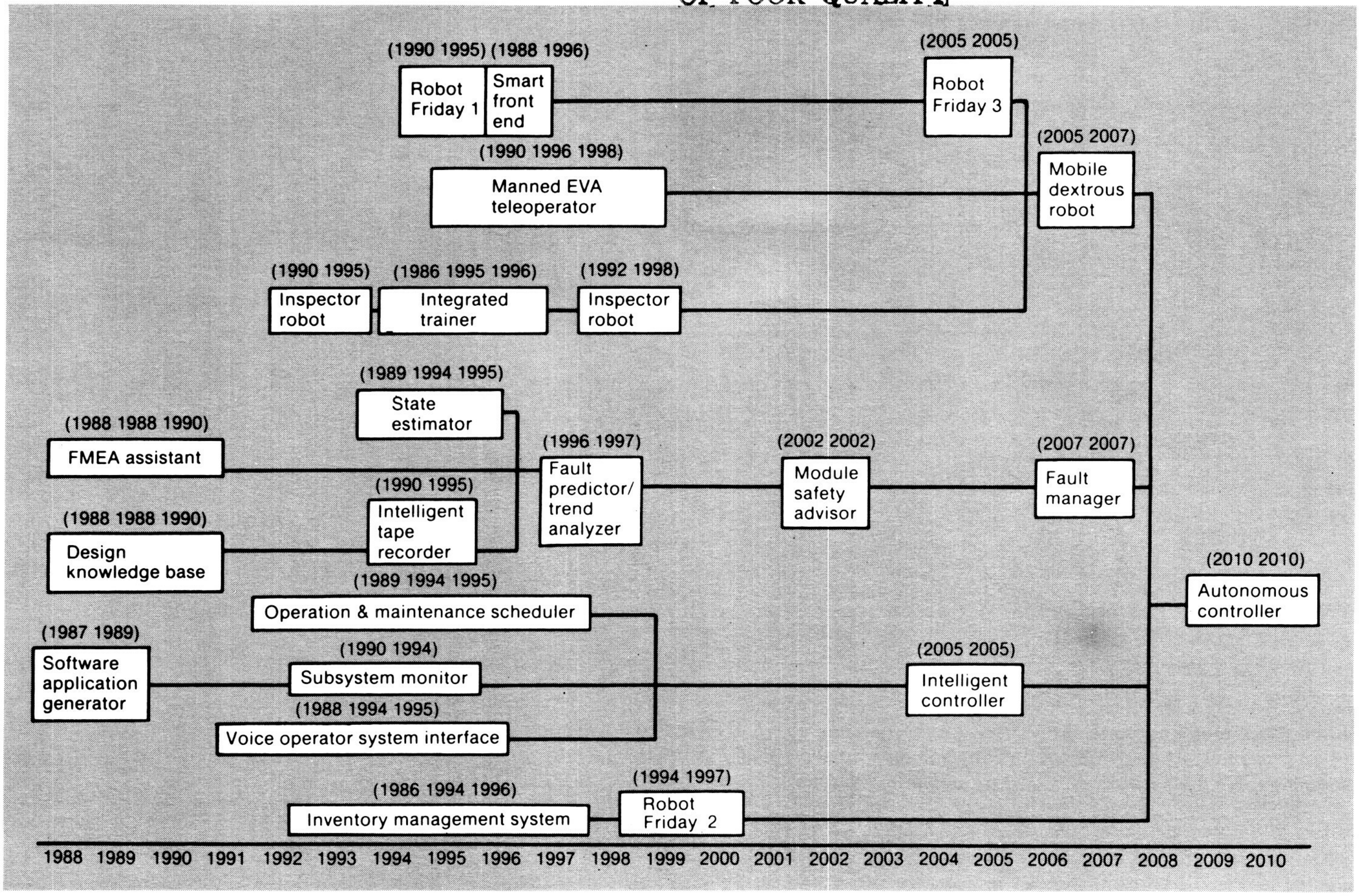
Some contractors have not completed or reported cost studies. And some contractors have not made specific recommendations for the initial operating capability. But all contractors have progressed to conceptual designs for their high priority candidates. Some have noted that detailed design work is necessary to make firm recommendations for IOC automation and robotics and to specify hooks and scars for growth.

Work Package 1

The work package contractors at Marshall Space Flight Center—Boeing and Martin Marietta—have conducted phase B studies of automation and robotics for the common pressurized modules to be used as laboratories, living quarters, and logistics areas; for the environmental control and propulsion systems; and for the orbital maneuvering and transfer vehicles.

The Boeing plan identifies 80 candidate A & R applications and emphasizes the automation of operations and maintenance to release crew time for science—as opposed to the automation of experiment operations themselves to increase the "amount" of science. Their eventual A & R target for operations and maintenance is an autonomous controller that will handle a number of candidate applications. A buildup sequence has been identified which includes elements of this controller at the initial operating capability and along the path of growth. The study indicates a significant increase in crew availability for science based on automation of station operations and maintenance functions. Plans for laboratory support include two A & R candidates—an experiment monitor for the materials technology laboratory (MTL) and a laboratory robotic system.

The Martin Marietta plan identifies 47 candidate A & R applications. It represents a basic trend to apply artificial intelligence to reduce the size of the ground control contingent and to use robots to progressively assume more of the duties of the crew in space operations, servicing, assembly, and repair. The Martin Marietta plan projects that advanced automation (knowledge-based and expert systems) will initially be applied on the ground, with early onboard implementation being limited to crew aids for monitoring, maintenance, and servicing. As confidence in onboard automated systems increases and more are developed, the degree of autonomy will increase. The plan projects that initial automation of robotics will be limited to low level manipulation control, teleoperated, with a need for ground control. The study includes requirements and a conceptual design for a robot to operate inside the materials technology lab and to serve as a smart front end on the OMV.



Development and implementation of automation and robotics will grow with the evolution of the Space Station. This example illustrates a proposed buildup sequence of A & R for operations and maintenance. (The years in parentheses are the year the technology will become available and the year it will be implemented, and, in some cases, the year an improved version will be available.) (Plan by Boeing.)

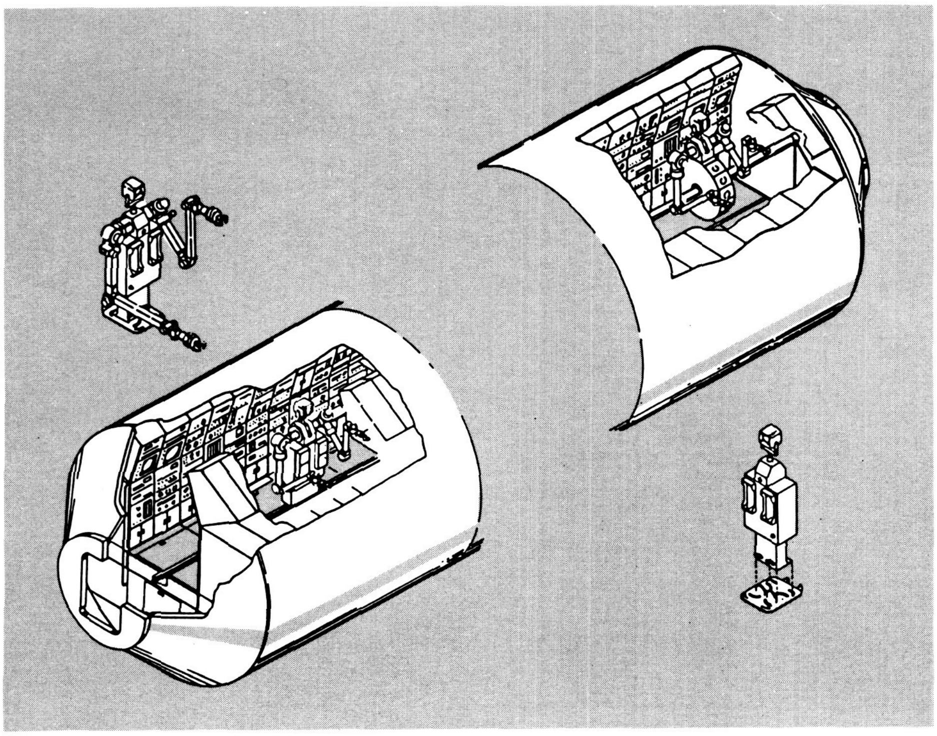
Since the last ATAC report, Martin Marietta has developed and demonstrated an approach to fault management for the environmental control and life support system (ECLSS) which incorporates expert system technology. This prototype expert system diagnoses fault conditions which otherwise could be detected only by human experts. While this application is for a specific system of the Space Station, the methods, techniques, and lessons learned will transfer to similar applications and reduce development time and cost.

Work Package 2

The work package contractors at the Lyndon B. Johnson Space Center—McDonnell Douglas and Rockwell—have conducted phase B studies of the structural framework of the Space Station; the interface between the station and a visiting Space Shuttle; mechanisms, including remote manipulators; attitude control; thermal control; communications and data management; a plan for equipping a module with sleeping quarters, a wardroom, and a galley; and a plan for extravehicular activity.

McDonnell Douglas has identified 58 candidate A & R applications. Forty-nine of these candidates offer savings in crew and ground controller time; four offer to increase station efficiency; and five offer safety advantages. The costs and benefits of these candidates have been assessed, and the candidates ranked. The applications recommended as first priority for the initial operating capability are (a) robotics for payload servicing and external inspection; (b) expert systems for monitoring the thermal control and power management systems, for fault diagnosis of the communication and manipulator systems, and for planning of station coordination and extravehicular tasks; and (c) advanced automation for smart camera control and servicing of the OMV, the orbital transfer vehicle (OTV), and EVA suits.

In their continuing preliminary design, McDonnell Douglas has selected two areas of focus: (1) the Space Station operations management system for integration



Having robots carry out functions within laboratory modules could minimize the need for human presence in hazardous environments and could allow scientists on the ground to conduct experiments in space. (Courtesy of Martin Marietta.)

and implementation of expert systems and (2) a generic space robot for detailed design and integration.

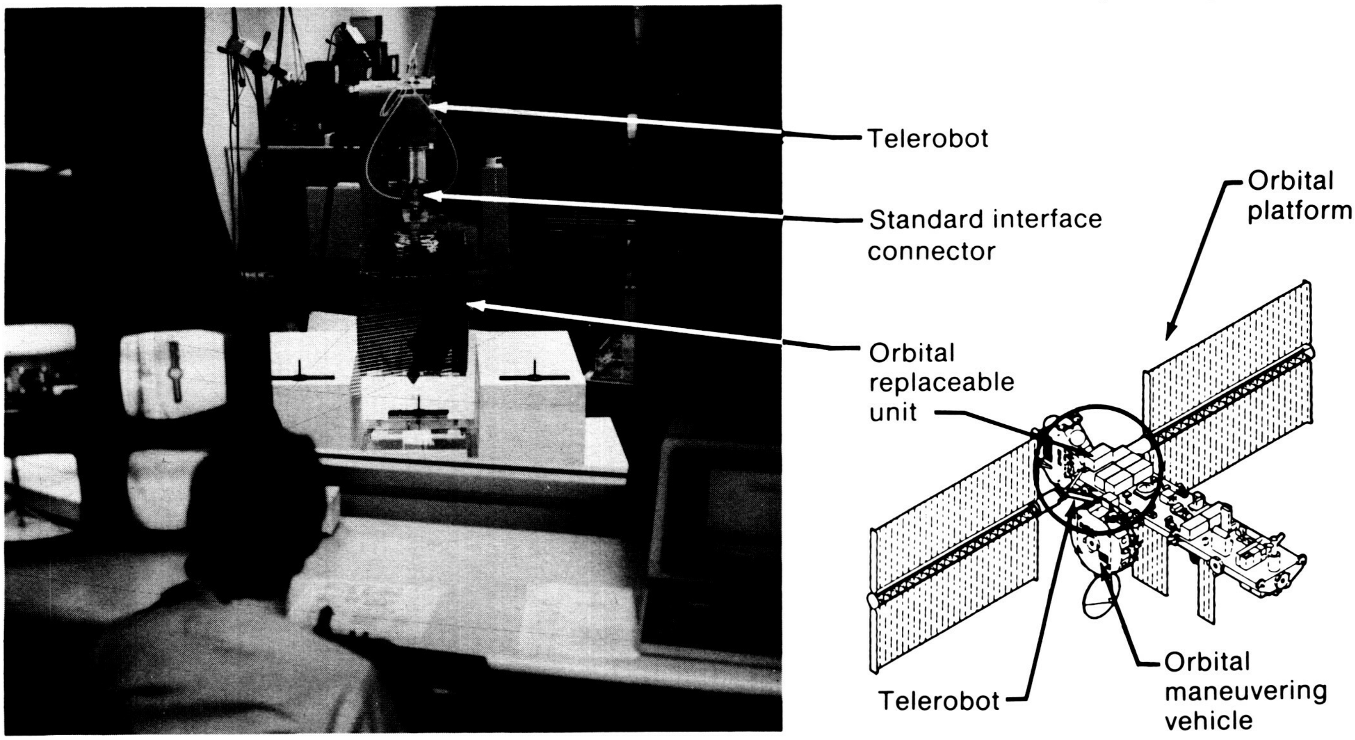
Rockwell has identified 78 candidate A & R applications. The expert system candidates have been grouped into four technical areas for further development: (1) mission planning for onboard activities and ground support operations, (2) resource management for the ECLSS, the thermal control system (TCS), the communication and tracking (C & T) system, the power management and distribution (PMAD) system, and the high level software of the DMS and for docking and berthing by the guidance, navigation, and control (GNC) system, (3) fault detection, isolation, and recovery (FDIR) for the ECLSS, TCS, and PMAD, and (4) performance monitoring of the ECLSS, TCS, and PMAD. Development and test efforts are underway in resource management for the communication and tracking system and in FDIR for the active thermal control system. Rockwell expects initial use of expert systems to be on the ground.

Rockwell's robotics studies have focused on three areas for the initial operating capability of the station: the transporter for the Canadian mobile servicing center (MSC), interchangeable end effectors for the MSC, and the telerobotic servicer. Candidate assembly functions for a robot and candidate orbital replaceable units for a robot to exchange have been identified.

Work Package 3

Work package contractors at Goddard Space Flight Center—General Electric and RCA—have conducted phase B studies of automated free-flying platforms and provisions to service, maintain, and repair these platforms and other free-flying spacecraft; provisions for instruments and payloads to be attached to the Space Station; and a plan for equipping a module as a laboratory.

During this report period, Goddard has become lead center for the telerobotic servicer and General



Laboratory demonstrations have simulated telerobotic changeout of an orbital replaceable unit on a free-flying platform. The telerobot would be attached to an OMV for transportation. The techniques demonstrated have potential for incorporation into the telerobotic servicer for more general use. (Courtesy of RCA.)

Electric is providing contract support. This support has included requirements integration and definition of architectural control specifications. Progress on the TRS is described in the following section of this report.

RCA has identified 11 A & R candidates for the platforms, 6 candidates supporting customer servicing, 4 candidates for attached payloads, and 10 candidates for a science laboratory module. Platform expert systems provide two functions—increased monitoring and autonomous planning. Robotic servicing concepts include a smart front end for the OMV and a rail-mounted servicing arm.

Studies of the A & R candidates for the science lab module indicate that the top three candidates are automation of the ECLSS for the vivarium, a robotic transfer system, and a robot to access the centrifuge.

Work Package 4

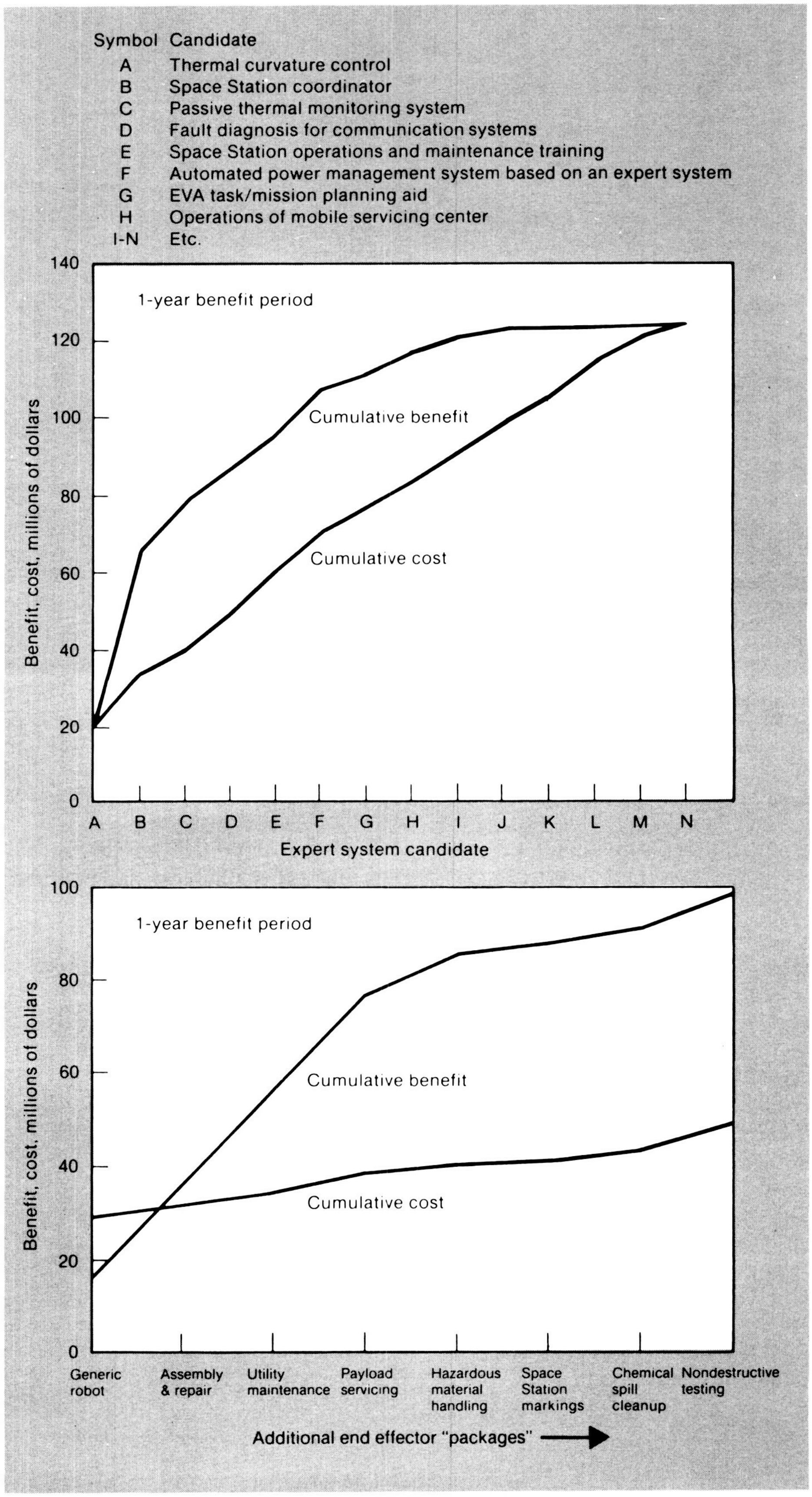
The work package contractor at Lewis Research Center, Rocketdyne, has conducted studies of the electric power system—generation, conditioning, and storage. The plan for automation of the electric power system is to combine conventional computer controls with crew-interactive expert systems at the initial operating capability and to grow to autonomous operation. The candidate expert systems are ones for scheduling the power allocated to each load and diagnosing the causes of failures in the electrical system. Initial automation is projected to be use of conventional algorithms for operation and for fault detection, isolation, and recovery, with an expert system as a diagnostic assistant. Whether the expert system will initially be flight- or ground-based has not yet been determined. Robotics proposed for the initial operating capability include a dedicated utility robot for servicing the power generation system and a telerobot for inspection.

Cost/Benefit Studies

ATAC Progress Report 2 described the benefit in lower life cycle cost of implementing advanced automation for the power management and distribution system. Two of the study contractors have completed costing studies for their A & R candidates which further emphasize the value of automation and robotics in holding down the operational, or life cycle, costs of the station.

In one study, McDonnell Douglas estimated the initial cost and annual benefit (in operating cost savings) for the accumulation of their A & R candidates in expert systems and robotics. As the two parts of the figure show, there is a significant difference in favor of the benefits in a 1-year period for the higher ranking expert systems candidates and for the candidate robotic capabilities.

In another study, Boeing estimated the cumulative cost and value of automation of station operations and maintenance. A figure shown earlier indicates that the cumulative value of crew time saved would exceed the cumulative cost of the automation equipment in approximately 3 years. This result is based on information in the figure shown here as to how much more time (in terms of crew size) would be available for science with the greater level of automation for operations and maintenance. Such analyses indicating payback of initial cost in about 3 years reiterate a projection illustrated in ATAC Progress Report 2.



Automation and robotics provides favorable cost/benefit ratios in terms of increased productivity of the Space Station. Estimates of the costs and the benefits of expert systems and of a robot and its end effectors are important to decisions on the priority of Space Station technology. (Analysis by McDonnell Douglas.)

Studies such as these estimate costs on the basis of the complexity of the capability added. Benefits are estimated on the basis of the type (extravehicular or intravehicular) and amount of crew time saved and thus made available for additional scientific work in space.

Priorities for A & R Implementation

At the request of ATAC, the work package centers have recommended a preferred sequence for implementing automation and robotics on the Space Station. Different rationales have been used to establish the priorities for automation and for robotics.

A "building block" approach has been used for advanced automation. The simplest application using the most basic information is the starting point. It is enhanced in terms of its integration into individual systems and the increased level of sophistication of its expert systems to produce the next application.

The robotics rationale was to assume a certain capability from the mobile servicing center, the available end effectors and tools, and the telerobotic servicer or a generic space robot and then examine needs and task complexity. The priorities for robotics represent a general ordering of the needs. Within each of the task areas, task complexity would determine the order of specific tasks added to the list.

Advanced Automation

1. Fault detection, isolation, and recovery (FDIR)

Subsystem monitor to
- Obtain relevant system measurements
- Detect violation of critical parameter thresholds
- Analyze input vs. expected system behavior
- Request additional data as required
- Make a limited trend analysis of data

Fault diagnostics to
- Detect and isolate faults
- Request additional data as required
- Request additional system tests

Anomaly handler and reconfigurer to
- Evaluate the impacts of different configuration options
- Implement the selected configuration change after crew approval
- Monitor the configuration during and after a change, with appropriate duration and level of scrutiny

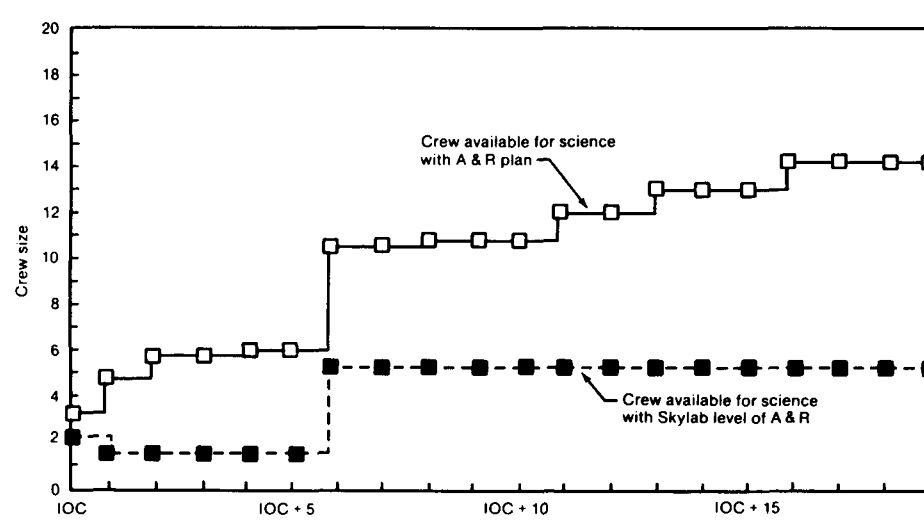
2. Short-term planning and scheduling
- Mission planner and scheduler
- Logistics planner and scheduler
- Crew activity scheduler

3. Resource management

4. Performance management

5. Training and instruction

6. Maintenance



The amount of crew time avaiable for scientific work in space will depend on the level of automation and robotics on the Space Station. (Analysis by Boeing.)

Robotics

1. Inspection and maintenance

2. Assembly and construction

3. Mission support

- Docking and berthing
- Deployment and retrieval
- Materials handling

4. Customer accommodation

- Installation and removal
- Materials handling

5. Astronaut rescue

Astronaut rescue appears at the bottom of the list, not because of lack of importance, but because additional hardware—some type of propulsion system—is required and was not included in the assumed capabilities.

Automation Growth Considerations

The approach to expert systems implementation described here permits easy growth. Therefore, specific candidate applications do not need to be identified. Serious candidates are generally among the applications recommended for the initial Space Station. But there is a general growth issue as to the location of the software for artificial intelligence (whether it should be hosted on the ground or in orbit). Expert systems for planning and scheduling should be hosted on the ground initially and then moved on orbit for operational use when adequate experience is gained. It may be appropriate to start development of planning and scheduling tools early in the program. Even if the tools are not fully developed, they could provide a great deal of assistance in the planning and scheduling process. General growth considerations that should be included in program planning are the following.

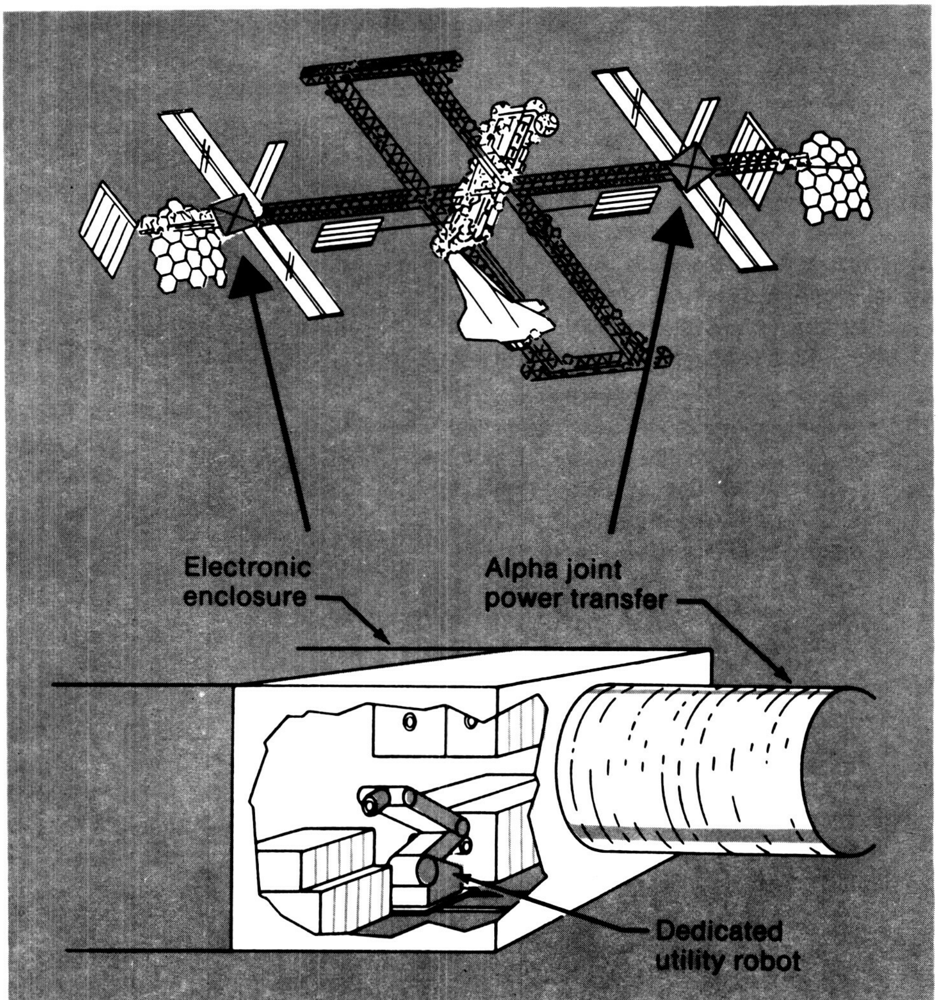
Software Support Environment

- The development environment should contain a well-structured expert system tool as well as allow for easy integration of expert system software with conventional software.
- The development environment should have a simulation capability to test prototype software before the chosen software is put through its actual verification testing.

AI Architecture

- An architecture that supports the integration of applications based on artificial intelligence (AI) with the rest of the software environment will be needed.
- The architecture must be flexible enough to allow expansion and growth without requiring implementation decisions too far in advance of the identification of the applications; hence, a relatively simple interface strategy is needed.

A dedicated utility robot would service components inside the electronics enclosure of the photovoltaic electrical storage system outboard of the alpha joint. (Courtesy of Rocketdyne.)



Specific Design Requirements

- For systems that will eventually have the capability of autonomous reconfiguration, hooks and scars must be made to ensure the software access that will allow control of the configuration.
- In many cases, the kind of sensors needed are those that output the actual measured values of the parameters being monitored, rather than simply giving a logical "good" or "bad" indication.

General Support Requirements

- The data management system should provide easy access to data bases and other support systems required for smooth operation of many types of software.
- For sophisticated applications, performance specifications (such as central processor unit speed, mass memory, and network bandwidth) should be kept as ambitious as is practical, to ensure adequate power for growth into tasks where software demands on the hardware may be heavy.

ATAC endorses these priorities as consistent with its original recommendations (ref. 1) for Space Station automation and robotics.

Integration, Evaluation, and Life Cycle Cost Analysis

A & R Assessment of Control Documents

An examination has been made of Space Station architectural control documents and baseline configuration documents to assess the extent to which ATAC recommendations and study contractor A & R recommendations are progressing into the design of the station. The ACDs and BCDs augment the Program Definition and Requirements Document by quantifying and documenting the integrated configuration of the station and its distributed systems and its individual flight elements. The documents, when reviewed, were in the process of being baselined.

TABLE 2.- A & R PROVISIONS IN SPACE STATION CONTROL DOCUMENTS

Document type	Document title	A & R application	Hooks and scars
Architectural control documents (ACDs)	Electrical power system	Fault isolation and resource scheduling - ?	0
	Data management system	Fault detection, isolation, and recovery at ORU level Self-test and self-verification Fault-tolerant operations Simplified crew interface Distributed system architecture	Growth without service interruption Standard interfaces
	Thermal control system	Expert system controller	0
	C & T system	Robotics - (TBD)	0
	GNC system	Hard automation - defers to DMS	0
	ECLSS	0	0
	Extravehicular activity	Repair by automation - not EVA function	0
	Manned systems	Fault detection, isolation, and recovery - ?	0
Baseline configuration documents (BCDs)	Lab module (USA)	X	X
	Columbus lab module	0	0
	JEM lab and exposed facility	0	0
	Habitat/station operations module (USA)	0	0
	Mobile servicing center	R	R
	MSS maintenance depot	R	R
	MSC transporter	0	0
	Service facility	0	0
	Attached payloads accommodation equipment	0	0
	OMV accommodation equipment	Robotic servicing, ORU replacement	R
	Pressurized logistics carrier	0	0
	Unpressurized logistics carrier	0	0
	JEM experiment logistics module	X	X
	Nodes	0	0
	Tunnels	0	0
	Airlocks	X	X
	Solar power modules	X	X
	Truss assembly	0	0
	Propulsion modules	X	X
	Polar platform	X	X
	Co orbiting platforms	X	X
	Columbus polar platform	X	X
	Telerobotic servicer	X	X

Legend R robotics requirements identified 0 not mentioned
? automation inferred only X document not available

As reflected in table 2, scant mention of A & R applications or of design accommodations for future automation and robotics can be found in these documents submitted by the work package centers. The positive exceptions are the ACD for the thermal control system, which contains a requirement for an expert system controller, and the ACD for the data management system, which lists multiple, significant hooks and scars for accommodation of the future growth of the station and embraces many of the concepts that were put forth in the initial ATAC report.

Noteworthy among the DMS hooks and scars are requirements for the incorporation of new hardware and software elements to accommodate growth, including the requirement that little or no service interruption will be allowed during the upgrades.

The concept of making the data management system responsible for performing fault detection, isolation, and recovery at the level of the orbital replaceable unit (ORU) permeates the DMS architectural control document. ATAC, in its initial report to Congress, detailed a number of scenarios for the incorporation of such automation on the Space Station. The notions of self-test and self-verification have also been included in the ACD, as have requirements for fault-tolerant operations in the DMS. Requirements for growth in major DMS capabilities are addressed in the document but not in much detail. Growth requirements for future incorporation of expert system technology appear to have been included.

Implementation Plan

No updated A & R Process Requirements Document providing for the tasks and decision processes required to ensure adequate consideration of automation and robotics across the program has been adopted. ATAC urges NASA to promptly prepare and approve a new A & R Process Requirements Document covering the remainder of phase B and the start of phase C/D.

Manual for Design of Automation and Robotics

A design manual (ref. 13) has been prepared and submitted to level B of the Space Station Program as a control document providing guidelines for accommodation of automation and robotics in the design of the Space Station. This stand-alone document captures the essence of the complete NASA ATAC A & R report (ref. 1).

The manual is a collection (which is to be updated periodically) of suggested approaches for use by level B and level C managers and contractors to assure that automation, robotics, and machine intelligence are incorporated into the design where appropriate. It gives guidelines intended to provide the hardware scars and software hooks necessary to integrate automation, robotics, and machine intelligence into the station design as these technologies become available.

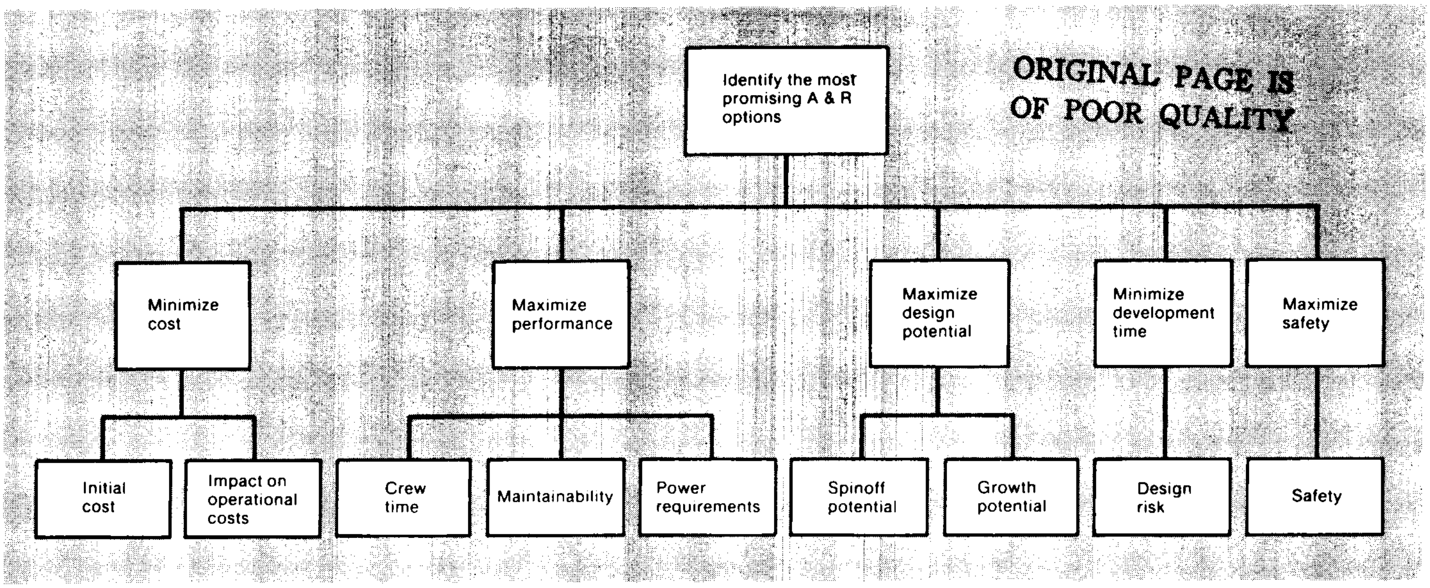
Life Cycle Cost Analyses

In its previous report, the committee encouraged prompt implementation of a "design to life cycle cost" methodology to stimulate incorporation of advanced automation and robotics in the Space Station.

Taking this life cycle costing approach to Space Station design will produce a station that by incorporating advanced automation and robotics will also attain the minimum overall cost. This costing approach should be integrated into a systems engineering analysis that will also consider such desirable design attributes as safety and spinoffs to the terrestrial economy, which are not measurable in terms of life cycle cost.

In accordance with ATAC's suggestion, the Space Station Program Manager requested the development of a life cycle costing method that would estimate the cost benefits that could be achieved by adding advanced automation and robotics to the Space Station.

A general approach to estimating the benefits offered by A & R candidates and to converging on an overall A & R plan for the Space Station that will strike the best balance among them has been proposed and initial steps implemented. Attributes such as initial cost, operating cost, crew productivity, maintainability, safety, and spinoff potential will be used to develop a measure of suitability, which can then be used to rank each of the A & R candidates. The first step is to emphasize candidates that have desirable characteristics in more than just the cost areas and to screen out candidates that have obvious drawbacks in some important attribute, such as safety or



An integrated systems engineering and cost-estimating approach has been recommended for decisions on Space Station A & R technology. Attributes (e.g., initial cost, crew time) which describe design goals would be used to rank the A & R options.

spinoff potential. A multiattribute utility theory approach is proposed to measure suitability. Using this approach, each candidate will receive a single ranking derived from all nine attributes. (See the accompanying figure.)

To arrive at a minimum life cycle cost design constrained to some DDT&E cost limit, an understanding of the mutual dependence of one Space Station functional element on another is needed. From this interdependence and from the set of demands that the station must meet, it is possible to estimate the sizes (power required, crew time required, etc.) of the functional elements needed. A modification of a sizing model known as the System Integration Model (SIM) is proposed as a means of studying the effects of introducing A & R design concepts. The SIM treats the work breakdown elements of the Space Station as a related set. From a design-to-cost point of view, this sizing step relates the conceptual design process to the cost-estimating process. It is in this and the following step that one can obtain an understanding of the cost effects of introducing automation and robotics into the station design.

Costing is the last major step. In this step, cost-estimating relationships are developed for each of the major A & R candidates that have potential for reducing the life cycle cost of the station. The cost-estimating relationships are then included in the station cost model. Once the sizing and costing are accomplished for individual A & R candidates, then analysis is made of commonalities among candidates which might provide opportunities for synergism and the results are iterated through the sizing and costing steps. As an example of possible synergism, servicing functions in several areas of the station may be accomplished by a single robot.

Since the time for completion of phase B efforts is so near, the life cycle costing approach is being considered for inclusion in the phase C/D requests for proposals.

End Effectors Study

The Space Station Program has initiated a study, led by Langley Research Center with participation across the agency, to develop a program-wide strategy for end effector development during phase C/D. With both the United States and its international partners expected to provide systems incorporating end effectors and with a multiplicity of program elements, interfaces, and users, the program needs to establish a uniform position on such things as terminology, available or expected end effector technology, functional requirements, task allocation, and gaps in end effector capability. Moreover, the program wants to start assessing the role that commonality, interchangeability, and redundancy can play in minimizing the need for additional hardware development in end effectors.

Configuration and Assembly Studies

During this report period, the Space Station Program has been addressing the Space Station assembly sequence and its requirements. The findings of these studies, when they are completed, will have significant effect on the development and use of automation and robotics on the station.

ATAC has been monitoring these studies and will address the findings significant to automation and robotics in a later progress report.

Of particular interest to ATAC is the extent to which the telerobotic servicer has been considered for use in the assembly process.

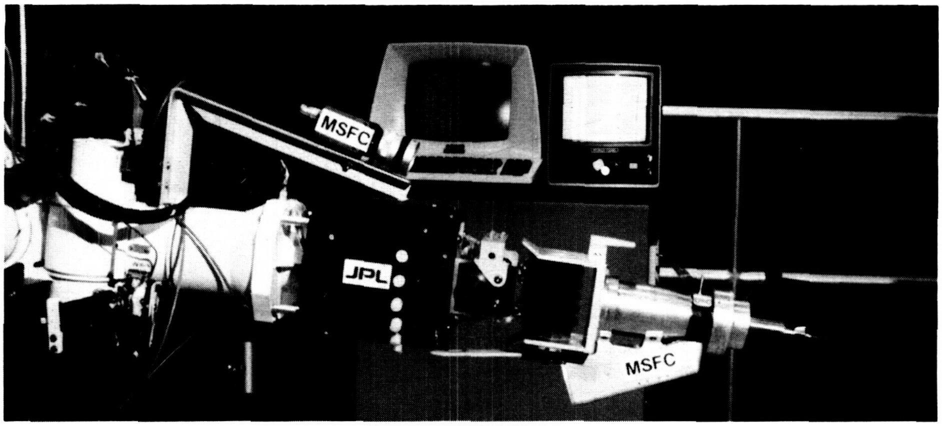
Technology Demonstrations and Evaluations

ATAC considers demonstrations very important for focusing the technology and convincing designers and managers of the readiness of the technology. In the previous report, several demonstrations were noted and, in this report, technology demonstration plans have been identified for the telerobotic servicer and for robotics and system autonomy.

An integrated A & R demonstration plan does not exist at this time, but study contractors have described some planned demonstrations.

For example, Martin Marietta (WP-01) is integrating a fault management expert system for the ECLSS with prototype flight hardware. A series of evaluations will be conducted in the fall of 1986 at Marshall Space Flight Center to assess the validity and reliability of the knowledge base and to determine test methods for candidate flight systems. Results of such expert system demonstrations and evaluations are providing important data for determining which applications should be used on the IOC and growth stations.

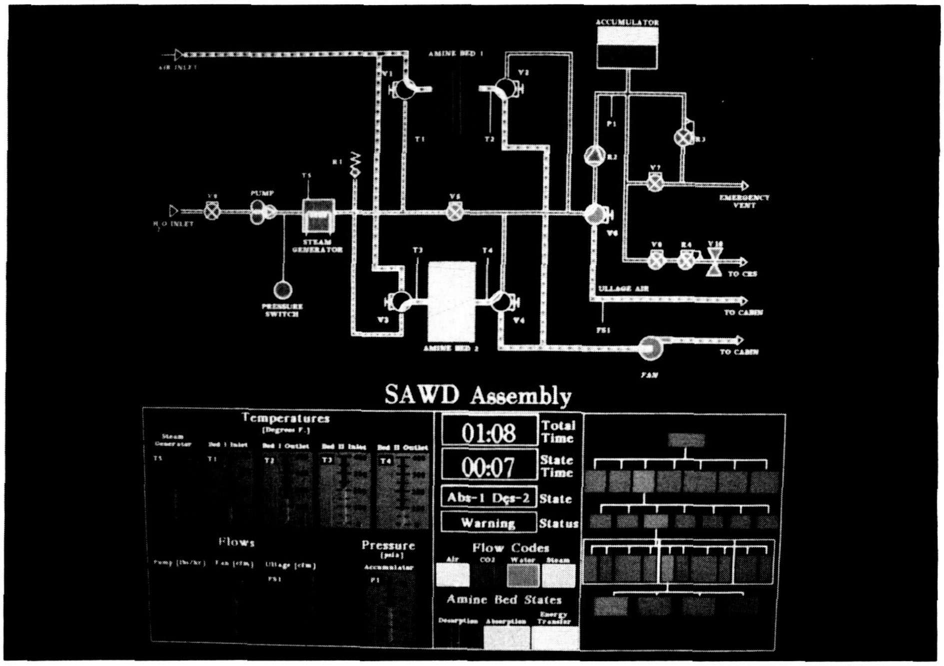
In this context should be mentioned the 14 test-beds established by the Space Station Program's advanced development project for advanced development of station subsystems and demonstrations at technology readiness levels 3-7. Although A & R tests are planned in several of these test-beds, the committee wishes to focus on one test-bed—the DMS test-bed—because of its potential significance to automation and robotics, especially to knowledge-based systems.



Sophisticated end effectors and operator displays will support remotely controlled robotic tasks. In this example, a "smart" end effector has been intermeshed with a protoflight manipulator arm. The end effector has force, torque, and grip-force sensing that is displayed to the operator on a video graphics bar chart indicating the magnitude and direction of force. The end effector is holding a rotary power tool with the forces displayed on the video monitor. (Courtesy of Marshall Space Flight Center; end effector by the Jet Propulsion Laboratory.)

The data management system is the communication and information processing backbone of the Space Station. It is responsible for the interconnection of most systems and elements and the transfer of data between them. The Space Station data management system will be the most complex and advanced spaceborne information processing system ever constructed. Because of the advanced nature of many of the DMS concepts, such as interpreting time-critical information from architecturally dissimilar systems, a proof of concept test-bed has been established at the Johnson Space Center. This test-bed will interconnect electronically the

Dynamic color displays are augmenting expert systems by providing real-time, multichannel information. In this example, the performance and state of the solid amine water desorbed (SAWD) assembly of the environmental control and life support system are being displayed. Such displays will assist the crew in making decisions and taking actions recommended by an expert system. (Courtesy of Martin Marietta.)



diverse systems which the station comprises. Thus it provides an ideal avenue for test and verification of A & R systems, many of which will be embedded in subsystems that interface with the DMS.

A comprehensive set of hardware and software tools has been designed to support the needs of both phase B contractors and subsystem designers to conduct tests of expert systems in the DMS environment. Composed of state-of-the-art Lisp language processors (which are special purpose "symbolic" manipulation computers) and backed by a complex expert systems communications bridge, this capability is designed to provide a pathway into the DMS environment.

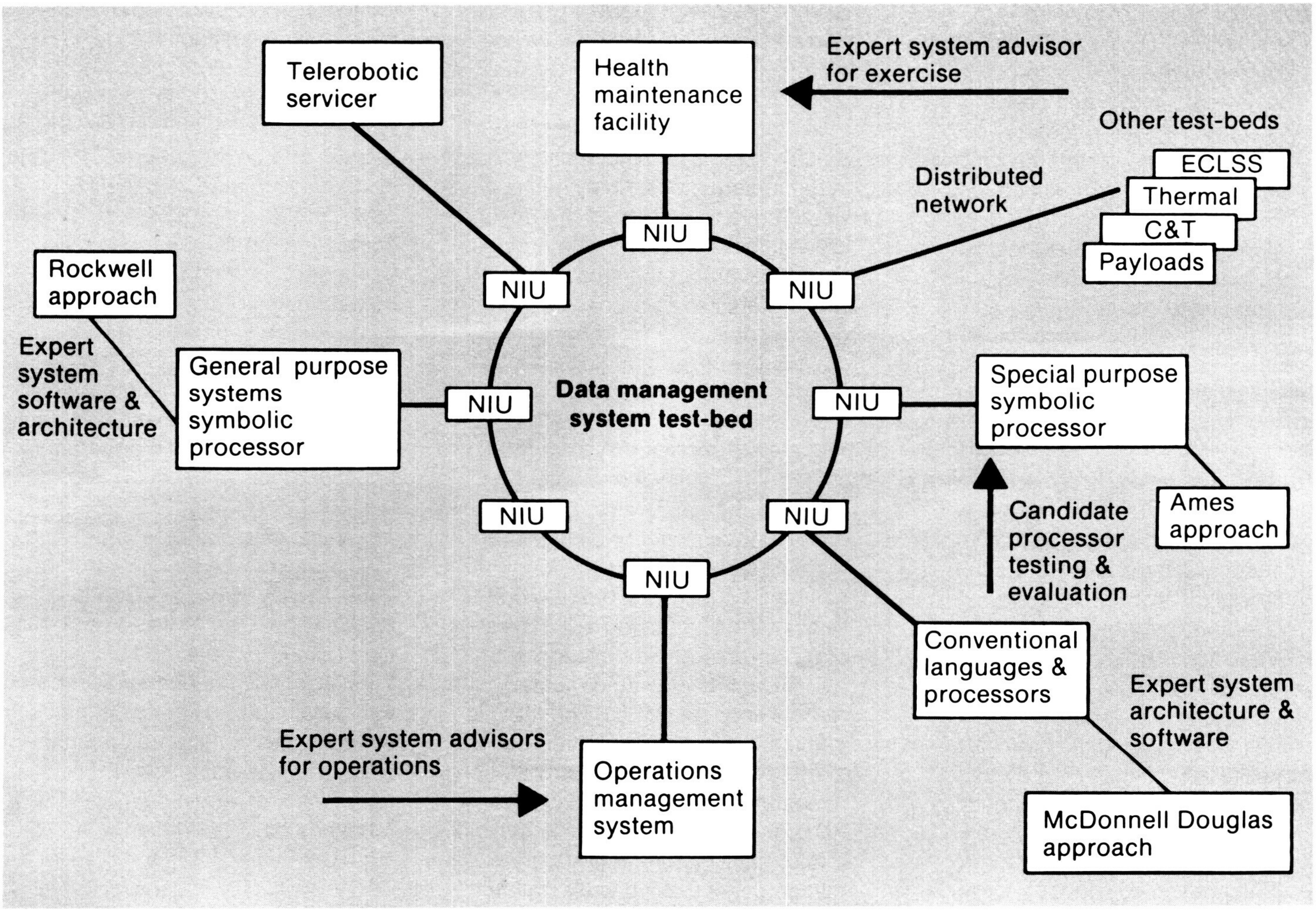
Rockwell International (one of the two WP-02 contractors) will evaluate the interaction of expert systems with the more conventional approaches to communication and data handling expected to be used by the DMS on the initial station. They will also be investigating the management and control of expert systems in a highly distributed environment.

Ames Research Center, which has the lead responsibility for OAST's research in system autonomy, plans to use the DMS test-bed to test the responsiveness of "symbolic" expert system processors and software which are candidates for space flight qualification.

McDonnell Douglas (the other WP-02 contractor) plans to explore the use of more conventional languages (e.g., ADA) and processors for expert system development.

These efforts will provide an opportunity to evaluate and demonstrate dissimilar approaches to A & R implementation on the Space Station. The committee has recommended that NASA continue such A & R demonstrations and the facilities which support them.

A data management system (DMS) test-bed has been established which provides a mechanism for evaluation of alternate approaches to expert system implementation on the Space Station. The test-bed includes network interface units (NIUs) as communication pathways for the expert systems and the subsystems and flight elements that require expert systems. (Courtesy of Johnson Space Center.)



Plans for a Telerobotic Servicer Using Congressional Set-Aside Funding

In November 1985, Congress directed that a portion of NASA funding be set aside for a flight telerobotic system to be delivered at the time of initial operating capability and used for station assembly and maintenance and, as a smart front end on the orbital maneuvering vehicle, for remote operations and servicing. ATAC has been highly encouraged by this action, which addresses a critical need seen by ATAC.

Candidate applications for such a telerobotic device have been identified by the Space Station study contractors (refs. 5-11) and documented in this and previous ATAC reports (see appendixes D and E). The requirement for robotic elements has been identified for numerous functions on the Space Station. These functions include both extravehicular activities and operations within laboratory and habitation modules which expand people's capacity in space and allow selected teleoperation from the ground.

Current operational scenarios indicate that requirements for assembly, verification, and maintenance of the initial station may significantly exceed the available extravehicular activity (EVA) time if robotic elements are not employed. Projection to similar functions in the post-IOC era, in addition to payload, platform, and satellite servicing, indicates a continuing and expanded need.

Provisions are being made for use of the Shuttle remote manipulator system (RMS) and for a mobile servicing system and the U.S. telerobotic servicer early in Space Station implementation. Possible functions of these robotic elements are

- Assembly of the Space Station, payloads, and other structures in space
- Servicing, maintenance, and repair of the Space Station (external), attached payloads, free-flying satellites, and platforms
- Support of deployment and retrieval—support of docking and berthing
- Transportation on the station
- EVA support
- Safe haven support

Many of these functions can be handled by a robotic system, thereby relieving the crew of heavy demands on their time and leaving them to carry out higher order functions. Operation of the station relies heavily on various physical actuations and manipulations which, in the absence of such systems, would have to be carried out by the crew alone. As noted in the previous report, several of the study contractors have proposed a generic, multipurpose robot equipped with various end effectors to accomplish many tasks.

The mobile servicing system (MSS) includes a mobile servicing center (MSC), a mobile servicing system maintenance depot (MMD), and an intravehicular activity (IVA) control station. The MSC will operate on the truss of the station and will consist of a U.S.-provided mobile transporter and a Canada-provided mobile remote servicer (MRS). The MSC is planned to be a teleoperated device, starting with support for early station assembly functions. Initially, it will have an EVA work station; later it will expand to include the IVA work station and a ground work station.

As described in ATAC Progress Report 2, there is a significant distinction between teleoperated devices such as the RMS and the MSC and devices which are telerobots. Teleoperation requires a human operator to be in full control at all times; while a robot has a degree of autonomy. A telerobotic device can be operated by a human and much of the time it must be. However, it incorporates some capability for independent action, typically the execution of simple, repetitive tasks which are part of a long procedure. For many tasks the human operator may instruct the robot in simple language and allow the robot to carry out the task autonomously.

Provision for the telerobotic servicer (TRS) has been made by the U.S. congressional set-aside funding within the Space Station Program. Plans call for control of the telerobotic servicer to be exercised through work stations on the National Space Transportation System (NSTS) Orbiter (during the assembly phase), on the core Space Station, and on the ground. The data system associated with the TRS will have distributed processors, computers, and software that are configured for autonomous operation. It will also have mass data storage capability and communication links that are designed to allow continuing evolution to greater levels of autonomy in robot plan generation and execution.

The initial planning meeting for the TRS initiative was held in January 1986. In May 1986, the Goddard Space Flight Center was selected as lead center for development of the TRS. A robotic servicer workshop was held in May 1986 to define initial requirements and functional roles, and several follow-on technical and administrative meetings have been held.

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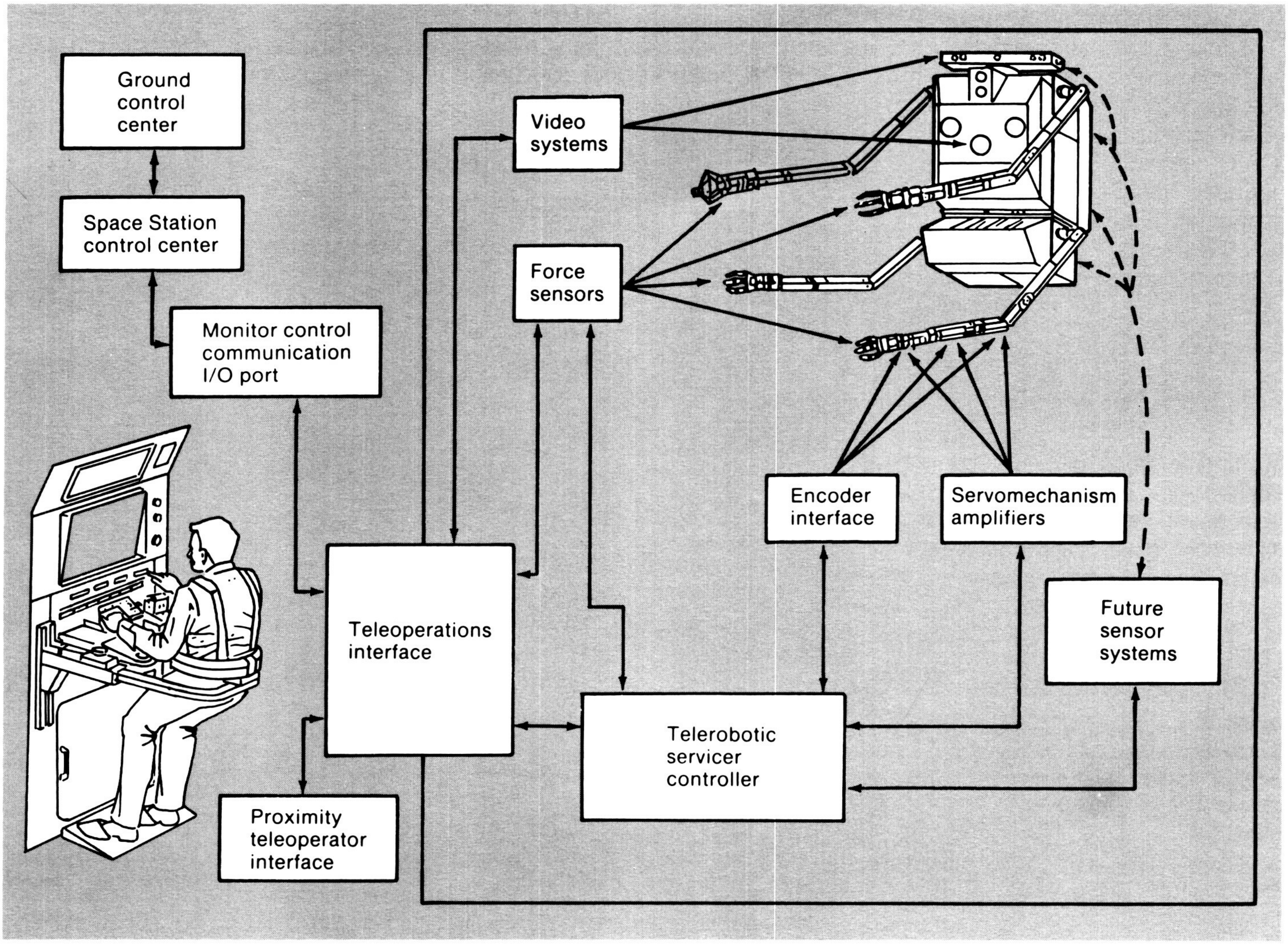


Computer architecture concepts are being defined for control of the telerobotic servicer. (Courtesy of General Electric.)

The report to the committee is that a detailed plan for the development of the TRS will be available in the fall of 1986. Basic elements of the plan already reported to ATAC are as follows. The basic objectives of the TRS program are to provide

- Early ground and flight tests to evaluate experimentally the assembly, maintenance, and servicing capabilities of the TRS
- A flight-qualified TRS to support assembly and early maintenance
- A TRS system design to facilitate post-IOC upgrades
- Incorporation of advanced telerobotic technologies into the TRS

The preliminary plan states that the TRS will have the capability of being used as a

- Smart front end on the NSTS orbital maneuvering vehicle
- Dextrous manipulator on the Space Shuttle RMS
- Dextrous manipulator on the Space Station MSC
- Dextrous manipulator within the Space Station payload servicing facility
- Smart front end on the Space Station OMV (when operational)

The TRS program is structured to provide (at first element launch)

- The telerobotic servicer with such features as
  - Dual arm cooperation
  - Multiple light sources
  - Force, torque, and position sensors
  - Redundant manipulators
  - Stereo cameras
- Ancillary equipment
- A man-in-the-loop control station with
  - Sensors for two-arm bilateral force and position
  - Stereo displays
  - Off-line interactive planning

The planned development of the TRS follows the overall plan for applying automation and robotics to the Space Station and for advancing A & R technology. Leveraging of the OAST generic A & R program will be provided, and OAST will play a major part in the development.

The major program phases for the TRS are

1. Develop requirements for and build a ground telerobotic system for test and verification.

2. Incorporate advanced technologies on an accelerated schedule for inclusion in the initial flight telerobotic servicer as those upgrades become available.

3. Upgrade the ground TRS to a flight qualifiable TRS.

4. Flight qualify the brassboard telerobot components for use in a flight test and tests of Space Station construction, maintenance, and servicing before the first Space Station assembly launch.

5. Define requirements for the flight TRS and carry out its design, development, test, and evaluation.

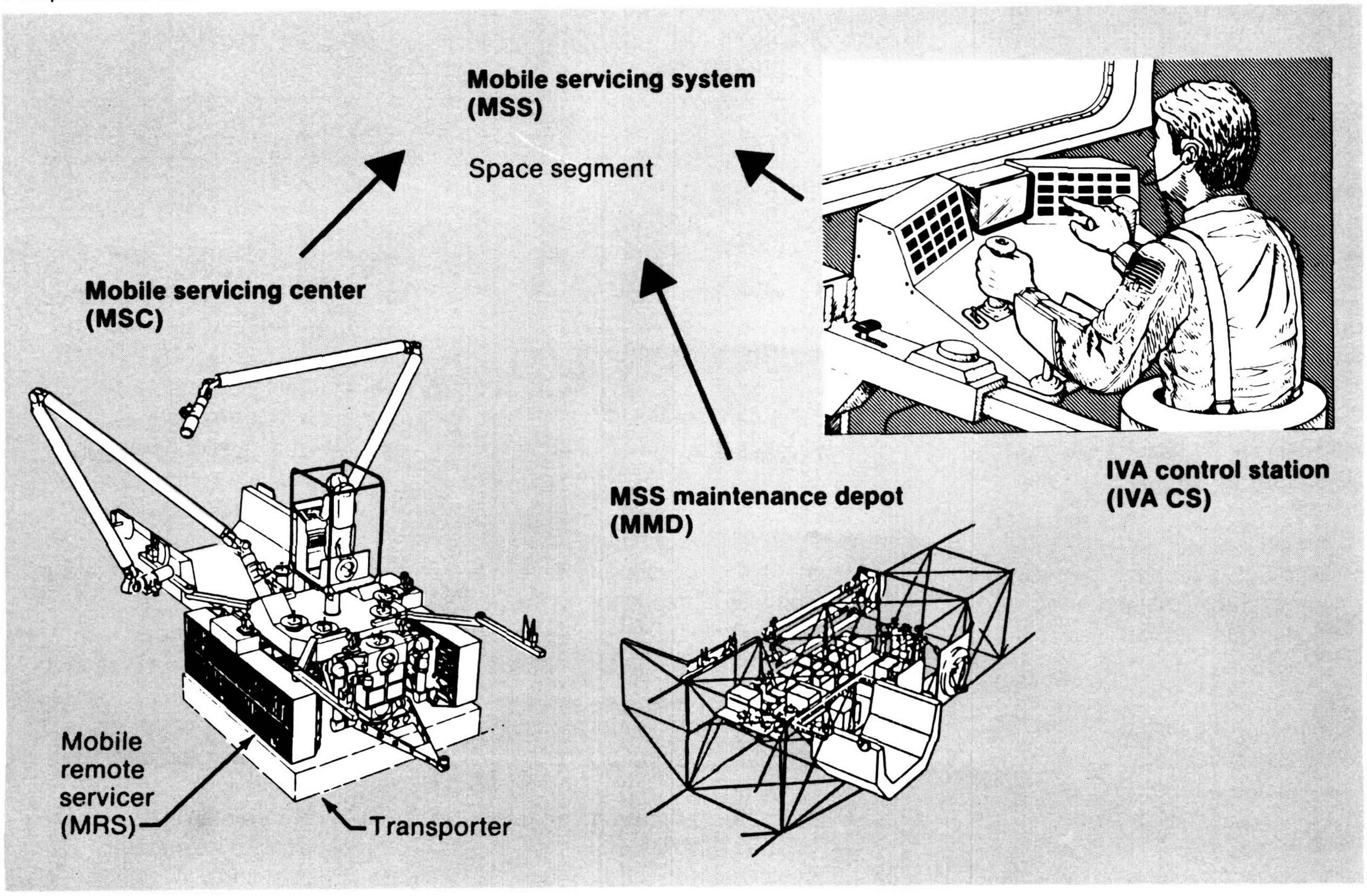
6. Identify, develop, and integrate advanced technologies into the flight TRS to provide increased post-IOC capabilities.

ATAC believes that this fundamental plan is sound, and the committee is encouraged by the actions now being taken and the cooperation of the various program and agency elements. It recognizes that there are obstacles to overcome but believes the task is feasible. It endorses the plans for the ground and Shuttle-based tests which, if the telerobot proves successful, will accelerate the use of the TRS on the Space Station.

It is ATAC's view that such a robot may be mandatory for early station use and that, in any case, the provision for its presence by the congressional initiative will lead to extensive utilization to the benefit of the station.

ATAC endorses the concept of both large-scale teleoperated manipulators built on Shuttle experience and a smaller telerobotic servicer of significantly advanced technology functioning in an integrated and cooperative environment.

Canada plans a versatile mobile servicing system (MSS). The mobile servicing center (MSC) of the MSS will be a teleoperated manipulator, initially with control by extravehicular activity and later with a control station inside the Space Station. Growth plans include a dextrous manipulator for attachment to the arms of the MSC.



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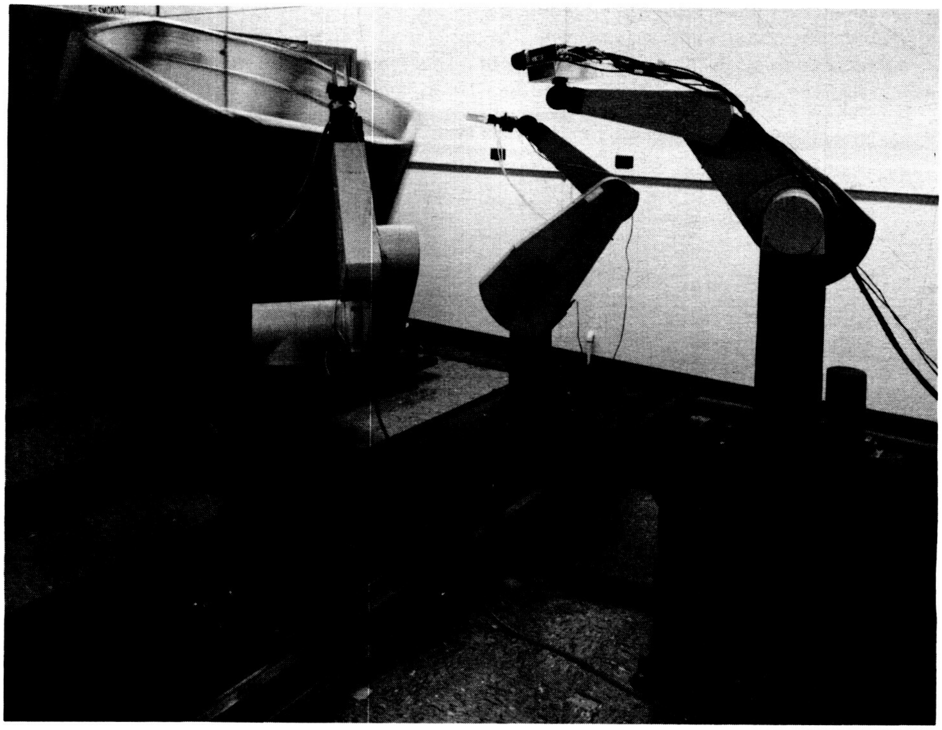
Progress in Research and Technology Base Building To Support A & R Applications

In May 1985, ATAC sponsored a workshop which reviewed much of the A & R work within NASA. The work was categorized according to the classification scheme shown in appendix F. A synopsis of the ongoing work, according to the classification scheme and the levels of technological readiness, was developed and has been kept up to date by ATAC. The updated synopsis is included as appendix G.

The Office of Aeronautics and Space Technology has continued its research program in fundamental aspects of automation and robotics. The OAST program has two major thrusts: telerobotics and system autonomy. The framework within which the work is proceeding consists of five core technology areas: (1) task planning and reasoning, (2) sensing and perception, (3) operator interface, (4) control execution, and (5) system architecture and integration.

The five core technology areas underlie both major technology thrusts—telerobotics and system autonomy. To ensure the integration of the evolving core technologies and to maximize transfer of technology, ground demonstration sequences are being developed for telerobotics by the Jet Propulsion Laboratory and for system autonomy by the Ames Research Center. Program funding is split about evenly between telerobotics and system autonomy, with two thirds for core technology and one third for ground demonstrations.

A telerobotic technology test-bed is being developed for demonstration of robotic servicing of satellites (module replacement). The test-bed will feature both teleoperation and robotic performance, with cooperative dual arm manipulation, closed-loop vision control, autonomous planning, and run-time control. The photograph shows a spinning satellite mockup with two manipulator arms and a third arm for stereovision cameras. (Courtesy of the Jet Propulsion Laboratory.)

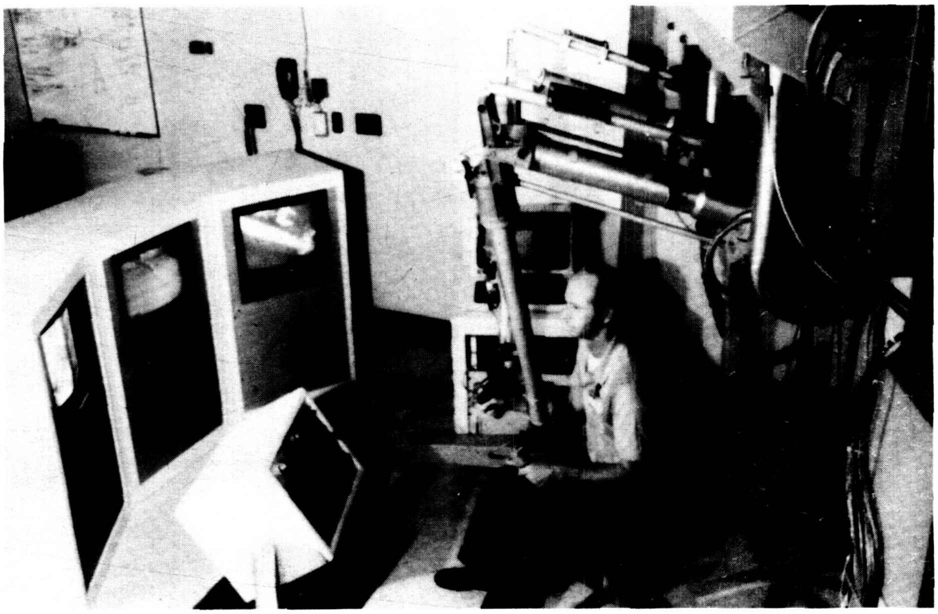


During the past 6 months, significant progress has been made in the two ground demonstration sequences and in providing assistance to the Space Station Program as plans are made for developing the telerobotic servicer for the initial station. The 1-year-old telerobotics ground demonstration team has formed a close working relationship with the newly formed telerobotic servicer design team at the Goddard Space Flight Center and has been instrumental in providing the basis for formulating a timely response to the latest guidance from Congress.

The telerobotics ground demonstration team has completed the first major milestone—a preliminary design review—for the first demonstration, to be carried out in fiscal year 1988. Demonstrated will be a telerobot with an architecture for evolution to higher degrees of automation as the technology is developed. This robot can perform spacecraft servicing (module replacement) in a fully automated robotic mode, in a supervisory control mode with a few high level commands, and in a remote manual (teleoperated) mode. The teleoperated mode (and the ability to switch to and from it) is necessary for the system to be able to revert to a more primitive mode in case the automated functions encounter unexpected problems.

The system autonomy ground demonstration program is also underway. The first demonstration (to be conducted at the Johnson Space Center), of an expert system for control of the Space Station thermal control system, will take place in 1988. During the last 6 months, the formal plan for this demonstration has been developed and accepted and the team to carry out the demonstration has been formed. By developing expert systems for control of Space Station subsystems, the number of personnel in ground control can be reduced.

Joint research in automation and robotics is being conducted between NASA and industry, universities, and other Government agencies. In this example, the man/machine interactions of a dual arm servomanipulator are being tested at Oak Ridge National Laboratory. The test is part of a Langley Research Center study of a space manipulator that can be used in a teleoperated mode or as a supervised robot. (Courtesy of Langley Research Center.)



Plans for Technology Transfer to the U.S. Economy

Efforts continue to be made by the NASA Office of Commercial Programs to effect technology transfer to and from NASA. Representatives of the Office of Commercial Programs have recently visited the Marshall Space Flight Center, John F. Kennedy Space Center, and Jet Propulsion Laboratory to discuss A & R research and development activities that have potential benefits for both Space Station and U.S. commercial interests. And the University of Wisconsin, Madison, has been selected by NASA to establish a Center for the Commercial Development of Space, specializing in space automation and robotics.

A & R candidates identified by phase B contractors have been reviewed in light of potential terrestrial applications. Special criteria to evaluate the spinoff potential of these and future candidates have been suggested for incorporation into ongoing multiattribute evaluations. A robotics data base of systems undergoing R & D and already commercially available in the United States has been formatted and data entry initiated for the RBASE 5000 information management system, for access and analysis by personal computer. The data base is being programmed at the Research Triangle Institute (RTI). This data base will be used in formulating a matrix of NASA capabilities and industry interests.

Technology transfer projects are being planned or initiated in the areas of expert systems, robotics simulation, design of an optical correlation device and system, and end effectors. The technology available at the NASA centers and probable commercial developers have been identified for each case.

In response to an announcement by the NASA Office of Space Station in the May 5, 1986, edition of *Commerce Business Daily*, approximately 18 U.S. firms expressed interest in participating in a joint NASA/industry project whereby the firm would privately fund and develop a dextrous manipulator system and NASA would add to it high-risk advanced robotic intelligence technology.

In response to many requests from the A & R community, NASA plans to sponsor a second symposium on Automation and Robotics and Advanced Computing in March 1987 in the Washington, DC, area. The symposium will stress applications of advanced automation and robotics to the Space Station and to the national economy.

Expenditures for Advanced Automation and Robotics

The committee recognizes its responsibility to assess the extent to which the Space Station Program has complied with the suggested utilization of 10 percent of program funds for automation and robotics. We maintain that it is too early to form a definitive judgment on the projected extent of compliance.

There is still no method of estimating the projected costs of design, development, test, and evaluation (DDT&E) of automation within the Space Station. The committee considers two mechanisms possible for obtaining such estimates. The most direct is from the phase C/D proposals, and ATAC has recommended that the RFPs require such a cost breakout. A second mechanism may be through the tracking of A & R candidates in the data base established by NASA, if cost breakouts are provided.

Estimates provided by NASA of Space Station expenditures devoted to automation and robotics have not changed from those listed in the previous report. This information is summarized in table 3.

Agency-wide funding devoted to automation and robotics for fiscal year 1986 is given in table 4, as in the previous report.

TABLE 3.— SPACE STATION FUNDING FOR AUTOMATION AND ROBOTICS

Activity	Funding, in millions of dollars		
	FY 85	FY 86	FY 87
Advanced development	1.6	2.9	4.2
Systems engineering and analysis	1.1	1.0	0.9
Operations	0.1	0.8	0.9
Space Station utilization	0.4	0.8	1.7
Phase B contracts (22 months)	←	7.7	→
Total, all years			24.1*

*Excludes congressional set-aside.

TABLE 4.- NASA FUNDING FOR AUTOMATION AND ROBOTICS

[Fiscal year 1986, millions of dollars]

Office and activities	Funding
Space Station	16.2*
Advanced development	
Systems engineering and analysis	
Operations	
Space Station utilization	
Phase B contracts	
Aeronautics and Space Technology	10.2
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	4.6
Robotics	
OMV servicing and refueling	
Automation	
Space Science and Applications	0.7
Definition of user needs	
Space Tracking and Data Systems	1.0
Improved flight operations	
Total NASA funding, approximately	32.7

*Includes $10 million congressional set aside.

Conclusions

Compliance with ATAC Guidelines

ATAC believes that the Space Station Program, the study contractors, and cooperating NASA programs have continued to strive, within resource priorities, to comply with the intent of the ATAC recommendations, to respond to the goals proposed by ATAC for the initial and the evolutionary station, and to meet the sense of Congress.

ATAC has expressed its view that the most critical needs for automation and robotics on the Space Station are capabilities

- To assemble and build the station
- To operate it autonomously
- To service efficiently the station, payloads, and satellites

ATAC does not believe that these needs have yet been adequately addressed. Work package contractors have studied and recommended A & R candidates supporting these capabilities. But these recommendations have only partially found their way into Space Station planning. Configuration and assembly studies, which are being conducted, plan for use of the NSTS remote manipulator system and the Canadian mobile servicing center but do not consider use of the telerobotic servicer. Integrated planning for station operations and system autonomy is limited, and therefore adequate benchmarks do not yet exist to drive design decisions to incorporate advanced automation. (Results of a meeting of all NASA centers on the subject of operations cost, which was held at Marshall Space Flight Center August 13-15, 1986, have not been reviewed by ATAC for this report.) Plans for the use of robotics for servicing are further advanced, and studies have been conducted of such aspects as robot mobility and end effectors.

Space Station Design

We cannot ascertain, at this time, the degree to which automation and robotics will be incorporated into Space Station design. Study contractors report plans to develop and implement automation and robotics on the station which are generally consistent with ATAC goals and recommendations. But the existing station baseline documentation does not reflect significant plans for automation and robotics, except for the TRS, the Canadian MSS, the thermal control system, and the data management system (which will require further validation).

Scant mention of IOC applications of automation and robotics or design accommodations for future automation and robotics can be found in the preliminary documents submitted by the work package centers for Space Station configuration control. And, although it may be too early to expect detailed designs that include automation and robotics, the dearth of attention or even awareness in these documents is of concern to ATAC.

Robotics

ATAC continues to be optimistic about the prospects for robotics on the Space Station. Funding has been set aside by Congress for this initiative, and planning for the telerobotic servicer is underway. But careful consideration to designing the station to be "robot-friendly" must be given if the robot is to perform the required assembly, maintenance, and servicing functions.

Advanced Automation

ATAC is concerned about prospects for advanced automation. The overriding objective to minimize costs and technology risks in order to meet IOC cost targets, without specific longer term goals in such areas as operating cost, productivity, and safety, is inhibiting the use of advanced automation in the initial station and inhibiting the hooks and scars and design knowledge capture required for evolutionary growth of automation and robotics.

We have a concern that, without adequate provision for advanced automation on the station, including the necessary development, the operation and maintenance costs for full utilization of the station may exceed the funding ability.

Design Knowledge Capture

There has not been adequate provision for the capture of design knowledge of the station, which is critical to the incorporation of automation in an evolutionary station. TMIS does not provide for it and therefore special provisions are necessary to include the requirements in the phase C/D RFPs.

Knowledge-based systems have been proposed to increase station reliability and decrease the required number of ground operations personnel by augmenting system control hardware with monitoring and control, planning and scheduling, and fault diagnosis. These knowledge-based systems require that as-built design knowledge be incorporated into the system. Without this design knowledge capture, ground operations personnel will have to be employed to become experts in the operation and diagnosis of less reliable systems.

Life Cycle Costing

The constraint to design the Space Station to an initial cost target without giving due weight to operational or life cycle costs is the primary inhibitor of automation and robotics for the station. NASA has espoused the incorporation of operational as well as DDT&E costs in the design-to-cost approach for the station. But this consideration is not reflected in the actions of (1) program managers (whose decisions are driven only by the minimization of initial DDT&E cost because there are no other, longer term cost targets) and (2) subsystem designers (who believe designs incorporating advanced automation and robotics will be rejected on the basis of initial cost).

ATAC has recommended to NASA, therefore, one of two alternatives:

- Either a funding augmentation or set-aside for advanced automation

- Or a directive to give operational costs a weight balanced with the weight of initial costs

In the absence of one of these alternatives, we expect to see

- Very limited advanced automation on the initial station
- An excessively costly process to incorporate evolutionary growth in advanced automation
- A station that will be operationally expensive
- A station that cannot have autonomous operation

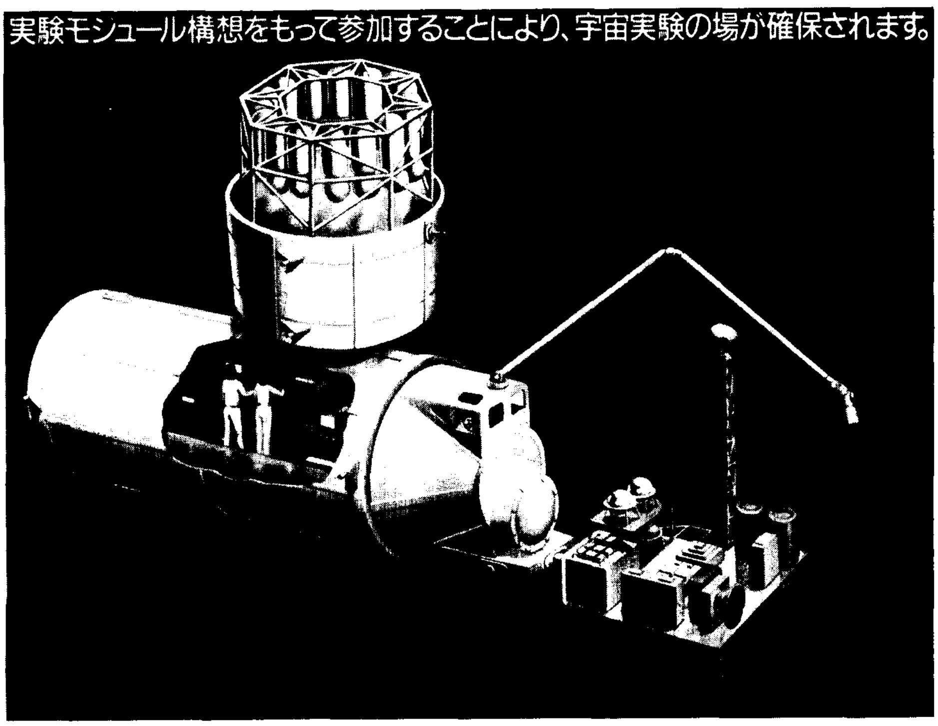
Phase C/D Requests for Proposals

The committee takes special note of the fact that the requests for proposals for the design and fabrication phases of the program will soon be issued. ATAC has recommended to NASA that a strong position be taken by the program that in the selection of contractors significant weight must be given to A & R considerations, including design knowledge capture and life cycle costing.

The requirements of the phase C/D requests for proposals and the proposal responses are critical if automation and robotics is to be utilized to meet the needs as viewed by ATAC.

Management Structure

ATAC further concludes that the program management structure has not been sufficient to allow adequate promotion of A & R technology and technical requirements. ATAC has recommended that NASA correct this deficiency and provide a greater voice to automation and robotics before the phase C/D RFPs are made final.



The Japanese experiment module (JEM) includes a remote manipulator for transport of materials between the logistics module and the exposed facilities.

APPENDIX A

NASA Advanced Technology Advisory Committee

Aaron Cohen, Chairman, Director of Research and Engineering, Lyndon B. Johnson Space Center (JSC)

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J. Larry Crawford, Director of Engineering Division, Office of the Chief Engineer, NASA Headquarters

Lynwood C. Dunseith, Assistant to the Director of Space Operations, JSC

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Henry Lum, Chief of Information Sciences Office, Ames Research Center (ARC)

Robert R. Nunamaker, Director for Space, Langley Research Center (LaRC)

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Giulio Varsi, Automation and Robotics Manager, Engineering Division, Office of Space Station, NASA Headquarters

APPENDIX B

References

1. NASA. 1985. Advancing Automation and Robotics for the Space Station and for the U.S. Economy. NASA TM 87566.

2. NASA. 1985. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 1—April through September 1985. NASA TM 87772.

3. NASA. 1986. Advancing Automation and Robotics for the Space Station and for the U.S. Economy, Progress Report 2—October 1985 Through March 1986. NASA TM 88785.

4. Pioneering the Space Frontier: The Report of the National Commission on Space. 1986. Thomas Paine, Chairman; Bantam Books, May.

5. Boeing Aerospace Company. 1986. Automation and Robotics Plan, WP-01. D483-50055-1, June 30.

6. Martin Marietta Aerospace. 1986. Automation and Robotics Plan, WP-01. SSP-MMC-00022, Rev. A, June 30.

7. McDonnell Douglas Astronautics Company. 1986. Automation and Robotics Plan, WP-02. MDC H2036A, June.

8. Rockwell International. 1986. Automation and Robotics Plan, WP-02. SSS85-0190A, June 13.

9. General Electric. 1986. Automation and Robotics Plan, WP-03. June 30.

10. RCA Astro-Electronics Division. 1986. Automation and Robotics Plan, WP-03. June 30.

11. Rocketdyne Division, Rockwell Corporation. 1986. Interim Automation and Robotics Plan, WP-04. RI/RD85-319-1, June 30.

12. NASA. 1986. Program Definition and Requirements Document. JSC 30000, July.

13. NASA. 1986. Space Station Program Office Manual for Preliminary Design of Space Station Machine Intelligence, Robotics, and Automation. July.

APPENDIX C

Acronyms

A & R	automation and robotics
AI	artificial intelligence
ACD	architectural control document
ATAC	Advanced Technology Advisory Committee
BCD	baseline configuration document
C & T	communication and tracking
DDT&E	design, development, test, and evaluation
DMS	data management system
ECLSS	environmental control and life support system
EVA	extravehicular activity
FDIR	fault detection, isolation, and recovery
IOC	initial operating capability
IVA	intravehicular activity
MSC	mobile servicing center
MRS	mobile remote servicer
MSS	mobile servicing system
MTL	materials technology laboratory
NASA	National Aeronautics and Space Administration
NSTS	National Space Transportation System
OAST	Office of Aeronautics and Space Technology
OMS	operations management system
OMV	orbital maneuvering vehicle
ORU	orbital replaceable unit
OTV	orbital transfer vehicle
PDRD	Program Definition and Requirements Document
PMAD	power management and distribution
R & D	research and development
RFP	request for proposal
RMS	remote manipulator system
SIM	System Integration Model
TCS	thermal control system
TDRSS	Tracking and Data Relay Satellite System
TMIS	Technical and Management Information System
TRS	telerobotic servicer
WP	work package

APPENDIX D

Candidate A & R Applications for the Initial Space Station

Part 1—Program Elements Addressed by ATAC

Subsystem/program element	Function/functional element	Source (work package)
Electric Power	System health monitoring, fault recognition	2
Generation, storage, and conditioning	Failure prediction	2
	Fault isolation and reconfiguration	2, 4
	Maintenance, repair, retest	2, 4
	Failure cause diagnosis	4
Loads and allocation	Scheduling and management	2, 3, 4
Common module	On-orbit checkout	1
	Trend analysis	1
	Fault management	1
	Load management	1
	Bus configuration management	1
Laboratory module, platforms, and attached payloads	Trend analysis	3
	Fault diagnosis	3
	Controller	3
Guidance, Navigation, and Control	Maintaining the orbit	2
	GNC monitoring and maintenance	2
	Mission planning	2
	On-orbit checkout	2
	Mass properties validation	2
	Space traffic control	2
	Control of attached payloads	2
	Collision avoidance	2
	Deboost	2, 3
	Proximity operations	2, 3
Platforms, customer servicing/ accommodation	Rendezvous navigation	2, 3
Laboratory module, platforms, and attached payloads	Fault diagnosis	3
Communication and Tracking	External communications control	1, 2
	Tracking control	2
Common module	Fault management	1, 2
	Video control	1
	Audio/video distribution	1
Laboratory module, platforms, and attached payloads	Data rate selection	3
	Communication scheduling	3
	Rendezvous tracking	3

Part 1—Program Elements Addressed by ATAC (concluded)

Subsystem/program element	Function/functional element	Source (work package)
Information and Data Management	DMS monitoring and diagnosis	1, 2
	Fault diagnosis and performance prediction for external subsystems	2
	Continuity and opportunity planning	1, 2
	Fault recovery	1, 2
	Display interpretation	1, 2
	Robot control	2
Common module	Module safety advisor	1
	Payload interface controller	1
	Inventory management	1
	System status assessment	1
	Fault diagnosis	1
	Redundancy and configuration management	1
	Resource and maintenance scheduling	1
	Trend analysis	1
Laboratory module, platforms, and attached payloads	Trend analysis	3
	Fault diagnosis	3
	Subsystem status assessment	3
	Redundancy and configuration management	3
	Data base management	3
Environmental Control and Life Support	Data base management	1
	Configuration management	1
	Statusing	1
	Water management	1, 2
	Atmospheric management	1, 2
	Fault diagnosis	1, 3
	Trend analysis	1, 3
	Hyperbaric chamber operation	1, 3
Common module	Integrated controller	1
	Monitoring and statusing	1

Part 2—Program Elements Not Specifically Addressed by ATAC

Subsystem/program element	Function/functional element	Source (work package)
Thermal Systems	Inspection	2
	Assembly, repair, replacement	2
	Payload installation, servicing, and management	2
	Planning	3
Common module	Monitoring and statusing	1, 2
	Fault management	1, 2
EVA Systems	Customer service	2, 3
	Assembly support	2
	Rendezvous and docking	2
	EVA equipment support and servicing	2, 3
	EVA planning and monitoring	2, 3
Fluids	Storage and transfer operations	2
Structures and Mechanisms	Assembly of —Mounting plates —Truss articulation control	2
	Inspection of —Utility run —Truss articulation control —Lubrication	2
	Maintenance and repair of —Utility run —Bolt torque —Remote manipulator —Gimbal system	2
	Thermal curvature control	2
	Station utilities management	2
	Medical assistance in airlock	2
Modules	Connect/interconect —Berthing assistance —Utilities connection and verification —Latch verification —Inspection of seals —Tunnel inspection —Chemical decontamination —Airlock actuation	2
	Interconnect inspection and repair	2
Orbital Maneuvering Vehicle and Orbital Transfer Vehicle	Berthing and deployment	1, 2
	Navigation and control	1
	Fluid transfer	1
	Maneuvering	1
	Payload integration	1
	Maintenance and servicing —Checkout of orbital replacement units —Inventory accounting —Activity scheduling	1, 2

Part 2—Program Elements Not Specifically Addressed by ATAC (concluded)

Subsystem/program element	Function/functional element	Source (work package)
Logistics Module	Inventory management for items going to and from the Space Station	1
	Propellant transfer	1
	Spares relocation (inside and outside)	1
Laboratory Module	Experiment scheduling	1
Materials technology	Checkout of customer equipment interface	1, 2
	Experiment monitoring	1
	Chemical and physical analysis	1
Life sciences	Experiment operation	3
	Exacting, specialized tasks	3
	Fetching of supplies	3
	Test protocol verification	3
	Experiment data processing and management	3
	Sample analysis	1, 3
Operations	Crew training	2
	Station coordination	2
	Activity planning	2
	Shuttle proximity operations/berthing	2
	Shuttle interface inspection and repair	2
	Shuttle manipulator coordination	2
	Chemical decontamination	2
Propulsion	Propellant transfer	1
	Monitoring and statusing	1, 3
	Fault detection	1
Payloads	Checkout of attachment ports	3
User Interface	System monitoring and fault diagnosis	3
	Controller	3
	Servicing	3
General (Robotics)	Assembly	1
	Parts inspection and replacement	1, 3
	Materials handling (satellite servicing and repair)	1
	Payload installation/exchange	3
	Payload servicing (ORU replacement, transport, resupply, fluid transfer, and manipulation)	1
	Laboratory functions	1

APPENDIX E

Recommended Applications for the Initial Space Station

Knowledge-Based (Expert) Systems

Systems management—training and crew activity planning
Space Station coordinator
Data base management—subsystem assessment, trend analysis, fault management
Resource planning and scheduling
Thermal curvature control
Logistics
Onboard personnel training
Passive thermal monitoring
Fault diagnosis for communication and tracking
Power system control and management, including trend analysis and fault management
Environmental control and life support subsystem—trend analysis, reconfiguration management, data base management, built-in testing, monitoring and recording, fault detection and identification, and assuring atmospheric integrity
Guidance, navigation, and control—automated maneuver planning and control
Platform applications, including power system control, distributed data processing, and planners for guidance, navigation, and control
Laboratory module applications, including data management system and life support for experimental subjects
Experiment scheduling and monitoring
EVA task planning
Fault diagnosis for manipulators

Robotics

Space Station assembly
Inspection and repair of trusses and structures
ORU replacement
Utility run inspection and repair
Payload servicing—exchange, transport, resupply, fluid transfer, and manipulation, including interfaces compatible with both robots and humans
Laboratory functions—care of plants and animals, analysis of biological samples, and centrifuge access
Rendezvous and docking
Contingency event accommodation

Advanced Automation

Smart camera system
Automated power management (including automatic test and checkout) which incorporates fault-tolerant architecture and functions autonomously with ground override
Laboratory module automation, including cleaners for cages and plant growth chambers and a specimen-labeling device
Servicing of orbital maneuvering vehicle, orbital transfer vehicle, and EVA suits

APPENDIX F

NASA Categories for Automation and Robotics Work

1.0 Basic functional capabilities and issues

1.1 *Knowledge (Task planning and reasoning)**
Representation and reasoning—surface and deep knowledge
Problem solving, control methods, search techniques
Deduction and theorem proving
Knowledge acquisition and learning
Diagnosis, monitoring
Planning, simulation, execution
Perceptual reasoning, object recognition

1.2 *Sensing (Sensing and perception)*
Force, torque
Proximity, range and rate
Tactile, kinesthetic
Visual, optical
Auditory, acoustic
Pressure, flow, temperature, dewpoint, speed, voltage, current
Integration and coding of sensor information

1.3 *Actuation and manipulation (Control execution)*
Control technology
—Coordination
—Collision avoidance
—Compliance
—Error recovery
Manipulators—arms, end effectors, propelling mechanisms
Actuation in dynamic and distributed expert systems

1.4 *Human/machine interface (Operator interface)*
Displays
Force/torque feedback
Controls and input mechanisms
Natural language processing
Voice synthesis and recognition
Interfaces and user interface management
—Users of knowledge-based or expert systems
—Users of management information systems
—Reprogramming and maintenance
—Options for levels of automation
Automation tradeoffs
Sensor fusion

2.0 System capabilities and system issues

2.1 *Supporting software and hardware (System architecture and integration)*
Fault-tolerant architecture
Specialized artificial intelligence architectures
Programming languages
Uninterruptable and distributed systems
Resource management
Design accommodation for automation and robotics

2.2 *System design and integration (System architecture and integration)*
Environments for automation
Verification and validation
Automatic test and checkout
Automated software development
Knowledge engineering
Shells for knowledge-based or expert systems
Engineering automation
Design, programming, and documentation aids

2.3 *Knowledge-based or expert systems (no equivalent)*
Control and monitoring
Fault management, servicing and repair
Executives and hybrid
Planning/scheduling/sequencing
Engineering and programming support
Data base management
Distributed and interacting expert systems

2.4 *Robotic and telerobotic systems (no equivalent)*
Assembly and construction
Parts handling
Servicing and repair
Computer vision systems, automatic inspection

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*The descriptions in parentheses are the corresponding categories used by the Office of Aeronautics and Space Technology (OAST) for their research.

APPENDIX G

R & D Activities Related to Automation and Robotics

Institution	Objectives of the research	Potential Space Station use	Level
Category 1.1—Knowledge			
Ames Research Center	Representational issues including —Time (duration and causality) —Actions and their effects —Spatial information (models, CAD) —Truth maintenance Decision-making under uncertainty Learning Fault diagnosis Integrated decision-making for distributed expert systems	Astronaut and equipment scheduling System operation Construction Autonomous robots	2-3
Goddard Space Flight Center	Geometric knowledge base Autonomous reasoning for assembly/disassembly/replacement	Servicing and assembly	4
Goddard Space Flight Center	Development of standard formats	Autonomous robot servicing	5
Jet Propulsion Laboratory	Knowledge-based subsystem development and integration —Configuration planning —Global schedule planning —Failure diagnosis and reasoning —Execution monitoring	System autonomy Telerobotics Ground operations Automation	2-6
Jet Propulsion Laboratory	Knowledge-based system development tools —Blackboard —Conditions model —Memory model —Process model —Reasoning engine design language —Graphics debugging —Time representation model	Expert system development	2-4
Johnson Space Center	Capture of design evolution knowledge	Systems engineering	6
Johnson Space Center	Qualitative modeling of Space Station	System integration	3
Langley Research Center	Distributed artificially intelligent system for interacting with the environment (DAISIE): planner/controller interaction	Control	3
Langley Research Center	Fault diagnosis expert system (for aircraft cockpit) including temporal reasoning	Fault diagnosis	3
Langley Research Center	Expert system development —Design optimization —Reducing search space for analysis programs and data bases	General applications	1

R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (continued)

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Intelligent robot servicing via task automation including —Sensor data fusion —World modelling —Task planning —Task sequencing —Conflict resolution	Automation of robot servicing, ORU replacement	2
Marshall Space Flight Center	Automatic development of time-optimal algorithms for robot manipulator control	Development of robotic system for Space Station and free-flying servicers	4
Category 1.2—Sensing			
Ames Research Center	Optical information processors	System operation	2-3
Ames Research Center	Information understanding and extraction (sensor fusion)	Autonomous robots	2-3
Goddard Space Flight Center	Compliant force feedback and applications to use devices with such feedback	ORU replacement and assembly	4
Jet Propulsion Laboratory	Machine vision; construction of prototype hardware for a real-time image processing system —Development of an acquisition and tracking system —Development of a feature extractor and model matcher	Telerobotic sensing	3
Jet Propulsion Laboratory	Force and torque sensing Proximity sensing Tactile sensing Sensor fusion	Telerobots	6 3 3 1
Johnson Space Center	Development of TV systems for target recognition, identification, and attitude determination Voice command systems	Automated tracking	2
Johnson Space Center	Laser vision development Spatial positioning using controlled-position light beams Infrared remote control techniques	Robotic sensing and control	3
Johnson Space Center	Sensors for collision avoidance in space	Autonomous robots	3
Johnson Space Center	Closed-loop processing for robot vision	Autonomous robots	2
Langley Research Center	Laser-based image and rate/ranging systems	Autonomous robots	3
Langley Research Center	Focal plane preprocessing for improved sensitivity and speed		4
Lewis Research Center	Techniques for sensor-failure detection, isolation, and accommodation	System monitoring	4
Marshall Space Flight Center	Utilization of high accuracy charge injection device (CID) sensors in a hardware adaptive target-tracking system	Orbital maneuvering vehicle (OMV), orbital transfer vehicle (OTV), and Space Station docking, berthing, servicing	3-4
Marshall Space Flight Center	Vision sensor for a robotic system to remove solid rocket booster thermal protection during rework	Automated processes in the space environment	6
Marshall Space Flight Center	Optimization of lighting, video camera control, and transmission for OMV rendezvous and docking (through flat-floor simulation studies)	OMV and OTV operations and remote viewing	3

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Development of vision system for automatic docking using TV box scan and syntax pattern recognition	Autonomous docking and servicing	2
Category 1.3—Actuation and Manipulation			
Ames Research Center	Real-time control of limber manipulators with end-point sensing	Manipulators, robotics, and servicing	2
Jet Propulsion Laboratory	Two-arm force-reflecting hand controller "Smart" hand development Distributed control for space telerobot mechanization Hybrid (position and force/torque) control Dual arm manipulation Multifinger hand and controller	Telerobotics technology	2 4 2 2 2 2
Johnson Space Center	Robotic test facility for Space Station hardware interfacing requirements Actuator laboratory for advanced robotic and docking systems Programmable mechanisms for assisting the RMS in payload handling	Manipulators and robotics	2
Johnson Space Center	Control architectures for system autonomy	Station and robot control	3
Langley Research Center	Parallel-jaw end effectors with proximity detection Quick-change tool systems High-level command systems Six-degree-of-freedom force and torque sensors and displays	Generic robotics and teleoperation	3 5 4 6
Lewis Research Center	Smart remote power controllers and remote bus isolators for power limiting and fault detection and isolation	Autonomous electrical power system	4
Marshall Space Flight Center	Protoflight manipulator	Servicing and construction	5-6
Marshall Space Flight Center	Intermeshing end effector for use on manipulator arms and capture devices	Servicing and construction	5
Marshall Space Flight Center	Intelligent robot servicing via task automation including —Active compliance control —Static and dynamic force limiting —Dynamic path compensation —Collision detection	Automation of robotic servicing, ORU replacement, berthing	2-4
Marshall Space Flight Center	Inflatible end effectors which expand inside large, irregularly shaped space structures, thereby distributing the force loads evenly	Assembly, maintenance, and repair of space structures	3-4
Category 1.4—Human/Machine Interface			
Ames Research Center	Telepresence information and environments Procedural aids for system automation Models of human vision, voice input/output, command language	Improved human/machine interface	2-3
Ames Research Center	Development and evaluation of AI technologies for autonomous systems	System and subsystem automation	3-4

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R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (continued)

Institution	Objectives of the research	Potential Space Station use	Level
Jet Propulsion Laboratory	Evaluation and analysis tools to assess the merit of automating various functions and decide where the human/machine interface should be	Optimal extent of automation and robotics utilization	4
Jet Propulsion Laboratory	Fused sensor displays Force feedback evaluation Predictive displays Analysis of human factors associated with operating a telerobot in zero gravity Operator interface to dual arm telerobot	Teleoperation	2-4
Johnson Space Center	Development of virtual-image, helmet-mounted displays Anthropomorphic hand manipulator Automatic control of EVA cooling	More efficient extravehicular activity	2
Johnson Space Center	Advanced interface technologies—use of speech synthesis, voice recognition, and natural language integrated with expert system applications	Improved human/machine interface	3-4
Johnson Space Center	Graphic knowledge displays to aid in interface with intelligent systems	System control and maintenance	2
Johnson Space Center	Distributed authority using intelligent systems	Station and robot control	2
Johnson Space Center	Motivational displays for exercise	Crew health maintenance	3
Kennedy Space Center	Advancement of design capability by human/machine (CAD) interface	Improved human/machine interface	
Langley Research Center	Crew station design and evaluation —Real-time simulation —Expert system to handle human factors criteria —Integrated control and display Advanced display media—flat panels Advanced graphics —3-D displays —Multiple dynamic windowing —High performance graphic engines Advanced controls consolidation and work load reduction—voice, touch, keyboard, eye-slaved Information management —Concurrent processes monitoring —Intelligent automation criteria —Reconfigurable display concepts	More efficient use of crew time and work station space	2-4
Marshall Space Flight Center	Reconfigurable remote operator station with stereoscopic video, graphics, and voice/touch control capabilities	Telepresence interface servicing and assembly More efficient use of crew time	2-4
Marshall Space Flight Center	Graphical simulation for predictive display, off-line auto-sequence display, and system checkout	Teleoperations and automated servicing and assembly	2-3
Marshall Space Flight Center	Expert system allowing non-simulation personnel to perform studies with complex simulation systems via a natural language interface	Reduced-cost Space Station simulations	2-4

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Incorporation of 6-DOF hand controller used to operate manipulator arm	Control of remote servicer, OMV, telerobotic servicer (TRS)	6
Marshall Space Flight Center	Use of force-reflecting hand controller to return force and torque information to operator	Telepresence control of servicing	6
Marshall Space Flight Center	Optimization of lighting, video camera position, and operator aptitudes for accomplishment of servicing tasks	Remotely operated servicing	3
Category 2.1—Supporting Software and Hardware			
Ames Research Center	Programming environments for expert, fault-diagnosis, and procedure-planning systems Real-time simulation and modeling Tradeoffs between human understanding and machine processing and intelligence Automated capture of design information Automated software validation and verification	Expert systems in general Optimal human/machine interfaces and task partitioning Fault-tolerant systems	2-4
Ames Research Center	A spaceborne very high speed integrated circuit (VHSIC) symbolic processor for "intelligent" processing	Advanced "intelligent" processing	2
Goddard Space Flight Center	Rapid prototype of "smart" telescience work station	Remote investigator display and control	5
Jet Propulsion Laboratory	Self-checking computer modules Autonomous management systems for redundancy maintenance Advanced high-speed computers	More reliable and efficient computing Onboard command, control, and data processing	2-3
Kennedy Space Center	Expert systems software for operational system diagnostics, test, and control embedded as firmware on system hardware	Automated diagnostics, test, and control of Space Station systems	
Kennedy Space Center	Expert system for scheduling, planning, replanning, and resource allocation	Automated system scheduling and resource allocation	
Kennedy Space Center	Higher order language for automated procedure development and systems communications	User friendly language for Space Station system operations and software maintenance	
Langley Research Center	Multiplexer with fiber optics and wavelength division to allow for high data rates and simultaneous channels of communication over a passive interconnect	Control, communication, data transmission	6
Langley Research Center	VHSIC technology development —Multiplex interconnected processor to do asynchronous and spatial distributed data processing in a configuration that is fully self-testable —Algorithms to map tasks onto the processors (autonomous) —Strategic processor for joint and link trajectories —Coupling with sensor systems and image vision processing	Core processor (embeddable)	5
Langley Research Center	Multiplexer with wavelength division for a laser operating in free space to communicate over short ranges	Remote control and communication across robotic joints	2

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R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (continued)

Institution	Objectives of the research	Potential Space Station use	Level
Langley Research Center	Design and assessment methods for integrated, fault-tolerant flight control systems Methods for validating the performance and reliability of complex electronic systems A facility for research in advanced computer architectures	Fault-tolerant systems	2-3
Langley Research Center	Advanced information-network architectures —Integrated —Growable —Fault tolerant —Improved in capacity and speed of information flow	More reliable and efficient computing, data management, communications	4
Langley Research Center	Digital video that enables efficient and effective generation and reception/display of high quality video for remote Space Station operations	Mobile remote manipulator system	2
Langley Research Center	Video image processing to enable complex decision-making for onboard human/machine interactions	Autonomous proximity operations and remote operations	3
Marshall Space Flight Center	Machine-vision system for more efficient and faster recognition of 2-D images	Higher speed remote applications	3
Category 2.2—System Design and Integration			
Goddard Space Flight Center	Test lab for robot techniques in ORU interchange	Servicing of platforms, spacecraft, and instruments	3
Goddard Space Flight Center	Flight experiment/demonstration of teleoperated and autonomous robotic manipulation —Fluid resupply —Module replacement —Structural assembly	Service bay spacecraft servicing Attached payload servicing Platform servicing Structural assembly	4
Goddard Space Flight Center	Design and development of flight telerobotic system	Assembly and servicing	3
Jet Propulsion Laboratory	Telerobot demonstrations —Integration of teleoperation and robotics sensing and perception —Task planning and execution —Control execution and operator interface	Telerobotics	2
Jet Propulsion Laboratory	Telerobot run-time control	Telerobotics	2
Johnson Space Center	Demonstration of a technique for automated control, being tested on air-revitalization components of the environmental control system	Automatic control and monitoring of Space Station subsystems	3
Johnson Space Center	Simulation, including visual displays, of docking and berthing activities among the Space Station, Shuttle, and orbital maneuvering vehicle	Development and training	2-4

R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (continued)

Institution	Objectives of the research	Potential Space Station use	Level
Johnson Space Center	Computer augmentation/automation for integrating data formatting, computations, expert systems, displays, etc. in a distributed system	Orbital systems monitoring	2
Johnson Space Center	Support to definition of on-orbit assembly sequences and methods Berthing dynamics and simulation of orbital operations	Optimum assembly of the Space Station	2
Johnson Space Center	Expert system shells —Review capabilities of commercial tools —Pinpoint areas needing further development —Develop shells in conventional languages	Automation of Space Station functions	1-2
Kennedy Space Center	Development of a robotics test-bed to study the application of robotics to hazardous conditions such as refueling of rockets	Space servicing of satellites	2
Kennedy Space Center	Integrate distance sensing and robotic vision techniques to the control and movement of large structures	Mating, docking, and assembly activities	
Langley Research Center	Computer-aided assessment models —Space Station operations —Data management systems —Structural analyses	System design and operation	2
Langley Research Center	System validation techniques —System performance and reliability assessment methods —Emulation/simulation technology —Design proof techniques	Validation tools	2
Langley Research Center	Acoustic environment qualification testing	Voice control systems	2
Langley Research Center	Simulation of robotic systems to define and analyze performance Test-bed for AI and robotics interfaces Intelligent control of robots, vision systems, sensors, graphics, etc. Design of a space manipulator	Improved robots and robotic control	2-6
Langley Research Center	Enhanced structural dynamics testing using artificial intelligence	Structure design	1
Lewis Research Center	Development of power system test-bed with network control to evaluate automation strategies	Autonomous electrical power system	3
Marshall Space Flight Center	Simulation, including video displays, of rendezvous and docking activities of OMV and OTV	Development and training	2-4
Marshall Space Flight Center	Simulation of teleoperator and robotic systems to define and analyze performance of manipulator test-bed for evolutionary automation, manipulator control systems, and sensor interfaces	Improved teleoperator and robotic systems	3-5
Marshall Space Flight Center	Autonomous management of large spacecraft power system	Electrical power system automation	5
Marshall Space Flight Center	Expert system for maintenance of power loads priority lists	Common module electrical power system automation	3

R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (continued)

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Determining expert systems applicability and rapid prototyping for common-module electrical power system	Electrical power system automation	3
Marshall Space Flight Center	Flexible simulation of robot kinematics, dynamics, and control, allowing experiments in new manipulator designs, AI, and planning and control of robot paths	Reduce costs in evaluating new methodologies	6
Marshall Space Flight Center	Simulation and analysis of vehicle-contact dynamics using moving platform and force/moment sensors to determine vehicle interactions in space	Design, evaluation, and verification of berthing, docking, latching, and servicing mechanisms	6
Marshall Space Flight Center	Utilization of the intermeshing end effector to interface with EVA-compatible tasks	Servicing and assembly	4
Marshall Space Flight Center	Hardware system for autonomous docking utilizing high-accuracy solid-state sensors	OMV and Space Station docking and berthing	3-4
Marshall Space Flight Center	Expanded simulation capability to support studies of the OMV, free-flyers, the TRS, and the common module	OMV and OTV payload berthing Space Station maintenance and inspection	3-5
Marshall Space Flight Center	Demonstration of intelligent robotic servicing including —Task automation —Reflexive manipulator control —Sensor fusion —High fidelity task simulator —Prototype hardware	Evaluation of ORU designs, servicing techniques, sensors, controllers	2
Marshall Space Flight Center	Neutral bouyancy simulation to provide EVA crew training and support for development of payloads requiring telerobotic or manned maintenance or servicing	Design of serviceable items for space Servicing techniques	6-8
Category 2.3—Knowledge-Based or Expert Systems			
Goddard Space Flight Center	Fault diagnosis for TDRSS communications	Automated Space Station monitoring and safety	5
Goddard Space Flight Center	Technology Development Mission (TDM) experiment—expert systems for planning and scheduling	Payload automation	2
Goddard Space Flight Center	Expert systems for planning satellite operations and for scheduling and managing the network control center	Payload data systems management	3-4
Goddard Space Flight Center	Fault diagnosis for local area networks	Automated fault detection and correction	5
Jet Propulsion Laboratory	Expert systems for forming and testing hypotheses, planning configurations of systems, and planning schedules	Operations	2
Jet Propulsion Laboratory	Expert system application of electric power management including interactive load scheduling	Onboard operations	2
Jet Propulsion Laboratory	Expert system for hyperspectral data evaluation for geological exploration	Science experiments	5-6

Institution	Objectives of the research	Potential Space Station use	Level
Johnson Space Center	Expert systems for designing simulation software for —Design of control systems for flexible structures —Rendezvous and approach planning —Task interpreter for intelligent end effector	Proximity operations Manipulator operations	3
Johnson Space Center	Expert systems for Space Station avionics	Power management Optical attitude reference Electric mate/demate for *robotic applications*	2
Johnson Space Center	Expert system prototyping	Navigation, flight analysis and orbit determination Monitoring mission control software Scheduling power use	3-4
Johnson Space Center	Knowledge-based system for monitoring and controlling exercise in health maintenance facility	Crew health maintenance	4
Kennedy Space Center	Expert system for Shuttle cargo processing schedules and detailed "subschedules"	Logistics planning and support	2
Kennedy Space Center	Expert system for scheduling cargo directly from the manifests for each Shuttle flight	Logistics management	3
Kennedy Space Center	Expert systems for diagnosing liquid oxygen system faults and identifying candidate causes	Automated fluids management	5
Kennedy Space Center	Knowledge-based automatic test equipment that will design, execute, and control tests and analyze results	Laboratory and station operation	2
Kennedy Space Center	Expert systems for weather forecasting for Shuttle launch and landing	Logistics planning	2
Lewis Research Center	Expert systems, simulators, and facilities for studies in power management	Mission planning and scheduling for power growth and loads Onboard power management —Generation —Storage —Load distribution —Access to power system —Configuration —System monitoring —Fault and trend analysis	2-4
Lewis Research Center	Expert system for structural analysis Robotic manipulators and positioners State-estimation methodology	Power system analysis and control	2-3
Lewis Research Center	Expert systems to increase productivity and provide aid to new employees at the center	Program management	2
Marshall Space Flight Center	Fault diagnosis expert system for the test-bed for Space Telescope battery power	Fault diagnosis for various subsystems	3
Marshall Space Flight Center	Fault isolation expert system for electrical power	Fault isolation for various subsystems	2-4

R & D ACTIVITIES RELATED TO AUTOMATION AND ROBOTICS (concluded)

Institution	Objectives of the research	Potential Space Station use	Level
Marshall Space Flight Center	Electrical load expert systems for the common module that match the use of dynamically changing resources with available/proper electrical loads	Both off-line and near-real-time planning and scheduling	4
Marshall Space Flight Center	Expert system that plans the use of shared resources for Spacelab experiments and operations	Mission planning and operations onboard Space Station	6
Marshall Space Flight Center	Expert system to aid in more effective utilization of the Spacelab payload crew training complex (PCTC)	Crew training and onboard operations	4
Marshall Space Flight Center	Expert system for removing CO_2 from common module air	Improved environmental control and life support system	4
Marshall Space Flight Center	Analytical integration expert system for designing Spacelab payloads	Minimizing payload design time	3
	Expert systems for dynamic scheduling and fault isolation for cooperating payloads	Scheduling and fault isolation	1
	Expert system for spectrometer calibration	Self-calibration of instruments and platforms	1
Category 2.4—Robotic and Telerobotic Systems			
Goddard Space Flight Center	Design of ORUs, including tooling, manipulators, sensors, automatic control, and human interface Standardization of interfaces Uses of robotics	Servicing free-flying satellites scientific payloads, and platforms	2
Jet Propulsion Laboratory	3-D computer recognition of moving targets made up of complex polyhedra	Robotic recognition of targets to be manipulated or serviced	3
Johnson Space Center	A telerobotic work station with capability equivalent to a suited astronaut	EVA servicing or repair activities	3
Langley Research Center	Systems-level research in robotics —Evolution from teleoperation to a goal-directed robot —Integration and analysis of the total robot system —Dual arm coordination	Complete "integrated" robots	3
Marshall Space Flight Center	Robotic engine-welding system using off-line path planning and a vision sensor to correct the robot path in real time	Robotic use in manufacturing of propulsion systems and in on-orbit welding	3-6
Marshall Space Flight Center	Robotic system for removing solid rocket booster thermal protection during rework	Automated processes in the space environment	4-6
Marshall Space Flight Center	Integrated orbital servicer system for predefined ORU replacement	Automated servicing	5
Marshall Space Flight Center	Interchangeable tools for use by manipulator arm in servicing, assembly, and maintenance	Servicing, assembly, and maintenance	3-4

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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 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 third in a series of progress updates and covers the period between April 1, 1986, and September 30, 1986.

NASA has accepted the basic recommendations of ATAC for its Space Station 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 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 Space Station study contractors, research in progress, and issues connected with the advancement of automation and robotics technology on the Space Station.

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