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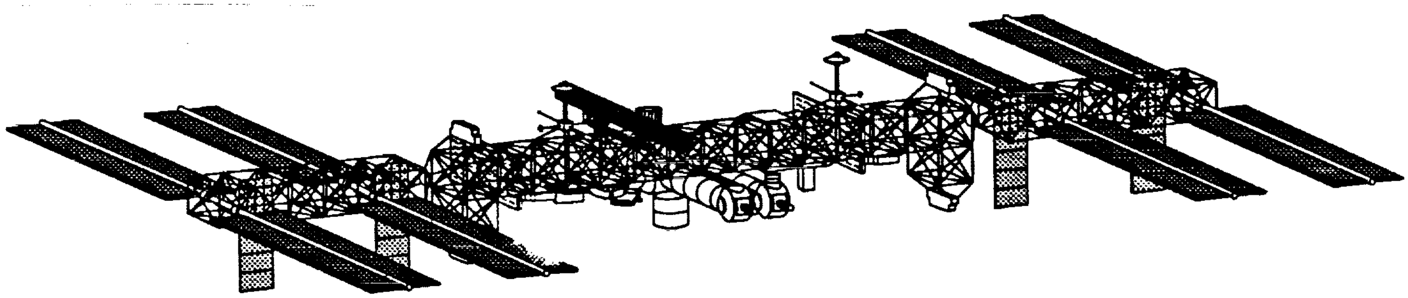
SPACE STATION FREEDOM AUTOMATION AND ROBOTICS:

AN ASSESSMENT OF THE POTENTIAL FOR INCREASED PRODUCTIVITY



MARCH 1990

SPONSORING ORGANIZATION:

ADVANCED DEVELOPMENT PROGRAM
SPACE STATION ENGINEERING
OFFICE OF SPACE FLIGHT
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SPACE STATION FREEDOM AUTOMATION AND ROBOTICS:

AN ASSESSMENT OF THE POTENTIAL FOR INCREASED PRODUCTIVITY

A Study Sponsored by the Office of Space Flight and Supported by the MITRE Corporation

March 1990

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TABLE OF CONTENTS

TABLE OF CONTENTS (concluded)

SECTION | PAGE

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

INTRODUCTION

This report presents the results of a study performed in support of the Space Station Freedom Advanced Development Program, under the sponsorship of the Space Station Engineering (Code MT), Office of Space Flight. The study consisted of the collection, compilation, and analysis of lessons learned, crew time requirements, and other factors influencing the application of advanced automation and robotics, with emphasis on potential improvements in productivity. The lessons learned data collected were based primarily on Skylab, Spacelab, and other Space Shuttle experiences, consisting principally of interviews with current and former crew members and other NASA personnel with relevant experience. The objectives of this report are to present a summary of this data and its analysis, and to present conclusions regarding promising areas for the application of advanced automation and robotics technology to the Space Station Freedom and the potential benefits in terms of increased productivity. In this study, primary emphasis was placed on advanced automation technology because of its fairly extensive utilization within private industry including the aerospace sector. In contrast, other than the Remote Manipulator System (RMS), there has been relatively limited experience with advanced robotics technology applicable to the Space Station. This report should be used as a guide and is not intended to be used as a substitute for official Astronaut Office crew positions on specific issues.

APPROACH

Documents were reviewed covering the areas of lessons learned from on-orbit operations, experience with advanced automation and robotics, productivity concepts, and Space Station Freedom operations requirements. Interviews were initially conducted with 23 current/former astronauts and payload specialists, including 6 Skylab crew members, as well as several ground support personnel with relevant experience. Following the assessment of the data collected, a second round of more specific questions was developed and distributed concerning potential applications of advanced automation and robotics and the resulting impact on productivity. The questionnaire was distributed to 32 current/former astronauts and payload specialists including all but one of the 23 interviewed plus 10 additional astronauts selected by Mike Lounge. Of the 32 receiving questionnaires, a total of 27 responded. Because inadequate data exist to support detailed quantitative estimations of the impact of advanced automation and robotics on Space Station productivity, qualitative and preliminary order of magnitude quantitative estimates were made based on the limited data currently available. The responses of astronauts, payload specialists, and ground support personnel were used to develop a summary of their views concerning the desirability of implementing advanced automation and robotics and the potential for increasing productivity.

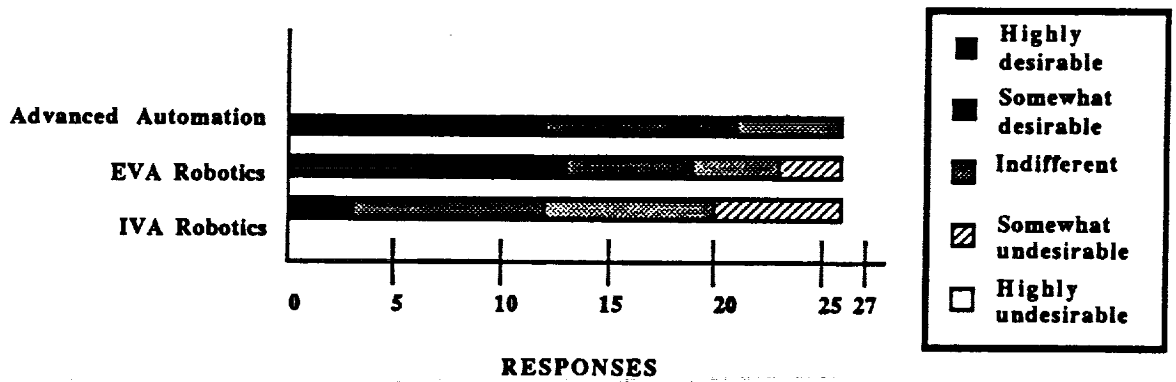
LESSONS LEARNED AND INTERVIEW RESULTS

The Space Station Freedom Program starts from a base of experiences gained in earlier programs. Of particular relevance are the lessons learned from Skylab, the first U. S. space station, which forms a reservoir of experience in long duration space operations. Since the basic mission of Space Station Freedom is scientific and technological research, the Spacelab missions are also of particular interest, along with other Space Shuttle and earlier NASA missions. Other sources of knowledge about long-term operations in hostile environments include the Soviet *Salyut* and *Mir* space stations, the U. S. nuclear submarine fleet, and Antarctic research stations.

Extensive published materials are available describing the experience gained from Skylab. Skylab demonstrated the ability of crew members to function effectively over extended periods on-orbit, and showed that most tasks are not significantly impeded in zero-gravity. Furthermore, crew members were able to perform major and complex repair and servicing tasks. Lessons learned include the need to plan for maintenance and repair, to improve the human interface to on-board computers and instruments, and to automate routine, time consuming tasks wherever practical. Lessons learned documentation from the Space Shuttle and Spacelab programs does not exist as such. Because these are ongoing programs, lessons learned are implemented where feasible as the program progresses. However, available documentation does provide pertinent background information.

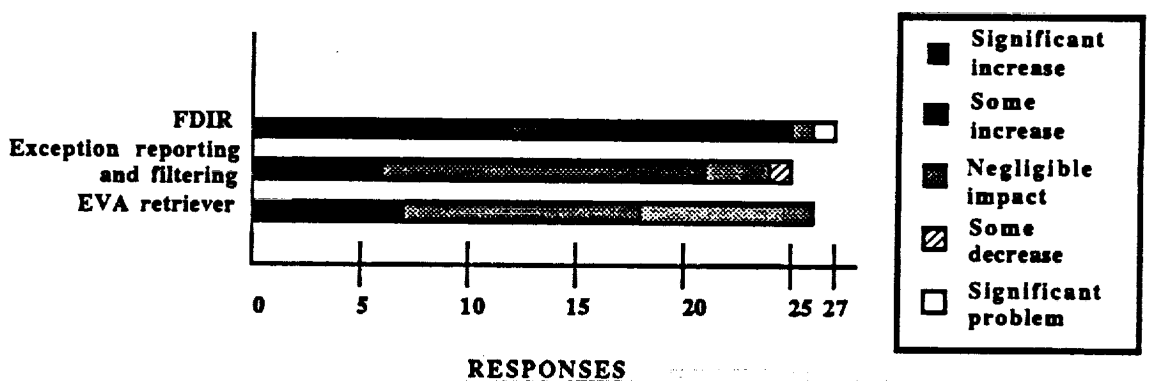
Recommendations from the current/former astronauts and payload specialists interviewed included automation of checklist items not requiring extensive human judgment such as the flight data files including malfunction procedures, calibration of certain instruments, and recording/downlinking of data. Some astronauts also suggested additional filtering with some degree of automated resolution of alarms, automated trend analysis of performance data, automated fault detection, isolation, and recovery (FDIR), and automated housekeeping and inventory management assists. Another area of significant interest was improvement of human-computer interfaces including graphical interfaces employing pull-down menus, windows, icons, and trackball pointer. While support existed for speech recognition and speech synthesis, some astronauts foresaw potential problems with these technologies for certain applications. General support was expressed for some proposed uses of robotic technologies. Strong support was expressed for on-board training including computer-aided training. Most of the interviewed astronauts expressed support for automation of payload/scientific activities, although preservation of the crew's capability to optimize and control scientific activities was emphasized. Ground support personnel were also interviewed and generally expressed support for increasing the automation level and improving the user interfaces of the control center and planning and scheduling activities.

The astronaut interviews were followed up with a questionnaire which addressed these same areas via a list of specific questions concerning crew member views on the potential impact of advanced automation and robotics on productivity. The questionnaire was designed to help ensure that each interviewee was asked the same questions in the same fashion. In answering the questionnaire, respondents were asked to assume that workable, reliable implementations of the technologies can be developed with thorough testing and shakedown of all such systems and that manual backup and human intervention modes would exist. According to this survey, astronauts/payload specialists are philosophically in favor of using advanced automation to increase Space Station productivity, with 81 percent of those responding rating it as desirable, 19 percent viewing it indifferently and none rating it as undesirable. EVA robotics were rated as desirable by 73 percent and somewhat undesirable by 12 percent with the remainder indifferent. In general, the astronauts/payload specialists viewed advanced automation and EVA robotics as desirable in improving productivity on the Space Station. While 46 percent of the respondents viewed IVA robotics as desirable in some form, the others were either indifferent (31 percent) towards IVA robotics or viewed it as somewhat undesirable (23 percent). It is interesting to note that none of the respondents viewed any of these three general categories as highly undesirable. These results appear in the figure below. The Skylab astronauts, with more experience in long duration missions, were more strongly positive in their overall assessments than were the others.



Astronaut Views Regarding Automation and Robotics

Results of the safety related questions appear in the figure below. FDIR was rated as having potential to contribute some increase to significant improvements in safety by 93 percent of the respondents. Automated exception reporting and alarm filtering was rated by 84 percent as having potential for some increase to significant improvements while an EVA retriever was rated by 69 percent to potentially increase safety. Only one respondent felt there might be any decrease in safety potential and that concern was related to the automated exception reporting and alarm filtering.



Astronaut Ratings of Safety Impacts of A&R Applications

OPERATIONS/PRODUCTIVITY PROJECTIONS

Although there are significant difficulties in defining productivity in terms that are easily measured, several studies have addressed productivity issues in different ways for the Space Station, including The Human Role in Space (THURIS) studies and the Space Station Human Productivity Study (SSHPS). These studies were to support achieving the goal of a 9 hour workday, 5 days per week. The THURIS methodology includes a set of generic activities and cost models which estimates the amounts and dollar value of crew hours saved in performing specific activities; its application to evaluating candidates for automation would require detailed definition of specific tasks in terms of generic activities and frequencies. A recent estimate of the value of on-orbit crew time is roughly $35,000/hr. SSHPS developed management plans related to productivity issues. Twelve of these plans address issues which involve candidates for use of automation or robotics. All but three of the 12 are currently being investigated - task performance assessment, habitable volume leak point detection, and on-orbit system certification.

Based on examination of workdays for Skylab, Spacelab, and other isolated and confined environments, it appears that an eight-hour workday works well, while generally a 12-hour shift cannot be maintained more than a few weeks (without degradation in productivity). Over a long period it seems that a nine or ten hour shift with one day off per week might be better in achieving more productive time on tasks. How much flexibility in workday duration that should be left to the worker is unclear.

Current Space Station workday planning templates have two shifts with a 12.5 hour duty cycle for each of two teams (11.5 hours off) including two handover periods between shifts. After allowing for exercise, hand-over time and on-duty meals, 8.5 hours is allotted for operations (system and user), of which 7 hours are planned activities, designating an average of 0.5 hour each to replanning, operations training, and planning reserve. With an eight person crew, the daily totals are 17 man-hr. (2 x 8.5) for system operations and 51 man-hr. (6 x 8.5) for user operations. This planning template does not include time for housekeeping and the intensive sampling and measuring activities of the Extended Duration Crew Operations (EDCO).

Spacelab mission support experience indicates the desirability of shortening the workday for ground activities to 8 hours, and increasing the use of scheduling programs and the flexibility of timelines to reduce required manpower levels. For Space Station Freedom support, there are differing viewpoints over the allocation of payload activity timeline planning between ground and station, with ground personnel indicating a preference for scheduling on the ground, and flight crew comments indicating a desire not to overload the crew and to allow flexibility in daily schedules. There is agreement on the need to automate ground scheduling activity where feasible.

APPLICATION OF ADVANCED AUTOMATION TECHNOLOGY

In this report the term advanced automation refers primarily to knowledge-based systems (including expert systems), advanced human-computer interfaces, and systems mimicking human cognitive abilities. The emphasis is on systems not currently used on spacecraft but which are sufficiently mature for use in the Space Station Freedom Program by the Assembly Complete stage or shortly thereafter.

Great progress has been made in the application of knowledge-based systems to practical problems. In the last five years these systems have become fairly common in business, industry, and government applications, and results have shown impressive operational and financial benefits. NASA has significant on-going efforts in knowledge-based systems, including a number of prototypes on Space Station Freedom testbeds. Examples of NASA systems which have shown demonstrable operational and economic payoffs include the Integrated Communications Officer Expert System Project (IESP), and the BOOSTER expert system, both in use in the Mission Control Center at Johnson Space Center. IESP has been estimated to pay for itself in two years of operation, and BOOSTER has been said to have paid for itself by promptly locating a main engine pump problem in

STS-26. Another fielded knowledge-based system in NASA is the Resource Allocation and Planning Helper (RALPH), an intelligent assistant for allocating/scheduling the antenna and computer resources of the Deep Space Network, saving 3.5 man-years per annum. JPL's Spacecraft Health Automated Reasoning Prototype (SHARP) expert system received wide attention during the encounter with Neptune by Voyager 2. SHARP demonstrated its value when it diagnosed a fault in a ground-based unit of the Deep Space Network after it noticed a drop in transmission quality from Voyager 2's 30 watt transmitter. Knowledge-based systems are also used by NASA contractors to support Space Shuttle payload bay reconfiguration, and the verification and validation of on-board software.

Advanced automation prototypes under development for the Space Station Freedom Advanced Development Program include applications for most major flight and ground systems. These applications include advanced human-computer interfaces, intelligent on-board and ground-based training systems, monitoring and control systems, fault diagnosis, isolation, and recovery systems, and systems for planning and scheduling. Advanced automation could also perform other time consuming tasks such as inventory management and control of camera alignment/pointing and lighting. Preliminary projections show that significant operations cost savings may be realized in both flight operations and in ground support through the use of these advanced automation applications.

APPLICATION OF ROBOTICS TECHNOLOGY

Current applications of robotics technology work well in structured or somewhat uncertain environments populated by well known objects; extensive research is underway oriented towards more autonomous operations in less structured settings. NASA's robot technology program is based on two parallel paths: development, space qualification, and operational integration of teleoperated manipulators; and research on increased autonomy for manipulators. Development of a practical supervised telerobot requires adding to its control structure a machine vision subsystem and a task planning subsystem.

The Space Station robotic systems include the Flight Telerobotic Servicer (FTS), the Canadian Special Purpose Dexterous Manipulator (SPDM), the mobility base, a redesigned Remote Manipulator System (RMS), the Japanese Experiment Module (JEM) RMS, and the Astronaut Positioning System (APS). These will be used to perform tasks including assembly assistance, maintenance, servicing, and inspection. This is consistent with the strong support for EVA robotics this study found among the astronauts, and their view that the automation of inspection tasks offered significant potential for increasing productivity.

Quantification of potential productivity gains can only be currently extrapolated using projected planned astronaut activity guidelines; however, studies have indicated that substitution of IVA teleoperated robotics into EVA time lines show significant reductions in crew time requirements. The reduction in EVA time gained by using robotics, at least in the first years of the Space Station, will be offset by the increased IVA time that will be required to support robotic operations. Using robotics will provide the direct advantage of reducing the requirement for the limited EVA time available, but will increase the demand for IVA. Advanced Development tasks in shared control will increase the efficiency of robotic operations and will permit some fully automated tasks which are supervised by IVA astronauts. In later years, some robotic applications will be capable of ground remote supervised control. Inspection tasks and worksite preparation activities are likely candidates.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study may be summarized as follows:

- The astronaut community generally has expressed strong support for the use of advanced automation and EVA robotics on the Space Station. In terms of potential productivity improvements, their collective view was that the applications with the greatest potential were automated inventory management, record keeping, and FDIR, improved human-computer interfaces, and automated construction and inspection with EVA telerobotics. Astronauts with the long duration flight experience of Skylab were somewhat more strongly positive in their views towards automation than astronauts and payload specialists whose only flight experience has been Space Shuttle missions. Current astronauts, on the other hand, with recent exposure to the degree of automation employed on the Space Shuttle may be less likely to consider automation a panacea (Low, 1990).

- There is a high potential for significant increases in productivity on Space Station Freedom through the application of advanced automation technology during the development and evolution of the Space Station. Areas which appear to offer the greatest potential include automation of payload operations, inventory management, and system monitoring and control (including FDIR).

- There is also high potential for significant increases in productivity in ground-based Space Station operations through the use of advanced automation, resulting in lower life-cycle costs over the life of the Space Station. Areas which appear to offer the greatest potential include Space Station Control Center functions, Operations Planning and Integration activities, training, and software maintenance.

- EVA robotics has the potential to increase on-orbit productivity. The most cost effective and technologically simple way to significantly add to astronaut productivity (as well as decrease astronaut EVA time) throughout external assembly, maintenance, and inspection operations during the early life of the Space Station may be to transfer control of the robotic elements to the ground for selected tasks. Ground control of robotic tasks with data latency requires an integrated approach to task and spatial planning, sensor data fusion, and robot control. Collision avoidance using this integrated approach has been demonstrated for a robotic inspection task with time delay representative of that experienced from the ground to low earth orbit. The Advanced Development Program is continuing its efforts to develop and demonstrate this technology given its potential to reduce IVA time for robotic tasks.

- A significant increase in the level of definition of Space Station activities and crew tasks is needed which includes their durations and frequencies over the life of the Space Station operations to provide a firm quantitative estimate of the expected benefits of advanced automation and robotics in terms of actual crew hours saved and thus available to support payload operations. Such data is also required in order to judge the adequacy of available crew time as a resource to support payload operations.

The study results support the conclusion that there are a number of areas of application of advanced automation and robotics which combine expected availability of the technology, potential for significant impact on station productivity, and support by the user community. In general, the Fiscal Year 1990 Tasks of the Advanced Development Program appear to be consistent with these criteria.

Based on the conclusions above, the following are recommendations for the development of advanced automation and robotics technology for the Space Station Freedom Program:

- Development of advanced automation and robotics technology applications should be actively pursued. General areas of emphasis should include knowledge-based systems for flight systems and for ground operations, improved human-system interfaces, and EVA telerobotics.

- Specific applications cannot be recommended solely on the basis of quantitative estimates of productivity benefits at present; general guidelines should be to develop systems which combine near-term technical feasibility, high potential for saving crew time on-orbit or reducing staffing on the ground, and which have the early acceptance and support of users.

- Adequate provision should be made in system design to accommodate future introduction of advanced automation and robotics applications.

- Additional effort should be devoted to developing data to provide the basis for more precise quantitative estimates of the impact of specific systems on productivity and life-cycle cost. This effort should include the collection of workload and activity duration data from Space Station Freedom once the station is permanently manned.

- Related to the point above, a systems engineering study approach to trade issues involving allocation of functions to a person, machine, or some combination thereof needs to be performed as a next step. Such a top-down approach should consider crew activities in two categories: (1) operations - where the routine events handled on a daily basis might be reduced from 3 hours/crew member day to 2 hours; and (2) mission activities - involving crew experiments and new crew jobs which provides greater potential for realizing productivity gains. Factors such as reliability, safety, etc., could then be factored in to give strong indications of high payoff applications.

SECTION 1

INTRODUCTION

1.1 PURPOSE AND OBJECTIVES

The Space Station Freedom Advanced Development Program has been established by the National Aeronautics and Space Administration (NASA) to demonstrate near-term pay-offs from the application of advanced technology on the baseline Space Station, and to enable the evolution of the Space Station over its projected thirty year life, in keeping with the needs of users and long term national goals. Under the sponsorship of the Space Station Engineering (Code MT), Office of Space Flight, the MITRE Corporation has conducted a study to assess the potential need for and benefits of advanced automation and robotics technology on the Space Station Freedom. The purpose of this report is to present the results of that study in support of Advanced Development Program planning and implementation.

The study consisted of the collection, compilation, and analysis of lessons learned, crew time requirements, and other factors affecting the need for advanced automation and robotics on Space Station Freedom, with emphasis on the potential for improvements in productivity and resulting enhanced mission capabilities and reduced life-cycle costs through the use of this technology. The lessons learned data collected were based primarily on Skylab, Spacelab, and other Space Shuttle experiences, consisting principally of interviews with current and former crew members, interviews with appropriate NASA personnel at Headquarters, Johnson Space Center, and Marshall Space Flight Center, and various reports and publications. The objectives of this report are to present a summary of this data and its analysis, and to present conclusions regarding promising areas for the application of advanced automation and robotics technology and the potential benefits in terms of increased productivity. n this study, primary emphasis was placed on advanced automation technology because of its fairly extensive utilization within private industry including the aerospace section. In contrast, other than the Remote Manipulator System (RMS), there has been relatively limited experience with advanced robotics technology applicable to the Space Station.

The intended audience for this report includes the management and staff of the Space Station Freedom Program at all levels, and particularly those involved in decisions concerning the development of advanced automation and robotics technology and its use on the evolving Space Station. This report should be used as a guide and is not intended to be used as a substitute for official Astronaut Office crew positions on specific issues (Low, 1990).

1.2 BACKGROUND

With a planned operational lifetime of thirty years, Space Station Freedom requires the capability to grow and evolve over time. This requirement was formally recognized in President Reagan's directive on space policy of January 5, 1988, which states that the Space Station will allow evolution in keeping with the needs of station users and the long-term goals of the United States. The Advanced Development Program was established under the Space Station Freedom Program (SSFP), to help define, develop, and implement a program to enable evolution of the station. The Advanced Development Program is managed by Code

MT, NASA Headquarters, and involves all NASA Centers and all four SSFP Work Packages.

The objectives of the Advanced Development Program include the enhancement of productivity on the baseline and evolutionary station, and reductions in operations and life-cycle costs. Thus the rationale for investments in specific technologies and applications should include an assessment of the potential for productivity increases and cost savings. The initial Advanced Development Program has focused on advanced automation and robotics, with emphasis on advanced automation and in particular, knowledge-based systems. The study described in this report has attempted to identify significant areas of application of advanced automation and robotics technology, and to assess the potential for productivity increases and cost savings from these applications.

1.3 SCOPE

For this report, and the study it describes, the term "advanced automation" refers to automation more advanced than what is currently implemented on the Space Shuttle. Thus advanced automation was assumed to include expert and knowledge-based systems, together with the associated human-computer interfaces. Emphasis was placed on technologies which are currently available or in an advanced state of development, reducing the need to consider technical risk explicitly. The term "robotics" was assumed to encompass the associated automation software and hardware, and emphasis was placed on teleoperated robotics for both EVA and IVA related applications.

Sources for potential applications were primarily existing reports and documents, as well as interviews with current and former astronauts and other NASA personnel. Applications on the Space Station Freedom Manned Base were emphasized, with some consideration also given to ground-based mission support applications. Potential applications on the Polar Orbiting Platform, and applications of knowledge-based systems to the design, development, and engineering of the station were not explicitly considered.

Although the specific details of the station configuration were not a critical factor in the assessments presented in this report, the study in general is based on the configuration as defined in June 1989. It is recognized that there is the potential for significant modifications due to the Configuration/Budget Review currently underway as this report is being written. Modifications leading to a simpler baseline design may result in an increased need for automation and robotics enhancements during station evolution, as well as an increased need for identification of "hooks and scars" on the baseline Space Station necessary to accommodate future growth and upgrade.

1.4 OVERVIEW OF THE STUDY APPROACH

The overall objective of the study, assessing the need for advanced automation and robotics in the evolution of Space Station Freedom, required the accomplishment of two supporting objectives. The first of these consisted of the compilation and analysis of relevant lessons learned from Space Station analogs to identify potential applications of advanced technology. The second was the identification of projected crew time allocations and ground personnel requirements for the operation of the station. This information was combined to form an assessment of the potential impact of the technology on station productivity.

The approach taken to accomplish these objectives was to identify, collect, review, and analyze relevant information. The data consisted of reports and documentation, and interviews with persons having knowledge of space operations. The documentation collected included lessons learned from Skylab, Spacelab, Space Shuttle, the Soviet space program, and terrestrial analogs to working in space; crew time allocations and productivity analyses for Space Station Freedom; and descriptions of advanced automation and robotics technology together with experience from its application and the resulting productivity and cost impacts. Interviews were conducted with current and former astronauts and payload specialists representing experience with Skylab, Spacelab, Space Shuttle, Apollo, and Gemini, as well as with astronauts in training. Following these interviews, a list of specific questions was developed and distributed, and the responses tabulated. Other NASA personnel with knowledge of Space Station productivity and crew time analysis, or with ground-based mission operations, were also interviewed.

The analysis of the data collected was oriented towards identification of applications with high potential, followed by assessment of potential benefits. The assessment of potential benefits was based primarily on high-level workday time allocations, experiences with similar technology, and judgment; it was impractical in most applications to forecast specific productivity increases in quantitative terms. This was the result of a lack of firm projections of crew activities and amounts of time required for each activity in sufficient detail for analysis, together with the difficulty of predicting quantitative impacts of a particular application of advanced technology to a specific activity. Thus the conclusions presented emphasize the judgments of operational personnel (e.g. astronauts) rather than quantification of productivity. More detailed descriptions of the approach taken in collecting data, including the interview process, and the steps taken to analyze the data, are contained in Section 2 of this report.

1.5 ORGANIZATION OF THIS REPORT

The remainder of this report is organized as follows. The approach taken in the study is described in detail in Section 2, including a description of the interview process and a discussion of how the collected data were used. Section 3 summarizes the results of the data collection process regarding the need for advanced automation and robotics based on previous experience. This section includes material from reports and interviews, and covers Skylab missions (3.1), Spacelab and other Space Shuttle missions (3.2), and experience from miscellaneous areas outside the U.S. space program which are analogs to the Space Station, including the Soviet space program and the U.S. nuclear submarine program (3.3). Section 4 discusses productivity projections and time allocations for Space Station Freedom. Included are summaries of basic concepts of productivity, and existing and ongoing work within the Space Station Freedom Program regarding productivity analysis and crew and mission support time allocations. Sections 5, Application of Advanced Automation Technology, and 6, Application of Robotics Technology, present overviews of the technology, describe experience with the technology, list potential areas of application, and assess the potential for improving productivity and effectiveness and reducing life-cycle costs on Space Station Freedom. Finally, Section 7 presents conclusions and recommendations arising from the study.

The appendices include an listing of the Space Station Freedom Advanced Development Program projects (Appendix A), a list of personnel interviewed during this study (Appendix B), the astronaut/payload specialist survey questionnaire and responses (Appendix C), background on productivity concepts (Appendix D), an overview of advanced automation technology (Appendix E), an overview of robotics technology (Appendix F), a list of NASA A&R contacts (Appendix G), principal authors of this report (Appendix H), references (Appendix I), a bibliography (Appendix J), and a glossary (Appendix K).

SECTION 2

STUDY APPROACH

Accomplishing the study objectives required the identification of potential applications of advanced automation and robotics technology on Space Station Freedom, identification of time allocations for projected activities of the crew on-orbit and mission control on the ground, and assessment of the potential for improvements in productivity from the use of advanced technology in the identified applications. Specific study activities fell into two categories: collection of data in the form of documentation and interviews, and assessment of the data to identify the potential benefits from application of advanced automation and robotics. The general approach taken in the study is described in Section 2.1 below, followed in Section 2.2 by a more detailed discussion of how the interviews were conducted and data collected and compiled.

2.1 DESCRIPTION OF THE APPROACH

The overall approach is illustrated in Figure 2-1. Initial activities, conducted in parallel, were the collection and review of documentation and the interviewing of current and former astronauts and other NASA personnel. Documentation reviewed covered the following areas:

- Experience from Skylab, Spacelab, other NASA missions, the Soviet space program, and other analogs to the working environment in space such as the U.S. nuclear submarine program
- Experience with advanced automation and robotics technology, both within NASA and more generally
- Concepts of productivity for humans living and working in space, including attempts to quantify the impacts of technology on productivity
- Space Station Freedom operations, crew activities and time allocations.

Interviews were initially conducted with 23 astronauts and payload specialists, including 6 Skylab crew members, as well as other individuals with experience relevant to the objectives of the study. Following the assessment of the data collected, both from interviews and documents, a second round of more specific questions was developed concerning potential applications of advanced technology on Space Station Freedom and the resulting impact on productivity. The conduct of these interviews is described more fully below.

The results of the initial round of interviews, together with the review of existing documents, supported the development of a list of potential applications of advanced automation and robotics, along with some guidelines pertaining to their development and use. The potential contribution of these candidate applications to the enhancement of productivity on Space Station Freedom was assessed based on the data collected regarding crew activities and time allocations, and ground support staffing. This assessment combined the judgments of astronauts and other operational personnel, the experience to date with advanced technology and its impact on productivity, and the judgment of MITRE staff regarding the

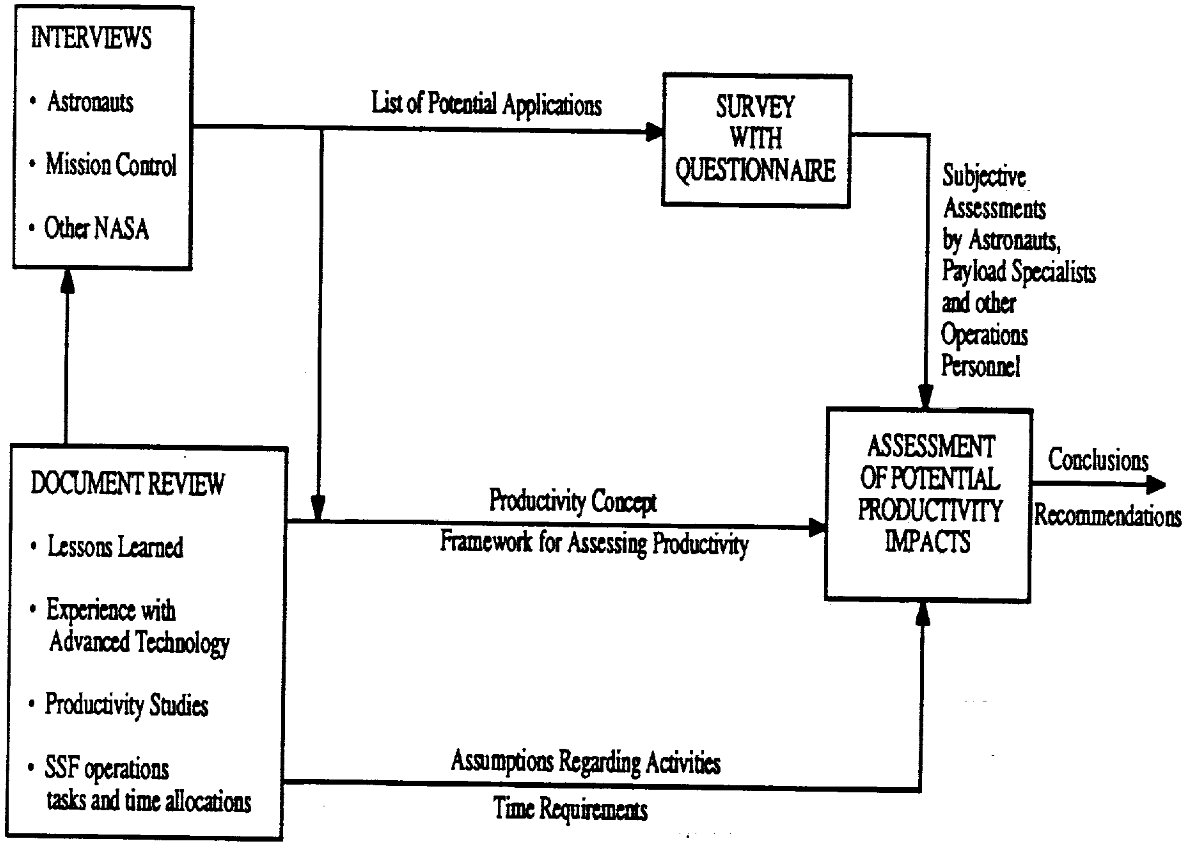


Figure 2-1 Study Approach

extent to which candidate application areas met criteria related to the potential for productivity enhancement. It was the assessment of the MITRE study team that the existing data regarding station operations, crew activities, and the effects of advanced technology are inadequate to support a detailed quantitative analysis resulting in an explicit numerical estimate of the impact of the technology on hours of crew time required and overall life cycle costs. However, certain conclusions can be drawn regarding the implementation of advanced technology applications for Space Station Freedom which are meaningful in terms of providing firm guidelines for automation and robotics thrusts.

The conclusions from the assessment of candidate application areas were compared with the projects supported by the Advanced Development Program during Fiscal Year (FY) 1989 and projected for FY1990. The Advanced Development Program tasks for FY90 are shown in Appendix A. The results were expressed in the form of recommendations concerning applications with the greatest potential for productivity benefits.

2.2 DATA COLLECTION AND THE INTERVIEW PROCESS

The gathering of information for the study included collection and review of documents and reports, initial interviews with current and former astronauts and other NASA and contractor personnel, and collection of responses to a specific set of questions developed following the initial interviews and document review. Document collection was straightforward; a list of the documents reviewed is included as Appendix I. This section describes the approach taken in the interviews, with emphasis on the interviews with current and former astronauts. A list of persons interviewed is given in Appendix B.

The interviews were conducted in an informal manner. A short list of general questions was prepared, but these were primarily intended to stimulate discussion and were not discussed uniformly in all of the interviews. The objective was to obtain the interviewee's views regarding previous experience indicating a need for automation and robotics, and desirable potential application areas on Space Station Freedom. The direction taken by each interview varied depending upon the comments and opinions expressed.

An attempt was made to have at least two persons from the study team present at each interview to allow the comparison of notes and impressions and to reduce listener bias in the interpretation of responses. Some of the interviews were taped, but in most cases notes were taken by hand.

Assurances were given to each contact that confidentiality would be maintained, and that any sensitive statements made would not be traceable to an individual. These assurances were given at the time of setting up an interview, and were reiterated during each interview.

In most cases the interviews were conducted at the individual's office. Trips were made to Marshall Space Flight Center and to Johnson Space Center to interview several contacts. Interviews were also conducted at NASA Headquarters, the Space Station Program Office at Reston, MITRE's NASA Headquarters Site, and other locations.

Using the results of the initial interviews, a list of more focused questions concerning the potential for productivity enhancement from use of automation and robotics was developed and presented to the current and former astronauts and payload specialists previously interviewed together with 10 additional personnel from the Astronaut Office at Johnson Space Center. A total of 26 responses were received. The responses were collected and merged into a tabular summary. This data formed part of the basis for assessing various applications of advanced automation and robotics technology.

SECTION 3

LESSONS LEARNED AND INTERVIEW RESULTS

3.1 SKYLAB EXPERIENCE

As the name implies, the primary purpose of Skylab was to serve as a laboratory for scientific observation in orbit at 235 nautical miles. The areas of investigation included astronomy, earth resources, physiology, materials processing, and behavioral science; Skylab also served as a platform to test both the technological and human capabilities to support long duration space flight and to perform useful work in zero gravity. The Skylab spacecraft was planned to have an eight month operational life to support three separately launched three man crews; it actually remained in orbit for just over six years, with its systems functional for most of that time. The crew missions were of increasing duration at 28, 59 and 84 days respectively. The Skylab complex consisted of the Orbital Workshop, the Apollo Telescope Mount (ATM), the Multiple Docking Adapter, the Airlock Module, and the Instrument Unit; the entire complex was placed in orbit by a Saturn V rocket. The crews traveled to and from the Skylab in Apollo Command Service Modules nearly identical to the spacecraft used in the lunar missions, launched by modified Saturn IB rockets. Despite serious problems during launch, including loss of one of the solar power wings and the micrometeorite shield during Skylab launch, the failure of another solar power wing to fully deploy, and other equipment failures during its orbital life, Skylab met the bulk of its scientific objectives, and allowed NASA to gain significant additional knowledge regarding human capabilities in space. Descriptions of the Skylab program appear in Belew (1977) and Holder and Siuru (1975).

The relevance of the Skylab experience to the Space Station program is obvious. Skylab was, in effect, the first U.S. space station, and is NASA's only direct experience with long duration manned space flight. In addition, its mission was predominantly scientific. However, limitations to the analogy between Skylab and the Space Station do exist. First among these is the fact that Skylab was based upon Apollo (1960s) technology making the level of automation available for Skylab very limited.

3.1.1 Skylab Document Review

A variety of documents, (see the Bibliography), were used as sources for this analysis. In general, these documents do not focus upon automation and robotics (A&R) due to the relative immaturity of the technology at the time Skylab was being planned and built. However they do shed light on various considerations related to A&R plans.

3.1.1.1 Human Capabilities

According to Skylab veteran Owen K. Garriott (1974), one major role of the human crew member is the flexibility he (or she) brings to the system, including the ability to respond to unforeseen events. Examples of major unforeseen repairs in Skylab included the freeing of the solar panel assembly and deployment of the shade during Skylab 2 and the replacement of the rate gyroscopes during Skylab 3. Examples of unforeseen scientific activities included observations of the comet Kohoutek and instances of the scientist-astronaut varying experimental protocols based on results or to take advantage of scientific opportunities.

The general consensus of reports from the Skylab program was that humans have the capability to perform essentially any task on-orbit that they can do on the ground, if equipped with the right tools. In particular, the moving of large masses was easy as long the astronaut could see around them to steer (JSC, 1974 and Bond, 1974). The primary limitations on human performance were found to be in the need to brace oneself to obtain leverage in the absence of gravity (JSC, 1974) and decreased accuracy in psychomotor tasks requiring accurate positioning (Connors, 1975). Extra-vehicular activity (EVA) posed additional difficulties in the lack of depth perception due to lighting characteristics and fatigue stemming from the requirement to maintain fixed positions and the effort to work against the stiffness of the pressurized suit. In addition, long term isolation ultimately has an effect on performance (JSC, 1974), a fact which is confirmed by Soviet space experience (Bluth, 1986) and experiences from the U.S. nuclear submarine program (Boeing, 1983).

Individual task completion times for Skylab initially exceeded preflight baselines but improved with practice (Connors, 1975 and Kubis & McLaughlin, 1974). Neutral buoyancy training provides a good means of estimating task completion times (McDonnell Douglas, 1984). Nonetheless, planners tend to overload schedules (Connors, 1975), from a desire to get as much done as is possible and because the actual in-flight contingencies are not always foreseen.

3.1.1.2 General Design Guidance

One of the lessons learned was the need for additional system flexibility (NASA HQ-PO, 1974), including the need for more flexible redundancy/failure management and the ability to change caution and warning limits as the environment changes and preset limits are found to be no longer appropriate (JSC, 1974). On the other hand, the crew (and the ground) must be provided with current information regarding system configuration including all settable parameters. Problems developed on Skylab when certain switch settings were modified by ground personnel without the knowledge of the crew.

The Skylab crew interface was significantly more complex than that in previous manned space missions (Bond, 1974) such as the Apollo missions. Crew interface with Skylab systems and experiments was effected primarily through panels of switches and indicators located at various places in the vehicle; a hexadecimal keypad was provided for data entry, and a teleprinter for uplink of textual information (e.g. instructions) from the ground. In addition, a large number of experiments appeared in the manifest, with many of them having complex interfaces (MSFC, 1974). In some cases the experimental apparatus did not allow the crew sufficient control to obtain optimal results, and in others the required crew interaction was needlessly time-consuming. A standard, user-friendly system interface is needed, which provides the crew (and the ground) with current information regarding system status, and which makes necessary interactions as easy as is possible.

A significant amount of on-orbit maintenance (a total of more than 250 separate unscheduled actions) was required during the three manned missions; particularly noteworthy were the previously mentioned freeing of the jammed solar panel and deployment of a solar shield on Skylab 2 and the erection of a replacement solar shield and rate-gyroscope replacement on Skylab 3. The Skylab design anticipated only limited maintenance requirements; in particular lack of foot restraints in some external areas complicated early repair work (JSC, 1974). Periodic replacement of ATM film cartridges required an EVA. Based on the Skylab experience, the NASA Centers felt that NASA should design for on-orbit maintenance (JSC, 1974) and place items expected to require service in pressurized areas to avoid the requirement for EVA (Schultz et al., 1974). Access should be provided to all parts of the vehicle (NASA HQ-PO, 1974, and JSC, 1974), and all systems should be considered as possible maintenance targets. An effort should be made to systematically capture design knowledge to aid the support of diagnosis and maintenance functions (NASA HQ-PO, 1974).

Additionally, the impact of experiments on operations must be considered. This impact includes inventory requirements, servicing requirements, and limitations on maneuvering. In particular, routine servicing of the ATM required an EVA.

3.1.1.3 Housekeeping

Experience with the habitability systems also pointed up specific areas, such as the routine cleaning of filters and the cleaning of walls, in which housekeeping functions could be more efficient. While most of these areas are not readily automated, one area of significant interest was inventory management. Skylab inventory management posed problems in tracking a large quantity of stores which could not easily be replaced. An additional difficulty was that small items tended to float away and become lost. Thus, inventory management, storage, and the handling of small items were particular problems. Since loose items tend to follow air flow in zero gravity, the flight crews learned to look for lost objects on air return screens, and a number of suggestions have been made to use airflow devices for the handling and control of small objects.

3.1.1.4 Automation and Robotics Needs

As was stated previously, automation and robotics were not considered major areas of interest in the immediate post-Skylab era, and the available documentation gives little coverage to these issues. However, additional automation was recommended (JSC, 1974) for those experiments in which the crew involvement does not include any evaluative or decision making functions, but is limited to following checklists. This principle could also extend to following checklists in some systems functions (NASA HQ-OSF, 1976). Additional automated assists for recording and reporting were felt to have value (JSC, 1974).

3.1.2 Skylab Astronaut Interviews

The consensus among the Skylab crew members interviewed generally favored automation, although there were some variances on specific items. Although Skylab used Apollo-era technology, Skylab was the first real use of system automation in space flight in the sense that the crew did not have to continuously monitor the systems. Table 3-1 summarizes the applications of automation and robotics technology suggested by both Skylab and Shuttle crew members. The following sections will provide additional explanation of the opinions/comments expressed by the interviewees.

3.1.2.1 Workload and Schedules

Skylab astronaut opinions about the workload varied, possibly reflecting the fact that the later missions placed greater demands upon the crew. Several commented that the fast pace characteristic of the relatively short Spacelab missions would be difficult to maintain for extended periods. The predominant view was that one "off" day is necessary per week, with crew activities on that day being optional. Also, sufficient time should be built into schedules for contingencies, and the crew should have the flexibility to reschedule tasks which are not time or resource critical. Several astronauts felt that an on-board, computerized re-scheduling capability would be useful.

Table 3-1
Suggested Areas for Advanced Automation and Robotics

Monitoring and control	
Screening of alarms	Resettable caution and warning limits
Trend analysis/incipient failure detection	Automated checklists/procedures
Automated external TV cameras and lighting	Automated inventory management
Electronic Flight Data File	Autonomous subsystems operation
Intelligent data reduction	Configuration Control documentation
Fault diagnosis isolation and recovery (FDIR)	
"What if" capability and explanation facilities	Medical/health advisor
Fire detection location and suppression	EVA suit maintenance advisor
Automated safing to prevent cascading failures	Switch in backup element & notify crew
Reconfiguration	Advisory systems
Payloads	
High definition television (HDTV)	Automated calibration/alignment
Electronic logging of observations,photographs,etc.	Sample analysis
Automated biomedical analyses	Feeding, cleaning of lab animals
Biological/Materials sample analysis	Calibration and alignment
Scheduling	
Schedule development (ground)	Rescheduling (on-board)
Edit capability	
On-board training	
Intelligent computer aided training	Heads-up displays
Video tapes	
Robotics	
External ORU replacement	Hazardous materials handling
Remote inspection of the exterior	EVA retriever
Housekeeping robots	Wall scrubber
Improved collision avoidance	Filter cleaners
Human-computer interface	
"Mac" style interface	Use of graphics
Speech recognition	Speech synthesis
Auto recording/downlink of notes	Electronic mail

3.1.2.2 Human Computer Interface

The human computer interface on Skylab was regarded as difficult to use. Particularly onerous was the requirement to enter long sequences of numbers at the keypad, which in some cases were calculated on the ground and read to the astronauts over the communications link. The teleprinter on the Skylab was useful, but a wider printout with graphics would have been better. There was much use of paper records and documentation on Skylab; this could be computerized. One Skylab veteran recommended that a user interface similar to that on the Apple Macintosh be used.

3.1.2.3 Scientific Activities

As was stated in the lessons learned documents, astronauts commented that some experiments required a crew member to execute a lengthy checklist without having any opportunity to exercise judgment or control the course of the experiment. This was particularly common in instrument calibration or alignment. In some cases, if the checklist was interrupted or an error was made, the crew would have to start the procedure again from the beginning. Where feasible they suggested that such checklists and repetitive activities (e.g. instrument alignment and calibration), should be automated where human judgment is not required, or at least "set-points" should be provided to allow recovery from intermediate steps.

In Skylab the astronauts were required to read recorded data (e.g. experimental results) to the ground over the communications link, usually once a day. Instructions were sometimes received from the ground in the same manner, although the teleprinter was usually used. Recording experimental results (and logging of samples and photographs) and transmission to the ground was another activity suggested for automation. Automated measurement of air required during exercise and measurement of human waste as well as biological and materials sample analysis were also mentioned.

Some crew members wanted to have flexibility in scheduling, at least around major tasks. Another suggestion was that time-critical actions be considered for automation, to assure that these actions be reliably performed at the proper time and to minimize the impact on other work and relieve the associated crew member stress.

3.1.2.4 Monitoring and Control

System monitoring is a tedious task which should generally be considered for automation. Several crew members reported excessive numbers of false alarms, which required them to interrupt work to deal with the alarm. This was particularly disruptive if it caused the interruption of work which was difficult to restart. To alleviate this problem, they recommended that caution and warning limits should be resettable, and suggested that development of systems to filter out spurious alarms might be considered. A number of astronauts suggested automated fault diagnosis, isolation and recovery (FDIR) systems. Also suggested were automatic recording of configuration/status, incipient failure detection, and automation of at least some of the malfunction procedures (MALs), e.g. those where the decision making is reasonably routine. At least one astronaut pointed out that contingency planning is a particularly difficult task, i.e. many of the failures which have occurred were not the expected ones and thus not the ones which were simulated.

3.1.2.5 Other Areas for Automation and Robotics

Other areas for which the astronauts suggested automatic assistance were housekeeping and inventory management. These areas were considered by most of the interviewed crew members as excessively time-consuming and unproductive, at least in the sense that they do not directly contribute to the crew's scientific work. In particular, the transfer of food from the logistics module to storage lockers, vacuuming of filters and screens, and the daily recording of consumption of food and other supplies were mentioned as burdensome. Several astronauts supported an automated inventory management system, for instance using a bar-code reader to record the use of supplies or placement of tools. While routine cleaning was not generally regarded as burdensome in Skylab (it required 20 man-days over the life of the program, or approximately 4 man days per month of occupation), some of the astronauts felt that an automated aid for cleaning behind the racks in the Space Station might be valuable. One astronaut suggested use of on-board training systems (e.g. intelligent, computer aided training or ICAT). Others recommended automated communications or fire detection/suppression/prevention.

Suggested robotics applications included external on-orbit replacement units (ORU) replacement, hazardous materials handling, various outside operations, remote inspections of exterior surfaces, and EVA set up (putting portable work platforms in place prior to astronaut EVA). Associated automation recommended included television camera/lighting control and pointing provisions supporting proximity operations. Strong encouragement was also voiced for an automated crew mounted retrieval system which would automatically return a disabled astronaut to the Space Station.

In general, tedious and repetitive activities and time critical tasks were viewed as candidates for automation. In automated systems, the crew must be able to ascertain that the automation is behaving properly, and the automation design should allow for graceful degradation and manual intervention/backup. Wherever possible, systems should be modularized to facilitate manual intervention/operation (as well as to support verification and validation). When procedures are automated, it should be recognized that some of the prepared procedures may be incorrect and in need of modification. Provisions should be made for easy modification of procedures and checklists within configuration management guidelines.

Emphasis was placed on the need for a strong infrastructure to support automation and robotics; this infrastructure would include the Data Management System (DMS), availability of sufficient internal and downlink bandwidth, and other supporting technologies as high definition television. Other advice given included designing automation features that support checkout and verification, having the software developers working closely with the end users from the beginning, ensuring the user-interfaces are really user-friendly, providing degraded and manual modes in the automated systems that are simple to use, developing systems with maintenance, repair, and modification in mind, building distributed systems, allowing for software compatibility, and considering security aspects. Some stressed that the Space Station Freedom Program should think in terms of more advanced technology.

3.1.2.6 Suggested Items to Remain Manual

Skylab astronauts interviewed suggested some items or activities which they felt should remain manual. These included hatch operations (at least have manual override mode), pressure equalization valves, EVA controls, and manned docking and maneuvers. They also generally felt that waste management should remain manual primarily for aesthetic or health reasons or because they did not see how it could be automated.

3.2 SPACE SHUTTLE EXPERIENCES

Thirty-two Space Shuttle missions have been launched as of December 1, 1989. These have included three Spacelab missions as well as a host of other scientific experiments. Interviewees included astronauts and payload specialists who had flown Spacelab missions, astronauts who had flown other STS missions, and astronauts who have been assigned to upcoming flights but have not yet flown. Some of the astronauts interviewed were currently working on projects directly supporting the Space Station.

3.2.1 Shuttle Documentation

No documents comparable to the Skylab "lessons learned" documents have been produced for the Spacelab or STS programs. A number of documents relating to Spacelab and ground support operations (MOD, 1985) were reviewed.

3.2.2 Astronaut and Payload Specialist Interviews

The views expressed by the astronauts interviewed varied widely. Some astronauts believed that all areas should be subject to automation and that NASA should aggressively push the state-of-the-art in A&R. At least one felt that NASA is spending too much effort on research and not enough on building the station. More control from the ground was mentioned as an alternative to on-board automation. However, opinions converged in areas regarding many specific A&R applications. General candidates for automation included monitoring of system state, repetitive actions, and time-critical actions not requiring human judgment. General recommendations included the provision of usable manual backups/overrides and intermediate levels of automated control. Many astronauts felt that "man-in-the-loop" operation was essential, at least initially, with slow evolution toward more automation to preserve timeline continuity, safety, and operability. Some mentioned that if it makes sense to automate something on earth, then it should probably be automated in space. However, a Skylab astronaut (Pogue, 1989) cautioned that while this is a good general rule, some things are actually easier to automate in space (due to the microgravity) and should not be overlooked. Several astronauts emphasized that automated systems should be designed so that they give the user clear insight into vital system operations. Warnings were issued about the tendency of physical systems to behave differently in the space environment than on the ground and that this must be taken into account.

3.2.2.1 Improved Human Computer Interface

General dissatisfaction exists with the system interfaces on the Space Shuttle. These interfaces were described as "unfriendly" and antiquated. The displays tend to be cluttered and consist primarily of columns of numbers. Several astronauts felt that too many keystrokes were required to call up the desired information or to take the desired action; one astronaut estimated that during a typical Space Shuttle mission, the flight crew makes 27,000 keystrokes. In addition, several astronauts felt that too many discrete controls (over 1000 lights, gauges, and switches) are present, particularly on the flight deck.

It was felt there are too many different computer interfaces on Space Shuttle (especially during Spacelab missions). These can include the Space Shuttle Data Management System (DMS), the Spacelab computer system, and computers for individual experiments.

In general, the astronauts wanted interfaces which make use of the best technologies available on the ground (e.g. pull down menus and the windows-icons-mouse-pointer style interfaces popular on current computer workstations, replacing the mouse with a trackball for zero gravity use). Another desire is better use of color and graphics. Speech recognition interfaces were not regarded as desirable for critical applications, but almost everyone who expressed an opinion could see possible uses of this technology for hands-busy control, e.g. for certain space suit or glove box controls. If used however, a backup means of control was strongly desired. Several astronauts felt that speech synthesis could be useful in certain applications for relaying information as long as the visual cues (e.g. warning lights and messages) were also retained.

3.2.2.2 Monitoring and Control

Generally, the astronauts supported the automation of monitoring tasks. However, there were mixed feelings about the need for additional automated screening/interpretation of alarms. Some thought that the shuttle caution and warning system of various levels designated by color and tone was adequate; others felt that there were excessive false alarms. One veteran suggested a "smart system" for critical warnings would be helpful. Several interviewees emphasized that the automated systems must not hide useful information from the crew and that somehow these systems take into account the problems of sensor reliability and accuracy. Several endorsed subsystems autonomy and trends analysis. A desired feature is "what if?" capability where the crew member can query the system as to what would happen if a certain actions were taken before committing to such actions. Resettable limits for caution and warning were thought to be necessary.

3.2.2.3 Fault Diagnosis, Isolation and Recovery (FDIR)

The astronauts strongly supported FDIR activities including automated load shedding and safing of systems though there were mixed views on automatic reconfiguration, especially in safety-critical systems. Most of those who supported automatic reconfiguration also emphasized that the systems must inform the crew and ground control of any configuration changes. Some were concerned about implementing automated control of safety critical systems while others felt that at least portions of even safety critical systems could be automated. Others wondered how automated systems would be able to handle multiple independent failures when current written malfunction procedures cover single faults. Concern was also expressed by some over the fact that failures that occur in space are often not those foreseen during mission planning, though prototype knowledge-based systems exist which employ causal modelling to handle such contingencies. It was also emphasized by several that an automated FDIR system should explain its reasoning. One astronaut suggested the use of simulation (SIM) results to help build FDIR expert systems. Another veteran astronaut suggested that even the use of advisory expert systems to recall fault procedures would be helpful.

Several astronauts expressed the viewpoint that the current paper Flight Data File (FDF) is unwieldy; the version currently carried on-board can weigh over 100 pounds. There was a general feeling that it could be at least partially automated (i.e. put into electronic form). One astronaut felt that flight crews might still want a paper copy on-board.

3.2.2.4 Automation of Payloads

There have been a number of experimental apparatus failures, particularly on experiments located on the middeck, although crew intervention has allowed the successful accomplishment of scientific objectives in most cases. Some payloads do not give the flight crew enough control to allow successful intervention in case of problems. Ground personnel have no access to the standalone computers on the middeck, and there have been situations in which automation did not work correctly. There was a general consensus that payloads should be designed for flight crew intervention.

Many astronauts supported further automation of the scientific payloads, where appropriate, as long as sufficient capability was retained for crew members to intervene/override the automation. The appropriate level of automation varies based on the nature of the research; automation was viewed as impractical for some aspects of life sciences experiments while it was considered that manufacturing processes should be completely automated. Even in life science experiments, it was suggested that the animal waste management and cleaning process somehow be automated. Additionally, it was suggested that an expert system or other automated system with confidentiality protection provisions include a data base for medical diagnosis, history, medical records, and clinic operations including exercise and body input/output parameters. Several suggested that experiment set up, operations monitoring, and observations recording should all be automated where feasible. Another strongly suggested that an historical database for flight science experiments be established because so many principal investigators proposing experiments seem to be completely unaware of similar experiments previously flown. Successful automation of a scientific activity on the ground appears to be a general prerequisite to automating it on the Space Station. Some crew members felt that telescience has not been particularly successful to date (at least, for materials processing) due to communications delay and lack of visual fidelity (color and depth perception), and that more work needs to be done in this area. Concern was also expressed about the need for a strong data management system (DMS) and sufficient downlink capability to support on-board science.

3.2.2.5 Telerobotics

The only experience with robotics in the Space Shuttle era is the Remote Manipulator System (RMS). There were indications that there have been problems with this system, but the only details available had to do with an excessive rate of false alarms in the RMS collision avoidance software, controllability (e.g. dynamic harmonics) and comments on the need for an improved user interface .

Several of the astronauts interviewed had opinions on planned Space Station robotic systems. General support existed for an EVA Retriever (which is not in the Space Station baseline) based upon safety considerations. This device was felt to be potentially useful in retrieving items lost during EVA, which has several safety advantages, in addition to possibly preventing the loss of needed equipment; the EVA retriever might even be able to rescue an astronaut who had become disabled or separated from the Space Station during EVA. Potential limitations of the device were identified as range, time to deployment, and the means to locate a lost item. In the case of an unconscious or disabled astronaut, there might be difficulties in effecting a rescue. Alternative concepts for astronaut rescue such as self rescue devices were also of interest. The Flight Telerobotic Servicer, on the other hand, was felt by many to have, at present, a poorly defined mission. However, there were suggestions that part of its mission could be for external inspections, thus reducing EVA time.

3.2.2.6 On-board Training

NASA currently puts a great deal of effort into detailed mission training, greatly increasing the astronauts' ability to perform complex tasks under difficult situations. Every effort is made to tailor the form and sequence of the training to the mission requirements; thus the last two SIMs performed before a mission are launch abort and landing, to maximize retention of these safety critical items. Video tapes of in-flight maintenance procedures have been carried on the Space Shuttle, but the practice was discontinued because no one used them. Of course, these missions have been relatively short compared to proposed Space Station missions.

The interviewed astronauts expressed nearly unanimous support for on-board training. Because of the long duration of a crew's "mission" on the Space Station (initially 45, later 90, and ultimately 180 days), insufficient time will be available to fully train the crew on the ground in all procedures necessary for the mission. In addition, over a six month period, much prior training will likely be forgotten. Thus, on-board training is strongly supported among the astronauts, although there are various interpretations of what might be involved. Refresher training is probably needed on seldom performed tasks such as repair procedures, piloting of an emergency escape vehicle, and docking. On-board training might also serve as a first exposure to the operating procedures of second segment payloads. A particular concern was refresher training to renew Space Shuttle piloting skills after a six month stay on-orbit. The desired forms of training range from the relatively conventional technologies, such as videotapes of repair procedures, to the relatively complex, such as on-board simulations, intelligent computer-aided training (ICAT) and use of "heads-up" displays to review material while making an EVA repair. One astronaut suggested the use of an actual system, such as the Remote Manipulator System, for practice/training, with precautions to ensure that the practice is performed in an area with no physical hazards. Another suggestion was to emphasize the capture of knowledge about procedures and systems behavior gained during training and then incorporate this knowledge in expert systems for use in monitoring and control as well as FDIR.

3.2.2.7 Scheduling

The Space Shuttle astronauts generally supported flexibility in the form of on-board capability to reschedule noncritical activities. Crew timelines were generally felt to be realistic, when there are no contingencies; but NASA has tended to schedule very tightly in the Space Shuttle and Spacelab with long workdays with little time allowed for contingencies. Such tight timelines in all likelihood, will not be workable in the Space Station environment. STS planning has recently been improved to schedule main/critical activities and provide a "to do list" for the rest. The astronauts generally preferred to have major and time critical items scheduled by the ground, with other tasks on the "to do list". There was widespread support for attaining on-board scheduling flexibility, which at least one payload specialist thought would be extremely beneficial when on the verge of scientific breakthrough. Although not brought up specifically by the astronauts, from a productivity perspective it seems that an on-board dynamic rescheduling capability would be highly desirable in the event of contingencies which effect new system configurations (such as power or thermal) in order to provide a fuller level of operation until a new baseline schedule can be generated. The mission/payload specialists with Spacelab experience generally felt that the Spacelab work pace could not be maintained over an extended 45-180 day mission.

3.2.2.8 Other

Opinions varied as to whether or not control of inventory was a major problem. Some astronauts felt that simple record keeping and discipline were sufficient for this problem, though the Skylab experience does not support this view. Others felt that a computerized inventory management system would be a useful aid in locating items quickly if the method of record keeping was not burdensome; the concept of something like a barcode reader for logging items was widely accepted.

Opinions varied as to how much autonomy the Space Station should have from the ground. The astronauts generally have less strong opinions as to how much automation should be involved in functions which are to be performed on the ground. A strong DMS was seen as necessary to support on-board automation; on the other hand, ground-based control would either require much expanded downlink bandwidth or would limit the ability to transfer payload data.

Other candidate areas for automation and robotics included EVA suit maintenance, check out, trend monitoring, and tracking of time-limited items as well as other unspecified EVA support activities. Also, various advisory systems, housekeeping systems (including a germicidal wiping robotic device for module walls), robotics for handling toxic samples, and ensuring enough bandwidth to accommodate future high definition television (HDTV) capability for the future were recommended. Principles emphasized included using automation and robotics to make the crew member's job easier (not replace the crew member), using such advanced technologies to make an immediate improvement in Space Shuttle missions (including Spacelab), and implementing the relatively simple applications early instead of just working on the harder problems with only promises for the future.

3.2.2.9 Suggested Areas to Remain Manual

Some astronauts felt that safety-critical system reconfigurations such as pressure equalization valves and hatches should remain manual. Others felt that certain scientific areas such as life science and materials processing are not particularly susceptible to automation. Other specific areas where automation was not favored or was regarded as infeasible (at this time) included manned docking and reboost, RMS (especially in support of EVA), and biological sample collection, although support for a better RMS collision avoidance system and improved user interfaces was voiced.

3.2.3 Ground Support

Space Shuttle missions involve a large "army on the ground" to provide the necessary support services. If the Space Station were to be operated the same way the cost of the quantity of support required would be significantly larger, and the support schedules used for Space Shuttle missions would be impossible to maintain.

3.2.3.1 Scheduling

For the Space Shuttle, the planning and scheduling activities focus around the crew activity plan (CAP). This consists of the mission timelines detailing the actions to be taken at specific times, often planned down to the second. This plan is both time and event oriented and is generated on a computerized system which records scheduling decisions while the actual scheduling and constraint checking are done manually. The EZCAP system, in which major items are scheduled and the remainder put on a "to do" list, was well liked by the crews but will not be continued in Space Station. The current process is highly labor intensive, with 5-10 people working one year to plan a typical shuttle mission.

Spacelab planning was the first attempt at distributed planning, with payload planning performed by the Spacelab Payload Operations Control Center (POCC) at MSFC and then integrated into the STS plan at JSC. The current software (used for Spacelab scheduling) is written in FORTRAN and is difficult to modify. More easily modified software for scheduling payload operations is desirable. Advanced scheduling methodologies making use of additional knowledge-based system techniques are being developed and are recommended. With multiple POCCs for Space Station, planning efforts will be further distributed, with integration performed at the Payload Operations Integration Center (POIC) to be built at MSFC.

The planning process needs to be further automated, beginning with automated constraint checking, and ultimately with the software doing time placement in the timeline. However, automated scheduling on board is regarded as a waste of crew time; plans are to give the crew the capability to edit schedules (move a single item in time) and ultimately the capability to move several items around over a period of several hours.

3.2.3.2 Space Station Control Center

In many respects the Mission Control Center (MCC) has not changed since the Apollo era. The Flight Director has overall control of a Space Shuttle mission. Seventeen console operators in the Flight Control Room (FCR or "front room") are responsible for performing specific mission functions, coordinating problem solving, and communicating needed information to the Flight Director. "Back room" teams in the Multipurpose Support Rooms (MPSRs) resolve problems in an interdisciplinary manner in support of the front room. The MCC is manned in shifts around the clock during a Space Shuttle mission, typically 6-7 days flight time plus 2 days for prelaunch support. The controllers interviewed recommended continued efforts to improve the user interface (the use of color, graphical, task-oriented displays is the first step in this direction), allow the software to recognize out-of-bounds conditions, and provide analysis of possible causes of anomalies. One problem with automation in MCC is the unreliability of sensors; a guideline exists that no action be taken unless there is independent confirmation of the problem, and any automation must allow for this factor. Automation might improve the performance and consistency of less experienced people in the control rooms, and in particular, reduce the training time required for control room personnel.

The existing Mission Control system dates back to the Apollo era. The consoles are not user friendly, with the displays consisting of columns of numbers. Mission Operations Directorate (MOD) and the Mission Support Directorate (MSD) personnel have been working to implement more modern technology, including graphics workstations for clearer information. Another effort has been to bring expert system technology to MCC. The Integrated Communication Officer Expert System Project (IESP), mechanical, and BOOSTER expert systems (known collectively as Real-Time Data Systems) are part of this effort and have achieved considerable success and acceptance among the flight controllers. Some positions (e.g. BOOSTER) are not manned during all mission phases, however. The Real Time Data Systems (RTDS) demonstrate how automation can improve the workload of the MCC personnel; these are discussed in Section 5 of the document. This is accomplished through better data displays, better analysis of the data, and use of artificial intelligence for monitoring, control, and FDIR applications.

The organization and operation of the Space Station Control Center (SSCC) is expected to be similar to that of the Space Shuttle at least in early phases. Differences will exist in console and support positions, of course; and the SSCC will need to be continuously manned 365 days a year. Flight controllers have reported this to be stressful, exhausting work, and maintaining extended operations for the analogous Space Station Control Center on a year round basis is recognized as a problem.

3.2.3.3 Flight Data File

The Flight Data File (FDF) is the primary documentation associated with a Space Shuttle Mission. It includes checklists and procedures for every activity/contingency which is expected for the mission. It is used as a reference by both flight and control center crews. For recent Space Shuttle missions, the paper copies of the FDF have weighed over 100 pounds. NASA has undertaken a project to investigate the feasibility of replacing the paper FDF with an electronic version. This concept has generally been supported by astronauts and ground personnel, but a mechanism must be provided for an individual to annotate "his" copy of the FDF with explanatory notes relative to individual duties; and a need is perceived for the astronauts to be able to maintain personal notebooks.

In Space Station Freedom the size of the FDF is apt to increase significantly, and problems with FDF configuration control will also be accentuated due to the length and complexity of the missions. Thus the technology and procedures for maintaining the FDF will be a crucial issue.

3.2.3.4 Training

Mission related training is an extensive effort within NASA. A variety of specialized facilities are used for training in such mission facets as use of the RMS, weightless procedures for EVA, as well as for training in the operation of individual spacecraft systems. Two of the most complex flight crew training facilities are the high-fidelity Shuttle Mission Simulator (SMS) and the Spacelab Simulator (SLS); these can be linked to MCC for integrated training of both flight and ground crews. NASA has implemented a Computer-Aided Instructional Trainer (CAIT) as a low-end system to fill the gap between textbooks and the more complex and expensive trainers. One problem is that the amount of training required, 12 weeks for a typical one-week Space Shuttle mission, makes the availability of the expensive high-fidelity trainers a serious constraint, and one which is apt to be even more limiting in the Space Station environment. Advanced computer-aided training techniques may be useful in providing relatively low-cost, high-quality instruction for the flight crews.

3.3 OTHER RELEVANT EXPERIENCES

Two additional major Space Station analogs were reviewed - the Soviet space program (in particular the Soviet *Mir* and *Salyut* space stations) and the U.S. nuclear submarine program. Both represent sources of experience with long duration manned presence in a hostile environment. However, such analogs can be deceptive unless the differences in the overall environment between the Space Station and the analog are well understood. Also, since the purpose of this document is an analysis of the potential benefits of automation and robotics in the Space Station, the primary interest in the analogs focuses on these areas rather than on psychosocial factors. Other examples consist of long-term operations in hostile environments, such as Antarctic research stations, but these are not significantly automated. However, they do reveal some of the problems related to equipment maintenance and modification that could occur on Space Station Freedom. The Antarctic teams performed extensive modification of equipment to the point that subsequent teams were unable to repair and maintain the equipment due to the lack of existing configuration knowledge.

3.3.1 The Soviet Space Stations

The Soviet Union has had an extensive manned presence on-orbit starting with *Salyut 1*, in April 1971 and continuing through the current *Mir* space station (core launched in 1986). The Soviets use slightly different technology, but the goals and expressed operational philosophy of their effort are reasonably similar to those of the U.S. program. Many of the experiments manifested on their space stations are similar to those supported by the U.S. space program (Bluth and Helppie, 1986). In interpreting the experiences of the Soviet space program, one must remember the underlying differences between the available technologies, the selection and training of the cosmonauts, and the underlying organizations and societies and their U.S. counterparts.

Because of the Soviet Union's relatively primitive computer industry, the level of computerization and complex automation in the *Salyut* and *Mir* systems is low by U.S. standards. However, they have automated some functions, and have expressed the intention to increase the level of automation in the future. It is worthy of note that the Soviets have successfully automated some things, such as the docking of unmanned resupply vehicles with their space stations (although Soviet cosmonaut Valentin Lebedev (1988) did express some dissatisfaction at being "out of the loop"), that would be difficult to sell in the U.S. program. The Soviets do appear to have had their share of equipment failures and concerns about failures attributable in part to poorly designed controls/procedures. These include the unintentional defrosting of a refrigerator due to poorly designed controls, and the unfounded concern that waste water had been recirculated into the fresh water supply (Lebedev, 1988).

The Soviets place a heavier emphasis on on-orbit repair than is traditional for the U.S. space program. Lebedev's (1988) book emphasizes the extent to which on orbit repair is critical and contains numerous instances of descriptions of repairs to equipment on the *Salyut 7* space station. The Soviet program regards manned presence as an enhancement to system reliability (Bluth and Helppie, 1986).

3.3.2 The U.S. Nuclear Submarine Program

Nuclear submarines can be thought of as an analog for the Space Station in that they exist for long durations in a hostile environment. However, the nature of the submarine mission is markedly different (military instead of scientific), as is the size and composition of the crew.

The nuclear submarine fleet has relatively little computerization/ automation, a situation which has been attributed, at least in part, to the influence of Admiral Rickover (Hemond, 1989) and is made possible by the size of the crew (110-130). The emphasis is on manual control of critical functions, such as the reactor, with exhaustive training in operations (Boeing, 1983). Nonetheless, system failures such as reactor scrams do occur somewhat frequently (Boeing 1983 and Hemond, 1989). The Navy is gradually increasing the level of automation in the nuclear submarine fleet, and it has been estimated that smaller faster craft carrying smaller crews would be possible if higher levels of automation were accepted (Hemond, 1989).

Another area for comparison is the emphasis on repair. The Space Station can be viewed as closer to a large naval vessel, which operates a continuous program of routine maintenance and has the capability to perform many emergency repairs while at sea (although major repairs may require a tender or port call), than to an aircraft, which is only maintained in the hangar (Slonin, 1989). In the submarine service the emphasis is on repair without surfacing, facilitated by exhaustive training, spares availability, and extensive record keeping of both the history of systems and of the source and pedigree of spares. Unlike the Space Station, however, submarines can surface in an emergency for service by a sub tender or return to port. Major repairs are always reserved for port call.

3.4 QUESTIONNAIRE RESULTS

A questionnaire was distributed to 32 current and former astronauts and payload specialists; the 32 included all but one of the 23 interviewed earlier, plus 10 additional individuals from the Astronaut Office. These included six astronauts with Skylab experience and seven with Spacelab experience (although these categories overlapped somewhat). Responses were received from 27 of the surveyed group, a response rate of 84 percent. The questionnaire consisted of three sections: one which asked the respondents to rate the potential of specific A&R applications for improving crew productivity, a second focused on the potential impact of specific A&R applications on safety, and a third which focused on the respondents' general opinions regarding the main A&R areas. The questionnaire and accompanying instructions as well as the detailed survey results are shown in Appendix C; the results were analyzed primarily by tabulation. Not all respondents addressed every item in the questionnaire.

In answering the questionnaire, respondents were asked to assume that workable, reliable implementations of the technologies can be developed with thorough testing and shakedown of all such systems and that manual backup and human intervention modes would exist. According to this survey, astronauts/payload specialists are philosophically in favor of using advanced automation to increase Space Station productivity, with 81 percent of those responding rating it as desirable, 19 percent viewing it indifferently and none rating it as undesirable. EVA robotics were rated as desirable by 73 percent and somewhat undesirable by 12 percent with the remainder indifferent. In general, the astronauts/payload specialists viewed advanced automation and EVA robotics as desirable in improving productivity on the Space Station . While 46 percent of the respondents viewed IVA robotics as desirable in some form, the others were either indifferent (31 percent) towards IVA robotics or viewed it as somewhat undesirable (23 percent). It is interesting to note that none of the respondents viewed any of these three general categories as highly undesirable. These results appear in Figure 3-1.

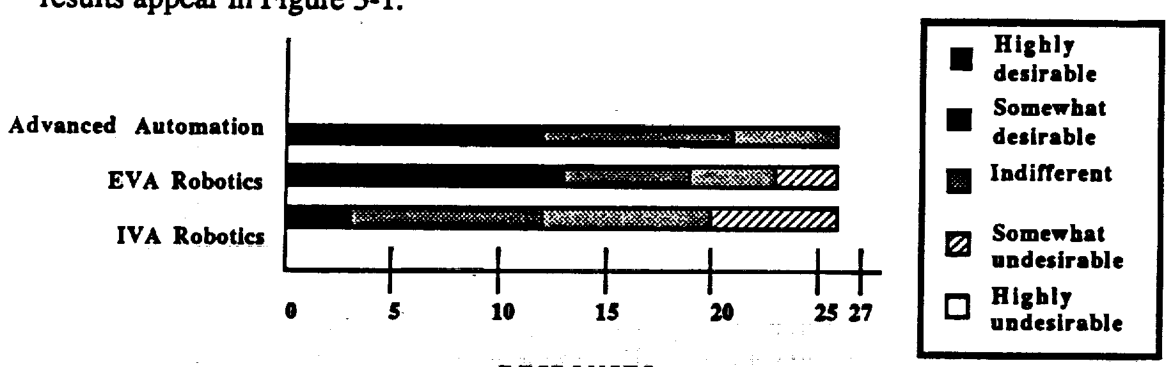


Figure 3-1 Astronaut Views Regarding Automation and Robotics

Results of the safety related questions appear in Figure 3.2. FDIR was rated as having potential to contribute some increase to significant improvements in safety by 93 percent of the respondents. Automated exception reporting and alarm filtering was rated by 84 percent as having potential for some increase to significant improvements while an EVA retriever was rated by 69 percent to increase safety. Only one respondent felt there might be any decrease in safety potential and that concern was related to the automated exception reporting and alarm filtering.

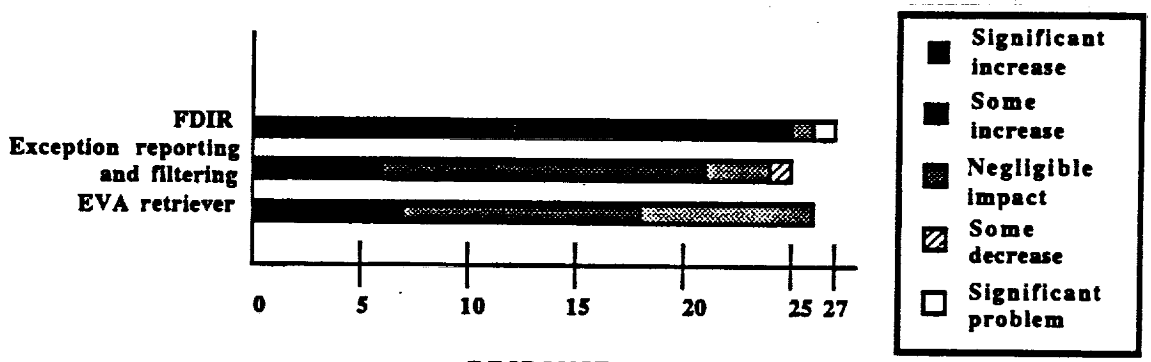


Figure 3-2 Astronaut Ratings of Safety Impacts of A&R Applications

Questionnaire results involving productivity impacts of specific applications of automation and robotics appear in Figure 3-3. Several specific applications stood out as heavily favored with **greater than 90 percent** of the respondents indicating the potential for some increase to significant improvement in productivity: **automated record keeping and documentation** (100 percent), **automated inventory management**, automated **FDIR, improved human-computer interfaces**, and **robotic construction**. On two of these, inventory management and improved human-computer interfaces, a majority of all the respondents indicated significant improvement potential for productivity.

Between 80 and 90 percent of all respondents indicated that potential for some increase to significant improvement in productivity exists for **robotic inspection**, automated **exception reporting/alarm filtering, external camera/light pointing** automation, **advanced human-machine interfaces** in general, **robotic external repairs**, systems automated **trends analyses, checklist automation, robotics** in general, automated **systems monitoring and controlling**, and **EVA retriever robotics**.

From 50 to 79 percent of the respondents came the expectation of productivity improvement from applications involving **payload automation** (79 percent), **on-board training systems** (72 percent), **payload automated data analysis** (71 percent), **Principal Investigator in-a-box** type experiment expert systems (65 percent), **internal cameras/lighting pointing** automation (58 percent), **cameras/lighting pointing automation in general** (58 percent), **speech recognition** (56 percent), **speech synthesis** (54 percent), automated **scheduling/rescheduling capability** (52 percent), and **IVA rack robot** (50 percent). Only one application, automated **housekeeping robots** (46 percent), received less than a majority of responses indicating belief of the application leading to an increase in productivity. Even in this case, most of the respondents indicated negligible impact while only 8 percent foresaw some decrease in productivity or significant problems related to automated housekeeping robots.

Twenty-six specific questions about A&R applications evoking 611 responses resulted in 465 indications (76 percent) of belief that these specific applications would lead to at least some increase in productivity while only 42 (7 percent) indicated some decrease or significant problems concerning productivity regarding specific applications. The 104 remaining responses (17 percent) indicated negligible impact on productivity.

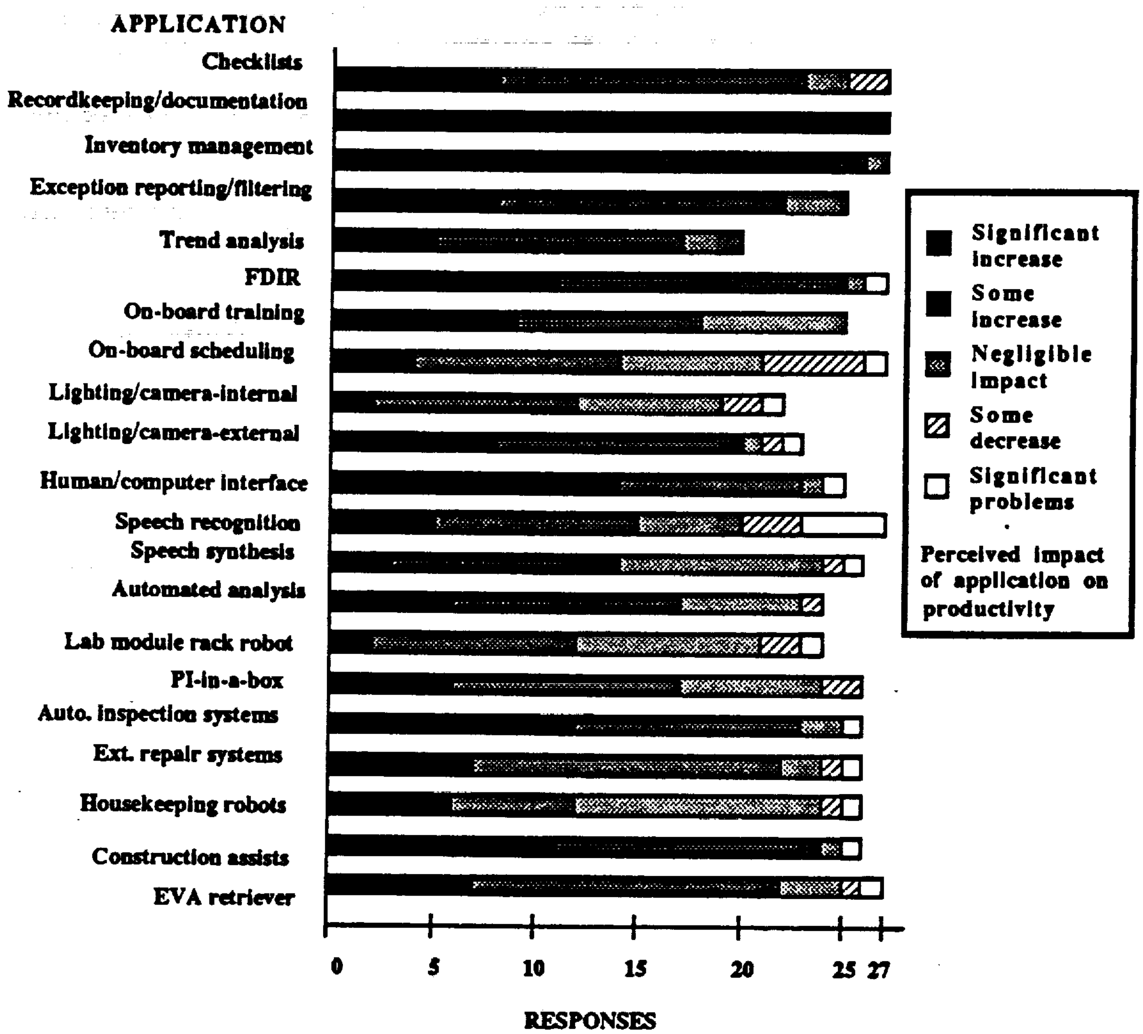


Figure 3-3 Astronaut Estimates of Productivity Impact of A&R Applications

In general, the results of the questionnaire are consistent with those of the interviews, although a few specific items differed somewhat from the predictions which would have been made based on the interviews. The main noticeable differences were in the ratings of the EVA retriever, while rated favorably, was not rated as highly in the questionnaires as was expected based on the interviews, and automated inventory management, which was rated higher in the questionnaires than was expected based on the interviews. However, the interviews did indicated that many of the astronauts favored an automated crew retrieval approach using a "spiderman" package or other back mounted system to return a disabled crew member to the Space Station. Other differences between the opinions expressed on the interviews and the results of the questionnaire may be attributed to interviewee doubts about the maturity or reliability of automated systems, which the questionnaire instructed the respondents to ignore or perhaps to the fact that a brief description of each application to be rated was included on the questionnaire (see Appendix C).

The questionnaires confirm the observation that Skylab astronauts, and to a lesser extent Spacelab veterans, are somewhat more favorable toward automation and robotics than other astronauts. This difference may stem from the fact that Skylab, and to a lesser extent Spacelab, represent long duration missions and that some of the advantages of automation are likely to be most apparent in the context of a long-term mission. Also, scientific efforts dominate both the Skylab and Spacelab programs as opposed to satellite deployments. Another possible factor is that the relatively low level of automation in Skylab has given the Skylab astronauts relatively little experience with the problems of automation, although two of the Skylab astronauts have also flown Space Shuttle missions. While the respondents were more supportive of automation and robotics in general (Figure 3-1) than of most of the individually specified A&R applications, the individual's general perception of automation may be influenced by the applications perceived as most promising (or perhaps, in a few cases, the least promising) by the individual.

A number of the respondents included written comments. Seven respondents noted that the stated assumption that the A&R technologies would be made to work reliably is a crucial concern; this is consistent with concerns expressed during the interviews about the ability to design correct and reliable systems. Two respondents emphasized the point that they favored automated fault detection and isolation but not automated recovery/reconfiguration schemes. Lastly, several astronauts emphasized that NASA should take a more aggressive role to include A&R technology applications in the Space Station program.

SECTION 4

OPERATIONS/PRODUCTIVITY PROJECTIONS FOR SPACE STATION FREEDOM

During the early 1980s, NASA conducted a Space Station Human Productivity Study (SSHPS) which proved valuable for issue identification and early program planning for Space Station Freedom. For SSHPS, productivity was defined as "the use of man to attain utilitarian objectives in the space station system" with the objective of a nine-hour workday (excluding weekends) composed of an average of six hours for payload activities and an average of less than three hours of operational maintenance. A routine EVA was envisioned as an eight-hour task with six hours of useful operations (Cramer, 1983; Cramer, 1985a; Cramer, 1985b). This approach has influenced the subsequent investigations of habitability issues and the development of habitability requirements which may aid in maintaining sustained human productivity during long duration spaceflight. Also, the current thinking on the framework for the crew workday (Lewis, 1989) reflects a workday similar to that articulated during SSHPS.

Bluth (1984) has noted that productivity concepts are in a state of continual evolution and that the term involves far more than the familiar cost to profit ratio, being a complex of perceived ideas (by the various program participants) on the subject. Measuring productivity has been found to be difficult because of both the quantitative and qualitative factors that contribute to human performance. Human performance is a mixture of processes - perceptual, mediational (cognitive), communication, and motor (Berliner et al., 1964). Motor processes are easily quantifiable, but in increasingly automated tasks, the other three processes (particularly mediational ones) become dominant in human performance. Thus, although tools for measuring components of human productivity in space are limited, spacecraft simulators (Atkin, 1987), THURIS (McDonnell Douglas, 1984; McDonnell Douglas, 1987), and recent optimization methods (Stuart, 1986) offer an initial means to assist in the refinement of investigations of candidate tasks for future automation and robotics.

Appendix D provides a more detailed background on the difficulties involved in defining and measuring productivity.

In recent years, researchers have attempted to develop quantitative indices of human performance in order to predict the optimal workloads for human operators, thus controlling productivity. Workload measurement techniques have been inclined to be specific to a small subset of tasks.

4.1 CANDIDATE TASKS FOR AUTOMATION AND ROBOTICS

As Nickerson has emphasized (1987), criteria should be formulated regarding what aspects of a space station's operation should be automated. "The rule that anything that can be automated (effectively, safely) should be automated is not necessarily a good rule." That is, there may be some functions that can be done suitably by either humans or machines that should be done by humans. One must consider not only the technical feasibility but problems of morale, perception of control, and the necessary maintenance of key skills.

Much has been written about the philosophy of which functions can be done better by humans and which can be done better by machines. The physiological limits and environmental requirements delimit the capabilities of the human, but human performance continues to provide unique abilities that will be unmatched for the near future. The major unique human abilities (Nickerson, 1987; Atkin, 1987) include the following:

1. Integrate information - from many sources and in many conventions and forms (particularly the rapid processing of diverse visual data).

2. Make judgments that are relevant, reliable and important - large decision capacity that infuses common sense as well as technical knowledge.

3. Respond effectively and rapidly to unanticipated events - excellent adaptive control system, improving with practice and transferring learned responses to new tasks.

4. Follow imprecise instructions and work toward high-level purposes.

5. Manual dexterity - the human hand.

6. Employ appropriate strength and dexterity - manipulation of large payloads in micro-gravity.

The first four abilities in the list derive from the phenomenal cognitive capacity of the human while the last two items reflect on the special human performance resulting from the coordination of physiological systems.

Examining the lessons learned from recent missions and regarding the conversations with a cross-section of flight crew members (see Section 3.0), it was noted that philosophical approaches, similar to the above analytically deduced list, were suggested as operational guidelines for automation and robotics. That is, the top four abilities appear to be imbued into the opinions of many types of astronauts, shaped by flight experiences of varying durations. In general, the common suggestions were as follows:

1. Automate the monotonous and repetitious tasks - particularly those with high frequency of occurrence such as system monitoring and routine experiment or payload measurements.

2. Automate the complex and time critical tasks.

3. Automate the hazardous/unsafe tasks.

4. Design automated components and systems with allowances for human intervention and manual override in mind - remember the human adaptability to the unexpected.

5. Automation is for assisting the human in performing his/her tasks, so notify crew of anomalies and options for corrective action and allocate to the crew judgment and decision functions - particularly for actions that are potentially hazardous to crew or station.

6. Introduce increasing levels of automation for systems incrementally - build trust in the machine by crew members.

Although different interviewees had their own value judgments (based on their specialized experiences and background) about what was most important to automate, there were frequent comments related to both the need to use the automation already available on the ground for spacecraft and the caution that one should not expect to be able to automate in space what is not already automated on the ground. However, it should be noted that micro-gravity sometimes make automation feasible or easier than on the ground. This includes the assembly of high mass structures (Pogue, 1989).

In attempting to gain further insight into the candidate tasks for automation and robotics for the SSFP, the human productivity management issues uncovered by the SSHPS (Lockheed, 1985b) as well as their current status were studied. Sixty-seven management plans, encompassing 113 identified issue areas, were developed. The majority of the plans dealt with habitability issues. Twelve plans appeared to be candidates for the significant use of automation and robotics to facilitate resolution. Most of these are either being studied by work package contractors or in work with some degree of implementation envisioned, although dependent on funding scenarios. All but three of these plans are actively being investigated or planned for consideration in the near future:

1. Task performance assessment - portable multi-test batteries had been suggested to measure how the human performance changes with long duration missions, and thus provide a quantification of biofunctional capabilities that could be used for the development of criteria and standards for task performance. Soviet *Salyut* and *Mir* experience indicated discrete drop-offs in crew performance at predictable points in the missions. These are at three months, five months, and toward the end of a year.

2. Habitable volume leak point detection - automated equipment would assist the crew in locating cabin leaks above minimal acceptability. This task was also noted as a candidate by some interviewees. Leak detection methodology of contaminants, such as ammonia, to the external environment is under investigation (Jolly and Deffenbaugh, 1989).

3. On-orbit system certification requirements - some believe many crew hours could be consumed in recertifying and calibrating equipment during a 30-yr. station life. This is not being addressed at this time apparently because of the early development status of the program. Some activity is underway for the initial certification of the station.

The caveat must be added that although the other nine candidates - equipment and food storage, data file storage requirements, trash-waste stowage and storage, water allocation for crew support, waste and trash collection methods, inventory management system development, on-orbit training, develop expert scheduling system requirements, autonomy technique selection/time phasing - are at least being examined in terms of inserting appropriate hooks and scars into the program, future budget constraints may prevent the full development and implementation of some items.

Although THURIS and other preliminary tools for estimation of the quantitative aspects of productivity neglect the unique and total aspects of human performance, cursory attempts to cost an astronaut-hour have been made (McDonnell Douglas, 1984 and Friedland et al., 1988). For example THURIS used approximately $32,500/hr. while a more recent estimate is on the order of $35,000/hr for non-EVA time (Friedland et al., 1988). Using this later figure, saving only one crew hour per week for a highly repetitive task through automation or robotics theoretically represents a savings or reallocation of $910,000 for a six-month period (26 hr. @ $35,000/hr.) which could be applied to an additional experiment. Other potential cost impacts include greater flexibility in task manifesting and reduced ground operations costs.

4.2 CREW WORKDAY

4.2.1 Previous Workdays in Space

In Skylab, the first space station, a daily routine was established for all three flights, which was in, most ways, comparable to the ground-based everyday activity with a Houston-based time reference (JSC, 1974; Johnston and Dietlein, 1977a). This meant the crew worked and slept during the conventional hours. Eight hours were allocated for sleep on each flight. Exercise was scheduled for 1/2 hr. each day on Skylab 2 (28 days), 1 hr. on Skylab 3 (59 days), and 1 1/2 hr. on Skylab 4 (84 days). Some scientists have concluded from their analyses that even though the three Skylab flights varied in duration and that the crews had pronounced variability in preflight training schedules and initial reaction to the spacecraft environment, in-flight task performance was relatively equivalent among the three crews (Johnston and Dietlein, 1977b). However, productive work did vary with mission day and flight. For example, the Skylab 3 crew began experiment operations with over 31 man-hr./day (3 men) and increased to 36 man-hr./day near the end of the flight while the Skylab 4 crew started at 28 man-hr./day (3 men) to over 33 man-hr./day in the later phase. It should be noted that "post-sleep" activities related to experiments and repairs were included as "productive " time. The increases were attributed to reduction in time for "overhead" tasks (food preparation, eating, housekeeping, etc.) achieved as experience was gained in living in microgravity (Johnston and Dietlein, 1977c). Some members of the Skylab 4 crew recalled that in a 14 hr. space workday, only about 6.5 hr. were really "productive" work (i.e. getting data or making something). Another recollection was that the Skylab 3 crew had considerably more time in ground-based simulators than the Skylab 4 crew and that this difference contributed to the slightly lower productivity in Skylab 4 when the initial activity plan was designed for Skylab 3 terminal production rates.

The beginning of the Space Shuttle era, with the first flight in 1981, heralded a new style in manned space operations. A reusable spacecraft had been built and with it a unique capability of carrying a manned laboratory into space, Spacelab, which permitted not only astronauts, but scientists and engineers to conduct experiments in the microgravity environment on a regular basis. The Spacelab missions on-board the Shuttle have been of no more than ten days duration, but the workdays have been intense, with timeline planning to the level of a minute. Experiment operations have been scheduled around the clock, with two shifts of 12-hour duty periods (Garriott et al., 1984). Apparently some crews needed 15 hr. to complete the tasks planned for 12 hr. Some of these crew members favor a 12 hr. workday for Space Station Freedom but with more of a skeleton of a timeline, having less granularity than that presently employed for STS. Some investigators have noted a difference in the perspectives of crews from the current short duration STS flights versus the long duration Skylab flights, particularly with respect to habitability needs ("camping trip" vs. a long duration event), including what level of productive work can be sustained in flight over a six-month period.

During the Space Operations Center (SOC) phase A design studies contractors tried to determine the requirements for a space station work schedule. In particular, Boeing personnel examined several isolated and confined environments (ICE), encompassing Arctic radar stations, Alaskan pipeline construction camps, nuclear submarines, and Antarctic research stations (Miller, 1989). They reached the conclusion that beyond 30 days of continuous 10-12 hr. shifts, one needed to provide one day off per week to prevent social problems and "burnout". Also, a nine to ten-hour workday appeared to be optimal to maintain productivity. Examining work shifts in factories with significant amounts of overtime, the first four hours were found to be about 90 percent productive, the next four hours, 75 - 80 percent productive, and the last two to four hours, 50 percent productive. Their analyses indicated that one could expect a 10-hr. workday to contain 75 percent productive time (i.e., 7.5 hr.). The final report recommended for a SOC, an eight-hour workday for six days per week for a crew of eight with one day off per week and two shifts when required (Boeing, 1982).

Other investigators (Alluisi et al., 1963) of human performance during confinement have indicated that for periods of two weeks, and perhaps longer, a properly selected crew could be productive on a work schedule of four hours on and two hours off. For a month, and maybe two to three months, a schedule of four hours on and four hours off would be better.

Perhaps if workers are free to set their own schedules, productivity may be enhanced. In a recent factory setting, when the workday was changed by request from five eight-hour days to four 10-hour days with three days off each week, employment attrition decreased and productivity remained the same (Lewis and Swaim, 1986). On the other hand, an ICE study on seven-month Antarctic station winter-over revealed that among workers who could set their own workday, disproportional amounts of time were spent at the beginning and ending months of the confinement in attempting to achieve productive work. This was attributed to increases in anxiety during these periods. Some participants indicated that a weekly schedule of work and free time should be set by the Antarctic station management to even out the workload during the winter-over period when there is no provision for leaving the area (Evans et. al., 1988).

In 1983, NASA brought together a broad range of experts, who were familiar with ICEs and work schedules in general, to discuss the optimal productive workday that should be selected for the ICE of a space station. Out of these deliberations developed the goal of 90 percent productivity for a nine-hour workday (five days per week) composed of an average of six hours for payload activities and an average of below three hours for operational maintenance. Thus, this became the framework for the present planning for Space Station Freedom. However, the management issue of the optimal work schedule was listed in the final report of SSHPS as one still requiring significant research, but this need has been neglected in the current planning efforts.

Much research remains to determine the optimal work-rest cycle for the confinement of a space station. In summary, what is known is that an eight-hour workday seems to work well on Earth in a normal environment as well as a confined environment, while generally a 12-hr. shift cannot be maintained for more than a few weeks (without degradation in productivity), and that perhaps a nine or ten hour shift might be better over a long period to achieve even more productive time on tasks. How much flexibility should be left to the worker for the workday duration is unclear.

4.2.2 Space Station Workday Plans

The current planning for the crew workday aboard the Space Station Freedom depicts crew availability times in terms of systems operations, user or payload operations, and overhead activities on a daily basis (Lewis, 1989). A crew size of eight is assumed with the following schedule sequence of activities as a general goal for each:

Postsleep	- 1.5 hr. (includes morning meal)
----------------------------------shift begins	
Handover	- 0.5
OPERATIONS	- 4.5 (or 4.0)
Exercise	- 1.0
Lunch	- 1.0
OPERATIONS	- 4.0(or 4.5)
Exercise	- 1.0
Handover	- 0.5
----------------------------------shift ends = 12 1/2 hr.	
Free time	- 0.5
Presleep	- 1.5 (includes evening meal)
Sleep	- 8.0

	24.0

Thus this workday, including two handover periods between the two shifts, results in a 12 1/2-hr. duty cycle for each team and a 11 1/2 hr off cycle. The schedule is flexible and the 8.5 hr. allotted for operations (systems and user) is actually 7 hr. of planned activities because 1/2 hr. is designated to replanning, 1/2 hr. operations training (average; may not occur each day), and 1/2 hr. planning reserve.

Therefore, the opportunities to enhance productivity with A&R appear to lie mainly within the systems operations and, of course, user operations in terms of improving the efficiency of procedures. Perhaps a small increase could also be obtained in increasing the automation of the handover, but that could negatively impact the obvious social component needed to maintain continuity among shift teams. The time allocation for exercise is driven by medical requirements to maintain the physical condition of the crew which in turn impacts productive work. An expert system is being developed to facilitate the application of correct protocols (tailored to individual needs) and to assist in motivating the crew to exercise. It has been reported by the Soviets that in long duration flight, it is difficult for crews to continue to devote a sizable portion of each day to exercising. Examining the operations hours, it should be noted that some crew members perform more user operations than systems operations due to their specialized training. However, an overall daily crew average (eight person) can be determined as follows:

Systems operations	- 17 man-hr.	(2 x 8.5)
User operations	- 51 man-hr.	(6 x 8.5)
Overhead	- 32 man-hr.	(exercise: 2 x 8 + on-duty meals: 1 x 8 + handovers: 1x8)
Total	- 100 man-hr.	

This typical workday will vary significantly when EVA operations (two crew members performing and one crew member monitoring for eight hr.), proximity operations (involves part of one shift time for two crew members), and transfer operations (STS at the station; involves entire shift) are occurring. Hence, these operations also become excellent candidates to investigate for the application of A&R to improve total station productivity.

Two additional types of crew activities have not been included in the current workday planning (Lewis, 1989). The Extended Duration Crew Operations (EDCO) program calls for certifying crew members for periods of up to six months. EDCO could involve significant additions to exercise periods and additions to biomedical sample preparations and analyses activities. This extra crew time could be considered as additional overhead or user operations. The other major activity is the routine housekeeping, including the regular cleaning of habitable areas and maintaining of an orderly environment. In general this is a shared task among all crew members. Housekeeping time was a common concern among the crew members interviewed. One estimate was offered that every six months, 20 man-days (eight-hour shifts around the clock) will be consumed in a germicidal wipe of the station to control microbial growth. Certainly elements of housekeeping and the routine sampling and measuring of EDCO should be high priority items to consider for A&R use to improve crew productivity.

Although, as described above, Lewis (1989) gives the most current available information regarding crew time allocations, these estimates taken by themselves are too broad to be useful in performing a quantitative analysis of the potential impacts of automation, because they basically divide the available time between payloads (75 percent) and systems (25 percent). Reynolds (1985), presents somewhat more detailed estimates gleaned from crew time studies done by MSFC, Rockwell, and McDonnell Douglas during Phase B studies. However, these studies assumed a crew of six and are marred by other inconsistencies and questionable assumptions. Also in some cases, recent design changes will probably impact these estimates (e.g., the EVA estimate is probably too low in view of the decision to use the current space suit design).

Nonetheless, for want of more recent detailed estimates, these data (primarily the MSFC estimates) can be used in conjunction with 1989 crew workday estimates to yield the crew activity projections in Table 4-1. The data in this table have been adapted from that supplied by Reynolds to represent a crew of eight, and to allow for one hour per day for handover, instead of 30 minutes, as is estimated by Lewis. That is, the activities hours are depicted in forms of 8 1/2 hr. of operation plus 1 hr. of handover. These estimates are also reasonably consistent with current plans showing 72 percent of the operations time devoted to payloads or mission specialist activities related to payloads. In this table the estimates are given in the form of equivalent astronaut-years for the sake of consistency with the data supplied for ground support. For instance, a crew of 8 times 1 hr. each for activity planning each day would result in 0.84 manyears for this task each year.

Table 4-1
Crew Time by Function

Activity Hours/Day	Total Hours/Day	Annual Crew Member Years
Activity Planning	8.00	.84
System Monitoring and Control	7.00	.74
Flight Control	1.04	.11
Flight Planning	2.00	.21
Training	2.00	.21
Inventory Management	1.90	.20
Internal Maintenance and Servicing	6.20	.65
External Maintenance and Servicing	6.10	.64
Proximate Operations	5.44	.57
Payload Operations	36.00	3.79
Reboost	0.32	.03
Total Operations	76.00	8.00

4.3 GROUND SUPPORT AND MISSION OPERATIONS

4.3.1 Spacelab Mission Support

Ground support for Spacelab (SL) missions has provided NASA the opportunity to develop the capability to support payload activities in a manned microgravity laboratory and to coordinate in real-time the conduct of experiments by astronauts, scientists and engineers. This opportunity, although for relatively short flights (7-10 days), can also provide experience which is transferable to the sustained ground support necessary for payloads operations on-board Space Station Freedom. Studying the experience documented in the SL-1 and SL-3 Payload Activity Planner's reports (Weiler, 1984; Hardage and Jackson, 1985) meaningful relevant observations were noted with respect to the phased workday, workload, and shift duration.

During SL-1, payload replanning activities were performed on a continuous 24-hour per day basis, divided into two 12-hr. cycles (six people per shift). The replanning teams endured a high workload which significantly exceeded expectations and practiced simulations. The primary causes were unusually large numbers of replanning and operational change requests generated by launch delay teleprinter use (instead of text and graphics system), temporary loss of Spacelab subsystems, experiment anomalies, and an extended mission length of one day. For some personnel, the 12-hr. shifts grew to 15-16-hr. A recommendation was made to consider 8-hr. shifts or to intersperse 12-hr. shifts with 8-hr. shifts for relief. Concern was stated over the exhaustive effect of 12-hr. shifts with increased chance of errors for long duration missions. It was also suggested that all team members should be at the payload operations center 7-10 days before launch to minimize fatigue effects induced by shifted circadian rhythms (for those crossing a number of time zones). Those fatigue effects appeared exacerbated by high workloads and long workdays.

For SL-3, the same SL-1 work schedules (12 hr.) were implemented for the replanning teams. Even though the workload was about what was expected, fatigue problems occurred similar to the SL-1 experiences, resulting in the corresponding suggestions to shorten the workday to 8-hr. and have every participant at the site five days before launch. Also, the comments were made that more personnel should be used to reduce the workload and, therefore, the chance of errors. One observation, "no single person needs to work on two different missions that are separated by only two months" (Hardage and Johnson, 1985), appears to express the hectic working environment that occurs as dedicated personnel do their best to help maximize the science yield of a mission.

Interviews with ground support personnel, further indicated a need for infusion of automation to alleviate past and continuing payload support problems. A suggestion was made that the manpower levels required for SL timeline planning should be reduced through the increased use of scheduling programs and that the timeline process needed to encompass more flexibility. The timelines for the previous SL missions were regarded as being too rigid. An integrated planning system was needed that would treat the whole system of constraints of all on-board systems and the various science disciplines. Also there was the suggestion that more intelligent computer-aided training (ICAT) would help with the training of ground support personnel.

Apparently current SL timeline planning is driven by on-board power level, data return rate, and actual available crew time. For SL, a rough estimate of crew time utilization as productive time is 70 percent. These three critical parameters will most likely be the main drivers for Space Station Freedom. Therefore, the application of Knowledge-Based Systems (KBS) to optimize the use of these factors would aid both Spacelab and Space Station Freedom.

Mission control support for SL missions has been provided with the JSC Mission Control Center (MCC) which dates from the 1960s. The number of flight console operators has been reduced from the Apollo era to 17 "front room" operators plus "back room" teams, but the consoles are not as user-friendly as they could be (see Section 3.2.3.2). Efforts are in progress to reduce the reported stressful workdays (9-10 days of support for the average STS missions) by implementing improved data displays and knowledge-based systems for monitoring, control, and FDIR applications.

4.3.2 Space Station Freedom Support

The current ground support plans for Space Station Freedom consist of an increment plan, execution plan and update plan derived conceptually from the Space Station Operations Task Force. The increment plan will be prepared 12 months prior to the mission and includes 90-day plans. The execution plan is developed six months prior to the mission, while the update plan is developed just prior to that increment (90 days). Manpower requirements for these plans include two teams (10-12 persons per team) for increment planning, three teams (10-12 persons per team) for execution planning, and support for weekly replanning (most of the same people noted earlier). Also, there will be requirements for five to six persons on consoles to work problems on a hourly basis (seven teams or 35-42 persons). In addition, a typical turnover of software developers is expected. So the numbers of required ground support personnel increase quickly, resulting in an additional requirement to reduce manpower through automation on ground and on-board processing.

Ground support personnel think that the longer duration missions (90-180 days) of Space Station Freedom will provide them with more flexibility, but the challenge still remains to adapt the schedules to the individual productivity levels of the various station crew members.

There are differing viewpoints over how much payload activity timeline planning should be done on the ground and how much on-board the station. The ground personnel lean towards doing most of the scheduling, including payload planning, on the ground due to computer processing and storage limits on-board. The software on-board should be adequate to enable the capability to deal with contingencies. At the same time, it is acknowledged that man needs to be taken out of the loop to some extent on the ground as well to reduce error and manpower requirements. Flight crew comments on the subject indicated a general desire to not overload the crew. It was suggested that there should be three plans everyday - (1) a policy plan of 7-10 days, (2) a plan for the day after tomorrow, and (3) today's plan. These plans should be uplinked in time for the crew to comment before implementing. The on-board dynamic rescheduling capability should assist the crew in inserting three types of tasks into their daily schedules - (1) mandatory tasks, (2) high priority tasks, and (3) shopping list tasks. The Soviet crew have expressed a desire to automate as many functions as possible. Generally, the *Mir* is out of communication about half of an orbit for each orbit, so control by ground support is difficult. One cosmonaut remarked that there are huge numbers of people on the ground who get lazy during long duration flights (Bluth, 1989b). Thus there is a common need expressed by all participants to automate ground scheduling activity where feasible, with the disagreements apparently being over how much should be aboard a space station.

Other dimensions to the ground support operations include the potential personnel increases required to support an evolving and growing station over a 30-year interval. For example, in the case of power growing from 75 kw to 300 kw, an estimate has been made that an initial 40 to 50 support personnel requirement will grow to 80 to 100 people. With the infusion of existing KBS technology to augment monitoring and fault diagnosis activities, the initial requirement could be reduced to 12 to 15 people, growing to 20 to 25 people for the 300 kw state (Weeks, 1989). This represents a significant productivity enhancement with the addition of KBS technology to operational support. A similar application could be made for other distributed systems requiring ground support for Space Station Freedom.

In summary, current ground support estimates can be derived from Mission Operations Directorate, JSC presentations (MOD, 1989; Webb and Shinkle 1989), and from material supplied by MSFC (Weiler 1989) personnel. These are recent projections (generally September 1989) and are presented in Table 4-2.

Mission control support for Space Station freedom will involve continuous daily support as opposed to the 1 1/2 weeks of intense support required for a Shuttle mission. The Space Station Control Center (SSCC) will require 5.8 teams with typically 60 positions (civil service and contractor) to support continuous console operations at three shifts per day (Webb and Shinkle, 1989). The number increases to seven certified teams to enable rotation of workers to non-console duties, and to eight teams (i.e., 480 positions) to provide for turnover stock. This projection does not include non-console supporting activities in the SSCC. Automation applications focused on the console functions and interfaces as well as the training of the flight controllers would increase SSCC productivity and reduce operating costs via manpower requirements reduction.

Table 4-2
Manpower Requirements for Ground Support (Man-years)

	FY 1993	FY 1995	FY 1997
Operations Planning and Integration	72	142	145
Trajectory Design and Dynamics	46	42	54
Space Station Control Center	41	269	339
Space Station Training Facility	102	25	135
Payload Planning	55	55	60
Payload Operations Support	35	35	42
Total	351	568	775

Additional information regarding productivity for the Space Station Freedom may be found in Appendix D.

SECTION 5

APPLICATION OF ADVANCED AUTOMATION TECHNOLOGY

As used in this report, the term advanced automation refers primarily to computer and electronic systems which exhibit intelligent behavior (usually referred to as expert or knowledge-based systems) or otherwise enhance the flight (and ground) crew's capability to operate the Space Station and perform payload activities. The emphasis is on systems which are not currently used in spacecraft. Thus even simple expert systems are considered "advanced automation" as are other automation approaches not currently used in spacecraft, while the avionics packages presently used in the Space Shuttle are not. An overview of available advanced automation technology is given in Appendix E. The reader is also referred to the *Space Station Freedom Program Capabilities for the Development and Application of Advanced Automation* (Bayer, 1989) and to the *Space Station Advanced Automation Study Final Report* (Friedland et al., 1988).

5.1 POTENTIAL APPLICATIONS FOR SPACE STATION FREEDOM

General categories of potential automation applications for Space Station Freedom may be derived from the literature. Specific potential applications come from suggestions by the astronauts and ground personnel, active and proposed projects at NASA and the contractor community, and the literature. The general criteria for tasks where advanced automation has potential are: repetitive or boring tasks, vigilance tasks, tasks involving cognitive processes only, time critical tasks, hazardous tasks, and tasks requiring knowledge the astronauts/users do not possess. Table 5-1 shows intelligent system applications under development for the Space Station funded by the Advanced Development Program. Additional funding for a number of these efforts is provided by the Office of Aeronautics and Space Technology's (OAST) Systems Autonomy Program and by Space Station Supporting Development funds within the work package.

5.1.1 Monitoring and Control Systems

A number of examples of knowledge-based monitoring and control systems exist in industry. NASA has already shown the value of such systems in applications such as IESP. The evolutionary automation of monitoring should continue, with the addition of knowledge-based systems for monitoring on the ground, and ultimately on-orbit. At the simplest level, monitoring systems might merely perform an exception reporting function, that is, notify a human operator when system behavior/status is outside of some preset bounds. In instances where the rules for evaluating expected system behavior are complex, context dependent, and subject to change, the process requires more expertise; and advanced automation technology may be needed. Another use of advanced automation technology would be to perform trend analysis on the systems being monitored, to both detect and avoid incipient failures and to better understand system behavior. Efforts applicable to Space Station Freedom include the Communications and Tracking (C&T) Central Processor Resource Manager expert system, the Thermal Expert System (TEXSYS) for the Thermal Control System (TCS), the Data Management System (DMS) Network Monitor, the Operations Management System (OMS) event evaluator, the Power Management and Distribution (PMAD) System Fault Recovery and Management Expert System (FRAMES) and Load Priority List Management System (LPLMS), and the payload Instrument Scheduler/Control System.

Table 5-1
Advanced Automation Prototypes Funded by the Space Station Freedom
Advanced Development Program

System	Monitoring & Control	FDIR	Planning & Scheduling	Training Systems	Automation Software & Hardware
EPS	APEX				
PMAD		FRAMES	LPLMS/LES MAESTRO		
PMAC	LeRC Activity	LeRC Activity	LeRC Activity		
C&T	Central Processor Resource Manager ES		Local Controller Fault Manager		
Thermal	TEXSYS	TEXSYS			
ECLSS	MSFC Activity	MSFC Activity			
Payloads	PI-in-a-Box	PI-in-a-Box	PI-in-a-Box	PI-in-a-Box	
			Instrument Scheduler/ Control ES	Payload-Assist module deploys-ICAT	
DMS	Network Monitor	Global FDIR			Advanced DMS Processorfs, Networks
OMS	Event Evaluator	Global FDIR	Short Term Activity Planner		
PMS			PMS Scheduler		
SSE				Design Knowledge Capture	Advanced Software Development Workstation
					KBS Ada Tools
RMS		Procedural Reasoning System			Advanced Human-System Interface

5.1.2 Fault Diagnosis, Isolation and Recovery

Fault diagnosis, isolation and recovery systems have also been demonstrated in industry. The high payback of such systems in space applications has been demonstrated by BOOSTER in the Mission Control Center. The automation of FDIR would provide several benefits--including rapid and reliable correction of problems and lessening the amount of time spent in training for situations which the expert system can handle. Systems to perform these functions would often be model-based rather than ad hoc, particularly early in the Space Station's operational cycle, and would thus require an accurate understanding of how systems operate. Some ad hoc knowledge could be gained through simulations (SIMs), the rest would need to be acquired through experience with the live systems. Efforts applicable to Space Station Freedom include the Electrical Power System (EPS) Automated Power Expert (APEX), FRAMES, TEXSYS, the Remote Manipulator System (RMS) Procedural Reasoning System, and an OMS FDIR prototype similar to Mission Control's IESP, BOOSTER, and mechanical expert systems.

5.1.3 Planning and Scheduling Systems

The value of planning and scheduling systems can be seen in the use of the AALPS, GATES, and RALPH applications. Activity planning/scheduling, both on-board and ground, can be facilitated using intelligent systems. Such systems generally comprise two functions--activity planning, which is the process of developing the sequences of actions/events necessary to complete some task, and scheduling, which is the process of assigning times to activities/actions based upon plans and resource constraints. Activity planning lends itself directly to solutions using knowledge-based techniques; and scheduling systems may use knowledge-based or expert systems techniques, although a variety of algorithmic and heuristic approaches are commonly used. NASA flight planning and scheduling activities are done on the ground, with little use of advanced automation. While the astronauts expressed a preference for flexibility in short-term scheduling, on-board planning/ scheduling aids may be essential because of the complexity of payloads, and the tightness of resource constraints. Relevant projects include the PMAD LPLMS and Loads Enable Scheduler (LES), and Payloads Management System (PMS) scheduler.

5.1.4 Human Computer Interface

General improvements in the human computer interface, such as the use of color graphic displays, pull down menus-icons-trackball interfaces, and design to group data/functions logically, would be of value. In addition, the Space Station program can benefit from use of expert system technology to minimize the amount of input required from astronauts by intelligent selection of defaults. Speech recognition technology may be useful in non-life-critical functions where hands free operation is desirable, such as in use of the glove-box and where a small set of discrete function exists. Automated verbal annunciation of some caution and warning information may be useful in the augmentation of visual cues. The automated audio recording of logs/observations, with direct downlink in audio form and transcription on the ground, might save considerable time; at some future time automated transcription might be possible. Applicable development efforts within the Space Station program include evaluation of complex interface technologies at JSC and MSFC and evaluation of the evolution requirements for cupola workstations at ARC.

5.1.5 Training

Training of novices in an area of expertise is a classical application of expert systems. Additional possibilities include an on-board training capability using multiple media and providing the capability to allow for refresher training in seldom performed tasks and first time training in low probability tasks, such as certain repair tasks. Expert systems can also be used to expand the capabilities of training/ simulation at reasonable cost both on the ground and on-orbit. Training results can be captured for possible inclusion in diagnostic expert systems. Relevant projects include the Payload Assist Module/Deploys Intelligent Computer Aided Training (PAM/D ICAT) system, Software Support Environment (SSE) and Technical and Management Information System (TMIS) projects addressing design knowledge capture, and the "Principal Investigator (PI) in a box" scientist's assistant. In addition to serving training functions, this last application is intended to give real-time advice to astronauts on the conduct of experiments.

5.2 PRODUCTIVITY IMPROVEMENTS FROM ADVANCED AUTOMATION

The fact that advanced automation technologies are finding applications in business and industry demonstrates that these technologies can be cost-effective and can significantly improve operations. Unfortunately relatively little specific cost/payoff information is readily available. While system users express confidence that productivity improvements exist, these are often impossible to quantify accurately; and, when cost/savings data exists, it is often incomplete, withheld for competitive reaons, or lacks sufficient background information to be of use in formulating projections. Generally, the productivity related benefits from use of advanced technology fall into several categories--less manpower required, shorter training periods, more consistent performance, better performance, and less stress on humans. Table 5-2 is a summary of the potential benefits of various areas of automation based on the literature and astronaut comments.

Table 5-2
Areas of Productivity Improvement from Advanced Automation

System Type	Workforce*	Speed	Accuracy	Training Time	Consistency
Monitoring & Control	++	++	+	+	++
FDIR	+	++	+	++	++
Planning & Scheduling (including dynamic replanning/rescheduling)	++	++	+	+	++
Human Computer Interface	+	++	++	++	++
Training	+	+		++	++

\+ moderate improvement
++ significant improvement

* Note: Workforce savings may be in number of people or in decrease in required work.

Manpower savings are an obvious form of potential savings. Anything which can be adequately done by a machine does not need to be done by a human; this will generally result in a net savings if it is possible to either augment the human operator or find him/her other productive work. The most significant savings in manpower costs are usually seen in monitoring and control and planning and scheduling systems. Based on the limited data available, successfully implemented ground-based automation systems aimed primarily at manpower reduction in narrow domains may have a first year payback in excess of 50 percent (the approximate rate of return on the investment on IESP). Payback for planning and scheduling systems may well be higher because less testing and backup is required. On-board systems will require more extensive verification and validation, but will probably have higher payback because of the extremely high value of an on-orbit astronaut-hour (see Section 4.2).

Speed and consistency are also potential benefits of automation. Both faster response times and consistent responses are generally possible through automation of such time consuming and repetitive and boring activities such as monitoring. In addition, humans do not perform repetitive and boring tasks very reliably, providing another potential advantage for automation; the use of user friendly interfaces can also significantly improve speed and accuracy on such tasks. XCON, NICBES, GATES, and IESP (see Appendix E) provide examples of the how automation can be used to improve response times and reliability. Since FDIR systems do not often deal repeatedly with identical contingencies, consistency is not generally as much of an issue as is correctness. While projections of benefits based on faster, more accurate performance are speculative, in such applications as fault diagnosis speed may prove exceedingly valuable, as in the case of NASA's experience with

BOOSTER. Another benefit from automated FDIR is that the resolution of faults is less apt to be held up while experts are located.

For space applications there is also a dichotomy in the treatment of on-board and ground manpower. On board manpower for Space Station Freedom is very expensive (estimated by some to be $35,000 per astronaut-hour) although the bulk of this figure obviously stems from fixed costs and overhead. The costs of ground support time are a more modest $50 per man hour, although fixed costs and overhead are included here, too.

Ground support activities cost savings are on relatively firm basis, both because automation can result in actual direct savings of manpower, and because real cost savings have already been demonstrated in analogous projects. It should be noted that IESP demonstrated a 25 percent savings in systems monitoring costs, although because this was a first effort, these realized savings are probably somewhat conservative; thus a high end savings of 50 percent is also considered for monitoring and control systems. Automation of planning and scheduling activities has demonstrated high payoffs when replacing completely manual systems with interactive graphics; in replacing lower levels of automation, as is generally the case within NASA, a lower range of savings can be expected (e.g. 10 percent to 25 percent). The payoff from FDIR systems is impossible to predict at this point, except that it has been demonstrated that such systems can more than pay for themselves. The cost savings possible from advanced training systems, largely stem from two sources, the use of lower cost technologies from some aspects of training and the shortening of required training times. The former is not quantifiable at this time, but the latter is apt to be on the order of (10-25) percent (based on IESP). IESP and other Mission Control Center applications have greatly reduced the time required to modify and extend applications software. This in itself, leads to greatly increased productivity. The savings due to the use of improved human computer interface are not easy to quantify (in part because it is difficult to separate the effects of interfaces from other changes, although once again they were demonstrated during IESP), but these interfaces are generally relatively low in cost and provide immediate benefits in user satisfaction if in no other area. Another area of savings which cannot be readily quantified is savings due to preservation of institutional memory through design knowledge capture in support of advanced automation

Potential cost savings from these types of automation in ground support applications are summarized in Table 5-3, based on the ground support requirements given in Table 4-2. A range of savings percentages is given, with a dollar savings estimates for each end of the range. The savings estimates for areas which are already relatively automated are naturally lower than those for areas which make little use of automation.

Saving on-board astronaut time presents a high potential payback; but, since the crew size and many of the costs contributing to the on-board hourly rate are fixed, the time saved must be diverted into other productive uses for this payback to be realized. In general, any time saved will be devoted to more payload (e.g. scientific work). While other factors such as electric power availability and total available resupply mass affect the ability to add payload activities, experience with the Skylab and Space Shuttle is that experiments with low resource requirements can utilize any astronaut time freed by automation. Furthermore, the development of scientific "facilities" on the Space Station will open significant research opportunities independent of the requirements to carry heavy, study-specific apparatus into orbit, although needs for resupply will still exist. Also, in many cases the natural alternative to spending crew time in monitoring and control of systems is to perform those functions on the ground rather than to automate them, so that for such activities as monitoring and control the opportunities to save astronaut time through automation may be somewhat limited.

Table 5-3
Potential Cost Savings from Ground Support Advanced Automation

Activity	Potential Savings (% reduction in task time)
Operations Planning and Integration	25-50
Trajectory Design and Dynamics	10-25
Space Station Control Center	25-50
Space Station Training Facility	10-25
Payload Planning	10-25
Payload Operations Support	25-50

Based on the crew time estimates and available productivity studies in Section 4, Tables 5-3 and 5-4 gives rough estimates of potential savings in crew time achievable through advanced automation. These estimates are only approximate because both the underlying crew workload data and the percentage of savings are only ball-park figures; and for each area a range is given for the potential percentage savings and dollar estimates based on the high and low ends of the range. However, the reader should remember that these savings do not necessarily translate directly into dollar savings, but could represent time which might more appropriately be devoted to additional payload activities.

Table 5-4
Potential Savings from On-board Automation

Activity	Percent Savings (% reduction in task time)
Activity Planning	5-10
System Monitoring and Control	5-10
Flight Control	10-20
Flight Planning	5-25
Training	10-25
Inventory Management	10-25
Internal Maintenance and Servicing	5-10
External Maintenance and Servicing	2.5-5
Proximate Operations	5-10
Payload Operations	5-10
Reboost	5-10

Further background on advanced automation technology and fielded applications may be found in Appendix E.

SECTION 6

APPLICATION OF ROBOTICS TECHNOLOGY

In principle, applications of the robotics technologies present a significant potential in improving the productivity of the Space Station Freedom operations. The technology could be targeted to handle routine tasks, perform inspection, and carry out maintenance and servicing activities in both IVA and EVA applications. The question that now arises is the degree that such potential can be realized at various stages of Space Station development. The answer to this question depends on a variety of factors, including:

- Status and availability of the technology as a function of time
- Requirements for assembly, housekeeping, servicing and maintenance activities
- Accommodations of designs allowing exploitation of robotics potentials.

In the remainder of this section it is assumed that such accommodation has been made and that the robotics technology will be used operationally as soon as it is available and can be safely applied. An overview of robotics technology is given in Appendix F.

6.1 POTENTIAL APPLICATIONS IN SPACE STATION FREEDOM

Section 3.4 of this report presented the results of the survey taken of the astronauts to capture their insights on the need for, and relative merits of, investing in advanced automation and robotics to increase productivity. As discussed earlier, the astronaut responses relevant to the potential of robotics to improve their productivity can be summed up as follows:

- In the near term, astronauts felt there is greater potential for the utility of EVA robotics than IVA robotics.

- In the near term, automated robotic inspection tasks are perceived by the astronauts as having the greatest productivity potential of the EVA functions.

As a result of the survey, the following discussion is separated into EVA and IVA sections, with the majority of the analysis being presented for the potential productivity improvements of EVA robotic activities

6.1.1 EVA Potential Applications

NASA is currently developing a Space Station robotic system which has four principal elements: the Flight Telerobotic Servicer (FTS), the Canadian teleoperated robotic arm (MRMS), the mobility base (the Transporter) and the Shuttle RMS. These will be used separately and in conjunction to implement a variety of EVA tasks. The choice of tasks is not firm at this time but it includes three basic classes of activities: assembly assistance, maintenance and servicing, and inspection. These classes of operations are essentially those suggested and evaluated by the astronauts in this survey, and thus it is useful to discuss the potential productivity improvements for each of these functional groups.

All of the system elements are telerobotic, i.e., their motions are controlled directly by an operator located either in a station module, or in a Space Shuttle or at an EVA station on the MRMS. They achieve the accuracies required for their varied functions by the ability of the astronaut to use direct or video observation to guide them. In this sense these operations will be extensions of the type of operations already carried out in various Shuttle missions by the EVA astronauts working in conjunction with the RMS.

However, in the following discussions of advanced uses of these systems it is important to realize that all of the arm elements (the RMS, the MRMS, and the FTS) are also programmable, i.e., all of their joints can be programmed to accomplish the movement of their end points to a given location within useful accuracies (on the order of a couple of inches for the MRMS and the RMS, and roughly a hundredth of an inch for the much smaller FTS.) These programmable accuracies, coupled with the NASA/NBS Standard Reference Model (NASREM) hierarchical control architecture of the FTS, provide the basis for early adaptation of planned automated procedures which enhance the potential for the adaptation of automated procedures. The following sections discuss the possible applications of robots based on the survey and literature.

6.1.1.1 Assembly Assistant Tasks

While the details are still under consideration, it appears that all of the robotic systems (the MRMS, the Transporter, the RMS and the FTS) will be used during assembly for various functions including:

- Transport of material from the Shuttle bay to the work site
  - Truss packages
  - Work jigs
  - Living and lab modules

- Positioning elements at the work site
  - Thermal radiators
  - Attached payload assemblies

- Support and positioning of the astronauts at the work site.

In the current plan the control of the robotic elements for these tasks will be accomplished by the astronauts from teleoperation workstations in the Space Shuttle and/or the Space Station and possibly from a remote ground station.

One way of dramatically increasing the effective productivity of the astronauts for these operations would be to provide ground control of various elements of the robot systems for simple tasks which can be accomplished while the astronauts are engaged in IVA activities and/or are in the EVA preparation cycle. The candidate ground tasks would be: 1) transport materials, 2) prepare the work site during the EVA pre-breathe period, and 3) inspect worksite for anomalies or to ensure all support equipment is in-place.

The major task of the large arms (MRMS/RMS) in this activity is to transport and position objects. The smaller FTS will primarily be used to hold objects in place during assembly, position attachment tools, and perform simple assembly operations in well-defined, jigged environments (GSFC, 1989a). Although primarily teleoperated, the required automation control technology is well understood and falls into the class of "pick and place" robots. The astronauts and the literature surfaced three major cautions in applying this factory based automation technology to a ground controlled space operations environment.

- Signal delay times: The ground operators will not have the direct vision of the arms and their workspace which characterized the Space Shuttle/RMS operations, and which is the basis of the teach pendant method of creating the automated routines of factory robots. Therefore, all the ground operator's information from sensors and video feedback will reach them with varying delay times of up to three seconds. Additionally, there exists the possibility of communication outages which must be allowed for.

- Size and complexity of the total workspace: Factory automation is based on robot operations from a fixed base in a structured workspace. The complexity of the Space Station robot operations, especially during assembly tasks, will require frequent updates to both the location of the robot's base and the structure of its workspace (i.e. reach envelopes and obstacles). To the extent possible, work envelopes should be pre-defined (everything has a place) and well structured (keep the work envelope uncluttered and simple).

- Implementing safety: Safety zones around factory robots will have to be implemented in space by a complex integration of the hardware, the software and the operational rules so that there is essentially no chance that either normal or failure mode actions could damage the Space Station or endanger an astronaut. The latter goal can be achieved, with some loss of capability and flexibility, by restricting all ground controlled robot activities to non-EVA periods. In the case of the FTS it appears feasible that a combination of a safe zone and safing devices/software will reduce the hazards sufficiently to allow astronaut activity in proximity to the FTS.

Rapid, graphical display of all planned movements relative to the surrounding Space Station elements for verification must be provided prior to implementation. Because of the control limitations of adopting state-of-the-art teleoperation and automation techniques, significantly smarter software and the integration of more reliable sensors capable of sensing and prohibiting dangerous motions as well as providing the ground controller with the information required to plan and proof safe trajectories and object manipulations, will be required.

6.1.1.2 Maintenance and Servicing Tasks

The current near-term concept for maintaining the Space Station and servicing the on-board experiments is based primarily on the exchange of system elements packaged to be easily attached and detached by either an EVA astronaut or by a robot. These orbital replacement units (ORUs) generally require the placement of a "release" tool (usually a powered driver coupled with a holding and force equilibrator device similar to the MMS tool used by the astronauts on the Solar Max repair mission) in multiple locations.

Maintenance and servicing tasks differ from the assembly tasks in two important dimensions. First the maintenance function will be required for the lifetime of the Space Station and second the range of masses to be manipulated will be small compared to the habitation/laboratory modules handled during assembly.

The productivity for these tasks could be increased in the same way as for the assembly assist tasks - teleoperation from stations or ground control of the robot operations. The majority of the maintenance tasks will be removal and replacement of standard ORUs (which are system elements packaged specifically for on-orbit replacement by crew members and/or robotics). The planned robotic friendliness of the ORUs, their relatively small mass and their fixed, known work-site environment, all tend to make the use of teleoperation from station or ground control reasonable options to the astronauts.

The FTS or SPDM will probably be the system used for the majority of the maintenance and servicing tasks. Current plans call for the FTS to be carried to the work site by the Transporter and the MRMS, and to function either attached to the MRMS or from a truss mounted work site. The efficiency of the ORU replacement task will be enhanced by the integration of automated sensor fed control software capable of stabilizing and controlling the FTS's contact operations (insertion/grasp).

6.1.1.3 Inspection Tasks

As noted earlier in section 6.3, the survey indicated that the opinion of the majority of the astronauts was that automated inspection tasks offered one of the best opportunities for increasing their productivity over the life of the Space Station. This conclusion is in agreement with the results of an early Space Station study of Automation and Robotics (McDonnell Douglas, 1986) which reported that in some cases, inspection tasks require 90 percent of the crew task time versus 10 percent for actually performing a repair.

Inspection requires, at a minimum, the ability to position an instrument probe or package so that any surface area or component of the Space Station can be examined through its sensor feedback. Advanced inspection tasks may also require that the package have the ability to physically interact with the suspect part, e.g. insert an inspection probe. The MRMS, the FTS, or the MRMS and FTS operating together, could be used for either of these inspection tasks types, depending on the degree of precision and system stability required to perform the inspection. Inspection of solar array panels, truss members/joints and payloads are the tasks most likely to be candidates for EVA reduction by using robotic inspection.

Again, ground operation of selected obstacle-free surface inspection tasks, especially those routinely and periodically scheduled, could be the most cost effective first approach to essentially increasing astronaut productivity for this class of activity.

6.1.2 IVA Potential Applications

As discussed in section 6.3, the astronauts in the survey indicated that, in their opinion, the potential for robots to increase their IVA productivity (e.g., lab tending) was significantly less than could be accomplished through EVA robotics. In addition there were some expressions of concern about working in proximity to an operating robot (such as an astronaut tending one lab experiment while a robot is servicing another experiment).

There are however some potential IVA robot uses that could probably be of considerable assistance in relieving the astronaut of time consuming, repetitive functions without involving the potential of inadvertent contact with a crew member (McDonnell Douglas, May 1989).

Rack and/or rail mounted manipulators capable of routine film change out, material transfer including toxic or otherwise hazardous materials handling, inspection, or automated housekeeping tasks such as vacuuming, germicidal wiping), or cleaning the interior of life science experiments should be examined as the IVA workload is more fully defined. It should be noted that the Space Station laboratory module interior can be considered more "friendly" to automated robots than the EVA world since the work cell environment can be made more amenable to layout like a factory robot with work cells segregated from astronaut activity areas.

6.2 PRODUCTIVITY IMPROVEMENTS FROM ADVANCED ROBOTICS

Given the limited astronaut experience base for quantifying astronaut productivity, and the present state of the planning for the design and operation of the various elements of the robot systems, only very general statements can be made about increasing astronaut productivity at this time. This study has suggested the technical potential of augmenting on-board robot control with ground remote control as one way to increase astronaut productivity.

A reasonable approach to project potential astronaut productivity gains by substituting ground control functions for selected on-board astronaut activities would be to build on the methodologies and task timelines developed in three previous studies which examined the effect on total astronaut activity time of incorporating the FTS into timelines which were originally planned as EVA activity only (see Appendix F for more detail).

The first two studies, (Smith et al., 1987 and Drews, 1989) developed methodologies which could be applied to on-orbit operations or to ground control augmentation. The studies indicated that even the substitution of an IVA teleoperated FTS into all-EVA timelines showed significant reductions in astronaut activity requirements. However, the reduction in EVA time gained by using robotics, at least in the first years of the Space Station, will be offset by the increased IVA time that will be required to support robotic operations. Advanced Development tasks in shared control will increase the efficiency of robotic operations and will permit some fully automated tasks which are supervised by IVA astronauts. In later years, some robotic applications will be capable of ground remote supervised control. Inspection tasks and worksite preparation activities are likely candidates. Ground control of robotic tasks with data latency requires an integrated approach to task and spatial planning, sensor data fusion, and robot control. Collision avoidance using this integrated approach has been demonstrated for a robotic inspection task with time delay representative of that experienced from the ground to low earth orbit. The Advanced Development Program is continuing its efforts to develop and demonstrate this technology given its potential to reduce IVA time for robotic tasks.

The third study (GSFC, 1989) examined the same subject with similar results and recommended four specific assembly tasks be considered for robotic augmentation:

- Resource pallet installation
- Thermal Control System (TCS) panel installation
- ORU installation
- Inspection operations using FTS on the MRMS

While these tasks were all studied as assembly elements, the third and fourth are representative of maintenance and inspection tasks respectively.

In each of the above studies, the savings in astronaut total time was achieved by transferring some EVA tasks to an IVA controlled FTS. (Smith et al., 1987) further noted that "A strong benefit of autonomous operation is the potential to reduce Station IVA for supervisory tasks and thus improve FTS value and productivity. However, these benefits must be examined in the light of their technical complexity against performing the functions telerobotically from the ground."

The astronaut cautionary comments support these conclusions and add the observation that:

- The advanced technologies required for safe ground control of the robot elements can lead directly to those required for augmenting the efficiency of the on-board robot control by the astronauts.

Both the (Smith et al., 1987) "note" and the above "observation" are important. In view of the state of development of robotic technologies, it is clear that full reduction in selected EVA activities using autonomous robots is not feasible in the near term. Therefore, the next best alternative to augmenting an already aggressive on-orbit work schedule, is to alleviate some of the simple but potentially time consuming EVA tasks with ground remote control. This solution would also help reduce some of the on-orbit IVA teleoperation workload. This alternative is currently only viable, considering time delay limitations, as long as the task remains simple with no requirement for high-rate closed loop force/torque feedback to the ground operator. The payoff, in terms of workload manifesting/flexibility, appears great enough to warrant initial development,test and ground application of technologies such as scene simulation, off-line spatial planning, shared control and predictive simulated control to offset time delay. These technologies, if proven first on the ground, will be more easily retrofitted into the Space Station robotic environment as the FTS evolves.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

This section states the conclusions of this study with respect to the potential for increasing productivity during the evolution of Space Station Freedom through the application of advanced automation and robotics technology. Based on these conclusions, recommendations are made concerning the technologies and application areas addressed by the Advanced Development Program.

7.1 SUMMARY OF CONCLUSIONS

The conclusions of this study may be summarized as follows:

- The astronaut community generally has expressed strong support for the use of advanced automation and EVA robotics on the station. In terms of potential productivity improvements, their collective view was that the applications with the greatest potential are automated inventory management, record keeping, FDIR, improved human-computer interfaces, and automated inspection with EVA telerobotics. Astronauts with the long duration flight experience of Skylab were somewhat more strongly positive in their views towards automation than astronauts and payload specialists whose only flight experience has been Space Shuttle missions. Current astronauts, on the other hand, with recent exposure to the degree of automation employed on the Space Shuttle may be less likely to consider automation a panacea (Low, 1990).

- There is a high potential for significant increases in productivity on Space Station Freedom through the application of advanced automation technology during the development and evolution of the station. Areas which appear to offer the greatest potential include automation of payload operations, inventory management, and system monitoring and control, including FDIR.

- There is also high potential for significant increases in productivity in ground-based station operations through the use of advanced automation, resulting in lower life-cycle costs over the life of the station. Areas which appear to offer the greatest potential include Space Station Control Center functions, and Operations Planning and Integration activities.

- EVA robotics has the potential to increase on-orbit productivity. The most cost-effective and technologically simplest way to significantly add to astronaut productivity during external assembly, maintenance, and inspection operations may be to transfer some control of the robot elements to the ground for selected tasks.

- A significant increase in the level of definition of Space Station activities and crew tasks is needed which includes the duration and frequency of those tasks over the life of the Space Station operations. This data will provide a firm quantitative estimate of the expected benefits of advanced technology in terms of crew hours saved and thus available to support payload operations. Such data is also required in order to judge the adequacy of available crew time as a resource to support payload operations.

7.2 RECOMMENDATIONS

Based on the conclusions above, the following are recommendations for the development of advanced automation and robotics technology for the Space Station Freedom Program:

- Development of advanced automation and robotics technology should be actively pursued. General areas of emphasis should include knowledge-based systems for flight systems and ground operations, improved human-system interfaces, and EVA telerobotics.

- Specific applications cannot be recommended solely on the basis of quantitative estimates of productivity benefits at present; general guidelines should be to develop systems which combine near-term technical feasibility, high potential for saving crew time on-orbit or reducing staffing on the ground, and acceptance and support by users.

- Adequate provision should be made in system design to accommodate future introduction of advanced automation and robotics technology.

- Additional effort should be devoted to developing data to provide the basis for more precise quantitative estimates of the impact of specific systems on productivity and life-cycle cost. This effort should include the collection of workload and activity duration data from Space Station Freedom once the station is permanently manned.

- Related to the point above, a systems engineering study approach to trade issues involving allocation of functions to a person, machine, or some combination thereof needs to be performed as a next step. Such a top-down approach should consider crew activities in two categories: (1) operations - where the routine events handled on a daily basis might be reduced from 3 hours/crew member day to 2 hours; and (2) mission activities - involving crew experiments and new crew jobs which provides greater potential for realizing productivity gains. Factors such as reliability, safety, etc., could then be factored in to give strong indications of high payoff applications.

APPENDIX A

SPACE STATION FREEDOM ADVANCED DEVELOPMENT PROGRAM

This Appendix contains a listing of the Fiscal Year 1990 tasks of NASA's Advanced Development Program as Table A-1. The Advanced Development Program is managed by Space Station Engineering, Office of Space Flight, NASA Headquarters, and involves each of the Space Station Freedom Program Work Packages and all of the NASA Centers.

Table A-1
Advanced Development Program - FY90 Tasks

Project Title	Center	Task Manager
Flight Systems Automation		
Power Management & Control Automation	LeRC	Jim Dolce, Jim Kish
ECLSS Automation	MSFC	Brandon Dewberry
PI-in-a-box	ARC	Peter Friedland
Thermal Control System Automation	JSC	J. Dominick, K. Healey
On-orbit Crew Training Prototype	JSC	Barbara Pearson
Power Management & Distribution Automation	MSFC	Bryan Walls
Ground Operations Automation		
Real-Time Data Systems	JSC	Troy Heindell
Intelligent Computer-Aided Training	JSC	B. Savely, B. Loftin
Instrument Scheduler Expert System	GSFC	Larry Hull, Karen Moe
Transition Flight Control Room	JSC	Al Brewer
Space Station Information Systems		
DMS Advanced Automation	JSC	W. Mallary, K. Douglas
OMS Fault Detection, Isolation, & Reconfiguration	JSC	Mike Kearney
OMS Advanced Scheduling System	JSC	Rick Eckelkamp
TMIS Design Knowledge Capture	ARC	Peter Friedland
KBS Scheduler Re-host	JPL	Rich Doyle, Eric Biefeld
Advanced Payload Simulator	SSC	Wendy Holliday
Optical Protocols for Advanced Spacecraft Networks	JPL	Larry Bergman
Advanced Automation Tools & Architectures	ARC	Ellen Ochoa
Computer Integrated Documentation	ARC	Guy Boy, Peter Friedland

Table A-1 (continued)
Advanced Development Program - FY90 Tasks

Advanced Automation Software, Hardware, Human Factors		
Advanced Software Development Workstation	JSC	Ernie Fridge, Bob Savely
ART/Ada Tool Prototype	JSC	Chris Culbert
CLIPS & CLIPS/Ada Extensions	JSC	Chris Culbert
KATE/Ada Tool Prototype	KSC	Barbara Brown
KBS Integration Environment	ARC	Henry Lum
Fault Tolerant Software Architectures	ARC	Ann Patterson-Hine
MAESTRO Advanced Scheduling Tool	MSFC	Bryan Walls
Digital Optical Computer Evaluation	MSFC	Charlie Jones
Space-qualified Multiprocessor	ARC	Allan Fernquist
Advanced Human-System Interface	ARC	Mike McGreevy
Telerobotic Systems		
Telerobotic System Technology	JPL	Samad Hyati
Architecture for Telerobotic Systems	JPL	Brian Wilcox
Automated Construction Testbed	LaRC	Al Meintel
Collision Avoidance Sensor Skin	GSFC	John Vranish
Telerobotics Ground Remote Operations	JPL	Bert Hansen
Crew/Equipment Retrieval Robot Design Study	JSC	Kathy Healey

APPENDIX B

PERSONNEL INTERVIEWED

This Appendix contains a listing of the persons interviewed during the course of the study.

Astronauts/Payload Specialists	Missions Flown	Non-NASA Employment
John-David Bartoe	STS 51-F (Spacelab 2)	NRL
Gerald P. Carr	Skylab 4	CAMUS
N. Jan Davis	assigned to STS 47 (Spacelab J)	
Bonnie Dunbar	STS 61-A, STS 32	
Owen K. Garriott	Skylab 3, STS 9 (Spacelab 1)	Teledyne Brown
Edward G. Gibson	Skylab 4	Grumman
Greg Harbaugh	assigned to STS 39	
Henry W. Hartsfield	STS 4, STS 41-D, STS 61-A	
David C. Hilmers	STS 51-J, STS 26, STS 36	
Jeffrey A. Hoffman	STS 51-D	
Joseph P. Kerwin	Skylab 2	Lockheed
Byron K. Lichtenberg	STS 9 (Spacelab 1)	Payload Systems Inc./CAMUS
John M. Lounge	STS 51-I, STS 26	
Jack R. Lousma	Skylab 3, STS 3	private consultant
Story F. Musgrave	STS 6, STS 51-F (Spacelab 2), STS 33	
Claude Nicollier	assigned to STS 46	
Robert F. Overmeyer	STS 5, STS 51-B (Spacelab 3)	McDonnell Douglas
Robert A. Parker	STS 9 (Spacelab 1)	
William R. Pogue	Skylab 4	CAMUS
Jerry L. Ross	STS 61-B, STS 27	
Rhea M. Seddon	STS 51-D	
Robert Springer	STS 29	
John W. Young	Gemini III, Gemini IX, Apollo 10, Apollo 16, STS 1, STS 9 (Spacelab 1)	

Mission Operations, Johnson Space Center

Al W. Baker
Stephen G. Bales
Theodore W. Eggleston
James R. Gauthier
William P. Gravett
Eugene F. Kranz
Charles R. Lewis
John F. Muratore
John W. O'Neill
Gerald E. Shinkle

Other NASA Personnel

B. J. Bluth	SSFP (Level II), Program System Engineering and Integration
Jon D. Erickson	JSC, Systems Development and Simulation
Stephen B. Hall	MSFC, Program Development Systems Integration (Editor, Human Role in Space)
Charles M. Lewis	MSFC, Man/Systems Integration
Keith H. Miller	SSFP (Level II), Program System Engineering and Integration
Jack W. Stokes	MSFC, Space Systems Chief Engineers
Jerry D. Weiler	MSFC, Mission Integration

Others

Brand N. Griffin	Boeing Aerospace/Huntsville
David G. Hammen	MITRE, Space Systems Division
Gordon L. Johns	MITRE, Space Systems Division
Richard L. Olson	Boeing Aerospace/Huntsville
Arthur N. Rasmussen	MITRE, Space Systems Division

APPENDIX C

SURVEY QUESTIONNAIRE AND RESPONSES

INSTRUCTIONS GIVEN TO SURVEY PARTICIPANTS

The attached questionnaire is being sent to current astronauts and former astronauts form the Space Shuttle and Skylab programs. Its purpose is to obtain your views regarding the prospective impacts of advanced automation and robotics technologies on crew workload and productivity in the evolution of Space Station Freedom. For purposes of this effort, advanced automation can be defined as automation more advanced than what is currently implemented on the Space Shuttle. Advanced automation includes, but is not limited to, expert and knowledge-based systems. It is important for us to understand the probably usefulness of advanced automation and robotics technologies so that the appropriate hooks and scars my be implemented and the appropriate development efforts planned. Your responses will be most valuable in determining where development efforts should be emphasized.

The questions on the attached sheet ask for your estimate of the probably impact of a number of proposed advanced automation and robotics technologies and projects upon Space Station Freedom crew productivity. You will be asked to rate each of these items on a scale ranging from "Significant improvement" to "Significant problems". Since these questions relate to the evolutionary period of Space Station Freedom, please assume, in answering them, that workable, reliable implementations of the technologies can be developed, that thorough testing and shakedown of all such systems will be performed on the ground prior to their incorporation into the station, and that manual backup modes will exist, along with design for human intervention. Thus you are asked to estimate the likely impact of a successful application on crew productivity, not the likelihood of a particular application being successfully implemented. Several questions ask for your assessment regarding a general area for automation along with several specific applications or proposals within that area; please answer each separately. Other questions deal with the impact of specific types of systems on safety and your general views on automation and robotics issues.

Questions About Automation and Robotics Applications on Space Station Freedom

I. Productivity: In your opinion, what is the potential effect on productivity on-board Space Station Freedom for each of the applications of advanced automation and robotics listed below? Please refer to attached pages for further explanation of questions.

	Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
1. Automated assists for checklist completion	___	___	___	___	___
2. Automated record-keeping and documentation	___	___	___	___	___
3. Automated inventory management	___	___	___	___	___
4. Automated monitoring and control	___	___	___	___	___
a.Exception reporting and alarm filtering	___	___	___	___	___
b.Trend analysis (e.g. recommend preventive maintenance)	___	___	___	___	___
5. Automated fault detection, isolation, and recovery (FDIR)	___	___	___	___	___
6. On-board training systems	___	___	___	___	___
7. Automated on-board scheduling/ rescheduling	___	___	___	___	___
8. Automated lighting, camera alignment and pointing					
a.Internal	___	___	___	___	___
b.External	___	___	___	___	___
9. Improved human/machine interface					
a.Human computer interface	___	___	___	___	___
b.Speech recognition systems for non-safety critical controls	___	___	___	___	___
c.Speech synthesis for crew alerts	___	___	___	___	___
10. Payload specific automation					
a.Automated analysis	___	___	___	___	___
b.Lab module IVA rack robot (e.g. for sample change out)	___	___	___	___	___
c."PI in a box" advisory systems	___	___	___	___	___

	Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
11. Robotic/telerobotic systems					
a.Autonomous inspection systems	___	___	___	___	___
b.Autonomous repair robot	___	___	___	___	___
c.Automated housekeeping robots (e.g. wall scrubber)	___	___	___	___	___
d.Construction assists	___	___	___	___	___
e.EVA retriever	___	___	___	___	___

II. Safety: In your opinion, what is the potential effect on safety on-board Space Station Freedom for each of the applications of advanced automation and robotics listed below?

	Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
1. Automated fault diagnosis, isolation and recovery	___	___	___	___	___
2. Automated exception reporting and alarm filtering	___	___	___	___	___
3. EVA retriever	___	___	___	___	___

III. Philosophy for A&R on station: What is your opinion generally regarding the desirability of using advanced technology during station evolution to enhance productivity?

	Highly Desirable	Somewhat Desirable	Indifferent	Somewhat Undesirable	Highly Undesirable
1. Advanced automation (e.g. expert systems)	___	___	___	___	___
2. EVA robotics	___	___	___	___	___
3. IVA robotics (enclosed)	___	___	___	___	___

Other Comments:

DESCRIPTION OF POTENTIAL A&R APPLICATIONS

Automated assists for checklist activities: Certain checklists are performed more or less by rote; these can be automated. Expert systems and other forms of automation could minimize crew input for following checklists and procedures in areas where human judgment is not required. These systems might perform calibration and alignment, for example. Another example would be an electronic version of flight data files.

Automated record-keeping and documentation: These systems might include automatic assists to the logging and downlinking of observations and events. For example, the crew could dictate logs rather than make paper or keyboard entries, with the automated downloading of appropriate information.

Automated inventory management: These systems would involve computerized systems for recording the quantities and locations of various inventory items. For example, a barcode reader might be used to record items removed from and replaced in storage to facilitate the tracking of the quantities and the locations of available items.

Monitoring and control: Automatic monitoring of system status might partially replace or supplement ground-based monitoring. Intelligent data reduction systems could alleviate data downlinking requirements. Automated exception reporting and alarm filtering would use expert systems to screen false alarms (e.g. those due to sensor failure) and report valid alarms to the crew or ground. Automated trend analysis systems would use performance data trends to predict failures and recommend preventive maintenance.

Automated fault detection, isolation and recovery (FDIR): These systems would identify system faults and failures, identify the probably causes, and make reconfiguration/repair recommendations. They could also potentially be used to support automatic reconfiguration of systems (e.g. automatic safing and load shedding).

On-board training systems: These systems might include trainers to perform refresher training on seldom used or critical skills, such as Space Shuttle piloting, CERV operation, and maintenance and repair procedures. Such training might incorporate video cassettes or disks, multi-media (video, audio and text) displays, computerized simulations, and intelligent computer-aided instruction.

Automated on-board scheduling/rescheduling: Such a system would allow crew to generate short-term schedules and replan around contingencies, as well as possibly to fine tune baseline schedules.

Automatic lighting, camera alignment and pointing: These systems might include remote camera pointing, automatic tracking of camera targets, and setting up in-vehicle lighting for photography/video.

Improved human machine interface: This category might include improved human-computer interface technologies such as the pull down menus-windows-icons-trackball technologies, speech recognition for non-safety-critical operations, and speech synthesis to augment visual indicators. Backup means of communication/control would be provided in the case of speech technologies.

Payload automation: Possible approaches would be incorporation fo expert systems for experiment monitoring and control, fault diagnosis and recovery (FDIR), data analysis, and systems to advise on experimental procedure (e.g. "PI in a box"). Other specific areas could include automated analysis of samples where feasible, and a rack-mounted robot for sample change out and other repetitive tasks.

Robotic/telerobotic systems: These might include robotic/telerobotic systems to scan the external station with television (or HDTV) camera allowing crew members to survey for damage without EVA. More sophisticated systems might be able to identify some types of damage automatically. Other suggestions have been housekeeping robots (e.g. robot wall scrubbers), external ORU replacement, and automated construction assists.

EVA retriever: This device would allow crew to retrieve objects (or disable astronauts) outside of the station, without necessarily requiring another astronaut to suit up for EVA.

QUESTIONNAIRE RESPONSES

This Appendix contains the specific questions asked in the survey of astronauts and payload specialists, together with counts of the frequency of each response to the questions. The tabulations are presented in Table C-1, by question, for the following groups:

Respondents (previously interviewed) with Skylab experience (6)

Respondents (previously interviewed) with Spacelab experience,but not included in the Skylab group (4)

Other Responses from Previously Interviewed Astronauts/Payload Specialists (9)

Responses from individuals from the Astronaut Office, JSC (not previously interviewed) - flight experience not known (8).

There were a total of 27 responses received. Many of the respondents did not answer every question, and thus the responses for an individual question do not necessarily total 27.

Table C-1

Total Responses - 27

1. Productivity: In your view, what is the potential effect on productivity on-board Space Station Freedom for each of the applications of advanced automation and robotics listed below? Please refer to attached pages for further explanation of questions.

1. **Automated assists for checklist completion**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	3	2	1		
	Spacelab	1	2	1		
	Other STS Crew	3	5		1	
Not Previously Interviewed	Astronaut Office	1	6		1	
Total		8	15	2	2	0

2. **Automated record-keeping and documentation**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	5	1			
	Spacelab	2	2			
	Other STS Crew	2	7			
Not Previously Interviewed	Astronaut Office	2	6			
Total		11	16	0	0	0

3. **Automated inventory management**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	5	1			
	Spacelab	3	1			
	Other STS Crew	6	2	1		
Not Previously Interviewed	Astronaut Office	2	6			
Total		16	10	1	0	0

Table C-1

Total Responses - 27

4. Automated monitoring and control

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	2	1	1		
	Spacelab	1	1			
	Other STS Crew	1	3	2		
Not Previously Interviewed	Astronaut Office	1	4			
Total		5	9	3	0	0

a. Exception reporting and alarm

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	4	1	1		
	Spacelab	1	3			
	Other STS Crew	2	5	2		
Not Previously Interviewed	Astronaut Office	1	5			
Total		8	14	3	0	0

b. Trend analysis (e.g., recommend preventive maintenance)

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	3		1		
	Spacelab	1	3			
	Other STS Crew	1	4	2		
Not Previously Interviewed	Astronaut Office		5			
Total		5	12	3	0	0

5. Automated fault detection, isolation, and recovery (FDIR)

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	4	2			
	Spacelab	2	2			
	Other STS Crew	1	6	1		1
Not Previously Interviewed	Astronaut Office	4	4			
Total		11	14	1	0	1

Table C-1

Total Responses - 27

6. **On-board training systems**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	3	2	1		
	Spacelab	1	2	1		
	Other STS Crew	3	2	3		
Not Previously Interviewed	Astronaut Office	2	3	2		
Total		9	9	7	0	0

7. **Automated on-board scheduling/rescheduling**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	2	1		2	1
	Spacelab		2	1	1	
	Other STS Crew	2	3	4		
Not Previously Interviewed	Astronaut Office		4	2	2	
Total		4	10	7	5	1

8. **Automated lighting, camera alignment and pointing**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab		2	1		
	Spacelab		1		1	
	Other STS Crew	1	4	1		1
Not Previously Interviewed	Astronaut Office	1	2	3	1	
Total		2	9	5	2	1

a. **Internal**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab		3	2		
	Spacelab	1	2		1	
	Other STS Crew	1	4	2		1
Not Previously Interviewed	Astronaut Office		3	3	1	
Total		2	12	7	2	1

Table C-1

Total Responses - 27

b. External

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	1	4			
	Spacelab	2	1			
	Other STS Crew	3	3	1		1
Not Previously Interviewed	Astronaut Office	2	4		1	
Total		8	12	1	1	1

9. **Improved human/machine interface**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	1	2			
	Spacelab	1		1		
	Other STS Crew	1	3			
Not Previously Interviewed	Astronaut Office	2	2	1		
Total		5	7	2	0	0

a. Human computer interface

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	4	2			
	Spacelab	2	1			1
	Other STS Crew	4	3			
Not Previously Interviewed	Astronaut Office	4	3	1		
Total		14	9	1	0	1

b. Speech recognition systems for non-safety critical controls

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	1	4	1		
	Spacelab	2		1		1
	Other STS Crew		4	2	1	2
Not Previously Interviewed	Astronaut Office	2	2	1	2	1
Total		5	10	5	3	4

Table C-1

Total Responses - 27

c. Speech synthesis for crew alerts

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	1	2	2		
	Spacelab	1	1	1		1
	Other STS Crew		5	4		
Not Previously Interviewed	Astronaut Office	1	3	3	1	
Total		3	11	10	1	1

10. Payload-specific automation

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	1	1			
	Spacelab		1	1		
	Other STS Crew		3	1		
Not Previously Interviewed	Astronaut Office	1	4	1		
Total		2	9	3	0	0

a. Automated analysis

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	2	2	1		
	Spacelab	1	1	2		
	Other STS Crew		5	2	1	
Not Previously Interviewed	Astronaut Office	3	3	1		
Total		6	11	6	1	0

b. Lab module IVA rack robot (e.g., for sample changeout)

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	1	2	2	1	
	Spacelab		2	1	1	
	Other STS Crew		3	4		
Not Previously Interviewed	Astronaut Office	1	3	2		1
Total		2	10	9	2	1

Table C-1

Total Responses - 27

c. "PI in a box" - type advisory systems

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	2	2	1	1	
	Spacelab	1	1	2		
	Other STS Crew	1	6	2		
Not Previously Interviewed	Astronaut Office	2	2	2	1	
Total		6	11	7	2	0

11. Robotic/telerobotic systems

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab		3			
	Spacelab	1		1		
	Other STS Crew	1	1		1	
Not Previously Interviewed	Astronaut Office		4			
Total		2	8	1	1	0

a. Autonomous inspection systems

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	3	3			
	Spacelab	3		1		
	Other STS Crew	4	3			1
Not Previously Interviewed	Astronaut Office	2	5	1		
Total		12	11	2	0	1

b. External repair systems

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	2	2		1	
	Spacelab	1	1	2		
	Other STS Crew	2	6			1
Not Previously Interviewed	Astronaut Office	2	6			
Total		7	15	2	1	1

Table C-1

Total Responses - 27

c. Automated housekeeping robots (e.g., wall scrubber)

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	2		2	1	
	Spacelab	2		2		
	Other STS Crew	1	4	3		1
Not Previously Interviewed	Astronaut Office	1	2	5		
Total		6	6	12	1	1

d. Construction assists

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	3	3			
	Spacelab	2	1	1		
	Other STS Crew	2	6			
Not Previously Interviewed	Astronaut Office	4	3			1
Total		11	13	1	0	1

e. EVA retriever

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	3	2	1		
	Spacelab		2	2		
	Other STS Crew	3	5		1	
Not Previously Interviewed	Astronaut Office	1	6			1
Total		7	15	3	1	1

Table C-1

Total Responses - 27

11. Safety: In your view, what is the potential effect on safety on-board Space Station Freedom for each of the applications of advanced automation and robotics listed below?

1. **Automated fault diagnosis, isolation and recovery (FDIR)**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	4	1	1		
	Spacelab	1	3			
	Other STS Crew	2	6			1
Not Previously Interviewed	Astronaut Office	5	3			
Total		12	13	1	0	1

2. **Automated exception reporting and alarm filtering**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	4	1	1		
	Spacelab		4			
	Other STS Crew	1	5	2	1	
Not Previously Interviewed	Astronaut Office	1	5			
Total		6	15	3	1	0

3. **EVA retriever**

		Significant Improvement	Some Increase	Negligible Impact	Some Decrease	Significant Problems
Previously Interviewed	Skylab	2	2	1		
	Spacelab		1	3		
	Other STS Crew	4	4	1		
Not Previously Interviewed	Astronaut Office	1	4	3		
Total		7	11	8	0	0

Table C-1

Total Responses - 27

III. Philosophy for A&R on station: What is your view generally regarding the desirability of using advanced technology during station evolution to enhance productivity?

1. **Advanced automation (e.g., expert systems)**

		Highly Desirable	Somewhat Desirable	Indifferent	Somewhat Undesirable	Highly Undesirable
Previously Interviewed	Skylab	4	2			
	Spacelab	2		2		
	Other STS Crew	4	4	1		
Not Previously Interviewed	Astronaut Office	2	3	2		
Total		12	9	5	0	0

2. **EVA robotics**

		Highly Desirable	Somewhat Desirable	Indifferent	Somewhat Undesirable	Highly Undesirable
Previously Interviewed	Skylab	3	1	2		
	Spacelab	2		1	1	
	Other STS Crew	6	2	1		
Not Previously Interviewed	Astronaut Office	2	3		2	
Total		13	6	4	3	0

3. **IVA robotics (enclosed)**

		Highly Desirable	Somewhat Desirable	Indifferent	Somewhat Undesirable	Highly Undesirable
Previously Interviewed	Skylab	1	3		2	
	Spacelab		2	1	1	
	Other STS Crew	1	2	5	1	
Not Previously Interviewed	Astronaut Office	1	2	2	2	
Total		3	9	8	6	0

APPENDIX D

PRODUCTIVITY CONCEPTS BACKGROUND

D.1 PRODUCTIVITY DEFINITIONS

The current NASA space station program, unlike previous attempts (e.g., Manned Orbiting Laboratory, 1964 - 1968; Integrated Manned Space Flight Program, 1969; Apollo applications Program (Skylab); Space Operations Center, 1980 - 1982), incorporated a human productivity drive early in the formative years. In November, 1983 a foundation was formed by the Space Station Technology Committee for the later Space Station Human Productivity Study (SSHPS) conducted by a cross section of major aerospace firms concerned with the efficiency of crews in manned spacecraft. It was acknowledged from the beginning of this effort that the definition of human productivity was difficult. For the SSHPS, it was defined as "the use of man to attain utilitarian objectives in the space station system" with the flight objective of a nine-hour workday (excluding weekends) composed of an average of six hours for payload activities and an average of below three hours for operational maintenance. Whenever a routine EVA occurred, an eight-hour task with six hours of useful operations was also envisioned (Cramer, 1983, Cramer, 1985a, Cramer, 1985b). The SSHPS goals were to define the design/operations requirements for the support of the human productivity and identify problem areas needing definition through the development of an inclusive list of management issues and accompanying management plans (Lockheed, 1985). It was believed that this approach would facilitate the development of the habitability requirements for Space Station Freedom which would ensure a sustained human productivity above 90 percent of the initial performance throughout a long duration flight (Cramer, 1983). The long tours for the Freedom Station were initially projected as 90-day intervals and, later, changed to 180-day intervals to accommodate resupply constraints. Currently, many of the management issues previously identified by SSHPS are being addressed in the Man Systems Working Group in the Space Station Freedom Program (SSFP). Most of those related to the use of automation and robotics to improve human productivity are being considered except for a few potential candidates (see Section 4.1.3).

Using the SSHPS approach to defining human productivity has proved to be useful for issue identification and early program planning, but "productivity" needs to be considered from additional perspectives. According to Nickerson (1987), one should consider not only human productivity and machine productivity but system productivity which is determined by several factors. One of the critical ones is the manner in which functions are allocated to people and to machines. Often, as in the case of manufacturing, the dominant opportunity for improving productivity is not attained by mechanizing the task of making or assembling of products, but in the organizing, scheduling, and managing of the total project. Also the linkage of social or interpersonal factors (both at the work place and outside) and productivity may be indirect, but nevertheless it is important. In other words, there are both quantitative and qualitative factors that comprise any estimation of the productivity of a system, such as Space Station Freedom. Thus, Freedom's productivity can be considered, on one hand, as the industrial productivity derived from space manufacturing, and, on the other hand, as the individual crew member's effectiveness and efficiency (or that of the entire crew complement) in completing his/her assignments which yield new and worthy scientific and engineering information. Thus, both types of productivity contribute to the system productivity of the station which will be heavily dependent upon complex human-machine interactions.

Bluth (1984) suggests that the concept of productivity is in a state of continual evolution. She noted that post-World War II, the numerical definition obtained by the ratio of cost to profit or, in other words, dividing the economic value by the labor cost, came under examination. In particular, Deming began to also consider the surrounding environment, worker conditions, organization, and other intangible constituents, such as customer satisfaction. Numerical production rates had not always worked as predicted. Bluth attempted to synthesize the converging opinions of those with practical experience in undertaking productivity programs. She formulated the paradigm represented in Figure D-1 to illustrate the complex of perceived ideas on the subject. The key term "perspective" underscores that value and cost, as viewed by persons related to the program and its products (e.g. Space Station Freedom and the information obtained from payload operations), are dependent on their own outlooks and, therefore, are important factors in decisions they make on the actions they will take.

Consequently, treating the term of "productivity" simplistically results in some difficulties that mandate consideration of both the contributing quantitative and qualitative factors. The human performance contribution to productivity has been found to be difficult to measure in a generic task-oriented manner and to assess in determining the actual workload experienced.

Human performance in systems, when considered as a major dependent variable in productivity, can be regarded as having the following taxonomy (Berliner et al., 1964) in processes and activities;

1. Perceptual processes	{Searching for and receiving information {Identifying objects, actions, events
2. Mediational processes	{Information processes {Problem solving and decision-making
3. Communication processes	
4. Motor processes	{Simple/Discrete {Complex/Continuous

The first three of these processes perform a large function in automated systems, particularly mediational processes. In recent years, there has been increasing emphasis on trying to measure these processes as both spacecraft and aircraft have undergone more automation. Being able to quantify these indices of human performance would enable researchers to determine when the human operator is overloaded, moderately loaded, and underloaded for a specific task (i.e., workload assessment). Generally, simulators form a major test-bed for these type of studies. However as noted in a recent assessment by Vreuls and Obermayer (1985), the existing analytical tools appear inadequate in either addressing all of "what" to measure or providing insight into "how" to measure. Further it was noted that in attempts to automate the measurements, frequently comprehensive recordings were made of everything reasonable and then cleaned up afterwards by discarding unwanted segments, using a variety of mathematical tools and attending to those measures that show experimental differences of interest. Vreuls and Obermayer summarized their findings with regards to four dominant problems with performance measures in the simulator environment: hidden and embedded nature of performance (unobservable internal processes produce overt actions); lack of general theory of performance; determining validity of performance

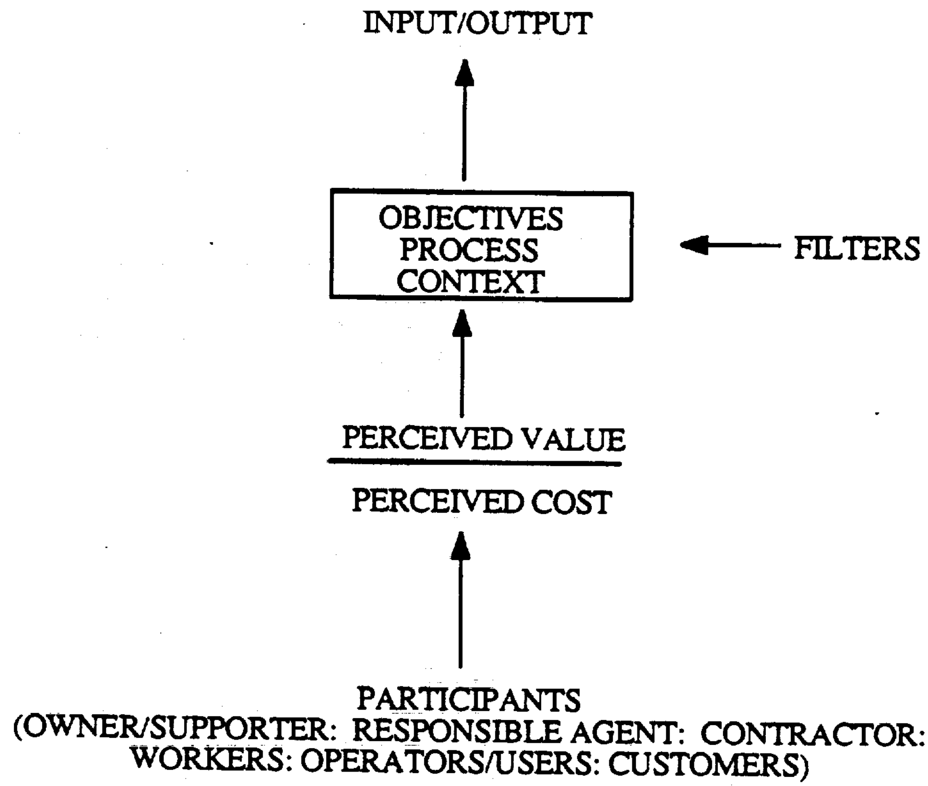


Figure D-1
Productivity: Contextual/Process Perspective

measures (individual variability in humans for rate of learning dictates that in order to obtain a predictability of measures in a training program, there must be empirical measures); and establishing criteria for performance (metrics in use describe experiences, but the scale of performance quality is operationally unknown for many tasks).

A perusal of the various current workload measurement techniques also shows that a given technique may be sensitive to one type of mental loading and not to another. For example, Wierwille et al. (1985) found in an evaluation of 16 mental workload estimation techniques in a simulated flight task which stressed mediational activity, that only seven were found to produce reliable changes as a function of loading.

The operation of an intricate system, such as the Space Station Freedom, will depend on the functions performed by both people and machines, and by both in interaction with each other. High productivity will demand that workloads be near the optimal level. Overload will increase the frequency of human error, reducing productivity. Underload will waste valuable resources and will contribute to boredom, both synergistically reducing productivity. Thus the correct estimation of workload is critical to improving productivity in space (Nickerson, 1987). However, Wierwille et al. (1985) noted that a significant consequence of automation is the shifting of the physical nature of tasks (motor processes) to those of more monitoring and performance evaluating. The latter type is considerably more difficult to measure due to the major cognitive components. Investigations in this area are still exploratory and represent considerable challenges for human factors researchers (Nickerson, 1987). In the specialized and limited communities, such as EVA, there is yet to develop a consensus on the appropriate measurements to produce meaningful comparisons between task or even experiments (Atkin, 1987).

Thus the problem of defining "productivity", which initially appears conceptually simple, is difficult when one attempts to find the appropriate metrics that could be used to measure human and machine performance in Space Station Freedom. As mentioned above, quantitative performance indices are inclined to be specific to a small subset of tasks, and then these still neglect the qualitative aspects influencing the performance of the tasks. Much research remains to improve quantification and validity of measures for this term.

D.2 Measurable Components

Nevertheless, realizing that "productivity" has both qualitative and quantitative components, and that the current state of knowledge does not permit the establishment of a reliable set of metrics for the former, one can consider the relevant quantitative approaches accomplished at this date.

Although in the case of the aircraft pilot, many simulator studies have been undertaken to measure performance and what can affect it, very little has been quantified for the case of the astronaut in the spacecraft simulator. That is, while spacecraft simulators have been an excellent device for the highly successful training of space crews, these environs have not incorporated the quantitative recording of performance measures and workload assessments. There are some plans to implement a type of performance tracking during training for Space Station Freedom scenarios. The underwater training facilities, at JSC, MSFC, and ARC could be regarded as specialized simulators for EVA tasks, but there remains contention in this small community, as noted earlier (Atkin, 1987), over the suitable metrics to use.

The Human Role in Space (THURIS) studies were initiated in late 1983 by Harry L. Wolbers, McDonnell Douglas Astronautics Company, under the direction of Stephen B. Hall at MSFC. The original objective was to provide information and guidelines in a form that would enable NASA program managers and decision-makers to establish the most cost-effective design approach for future space programs through the optimal application of unique human skills and capabilities in space. The study was partially built upon the results of the earlier MIT Automation, Robotics, and Machine Intelligence Systems (ARAMIS) study which developed a listing of 330 generic functional elements that were derived from the analysis of 69 space project tasks. ARAMIS options spanned the full range from fully human to fully machine. The ARAMIS study searched for the optimum mix of humans and machines for space project tasks, but detailed cost tradeoffs were not incorporated. Focusing on the viability of the application of automation and robotics to space activities and their related ground functions in the 1985-2000 time period, recommendations were developed for more study of telepresence, more study of expert systems for support of spacecraft decision functions, more specific study of payload handling and launch vehicle operations, and more study and development of space qualified microprocessors for spacecraft applications (Smith, 1983). THURIS used this foundation, analyzed other space projects, and developed a generic set of 37 activities from which it was believed systems, meeting future mission requirements, could be synthesized by assigning the principal criteria of performance, cost, and technological readiness metrics. The resulting mechanism was thought to provide a logical rationale for selecting the optimal human-machine interface early in the design process, and therefore, a cost-effective approach (McDonnell Douglas, 1984).

Within the THURIS study, cost prediction models were developed. Using the nine-hour day, five-day work week as in SSHPS, a total space station facility human involvement cost of $32,522 per hour (1984 dollars) was estimated. This was based on nine costing elements, four driven by time of use and five driven by frequency of use. Thus in this context, events taking a long time (relatively inexpensive support equipment used for tasks under one hour) or frequently repeated (generally inexpensive until about 1000 activations) become candidates for some degree of automation. In succeeding studies, the THURIS cost model fidelity and refinements were performed along with the development of a technology readiness database supportive of the application process (McDonnell Douglas, 1987). Nine mission scenarios were analyzed to validate the THURIS process, including Space Station Research Laboratory Modules.

Some who have examined or tried to utilize the THURIS methodology for space station productivity studies (Bluth, 1989b) have found that there is a lack of generalization of the activities, individual differences and experience in learning curves cannot be factored into the cost estimates, and performance variations of the human due to fatigue (as in EVA) or mission duration are not considered. Human steps in a task are variable and are not the same as that for a machine. Also THURIS cost functions are for individual tasks and do not depend on the completion times for the tasks, resulting in a less than complete analysis of all the costs of a given space scenario (Stuart, 1986). However, THURIS does appear to assist in refining an automation decision when one has a rough idea of what the candidates for automation are. Currently, the NASA HQ Office of Exploration is funding NASA ARC to modify a THURIS PC software application for analyses related to automation for a Mars base (Hall, 1989).

In 1985, a JPL study (Zimmerman et al., 1985) developed a method for human-machine trade-off analysis that employed decision analysis techniques which included combinations of cost, productivity, and safety. This approach formulated the trade-offs as an optimization problem in which a value for "person-hours" spent in Space Station activities was developed and "crew hours saved" were maximized by automating functions while staying under a cost target. The framework was a well-defined station with a fixed crew size. The use of decision analysis enabled the definition of a linear function subject to linear constraints.

Similarly another optimization approach was developed by Stuart (1986). His study assumed a variable crew size of human and machines, and employed overall cost as the only figure of merit. That is, human and machine productivity were directly embodied in the cost equations with the objective of minimizing the total cost of a particular job, resulting in a function that was basically nonlinear.

Tools for measuring components of human productivity in space are limited, but, as briefly discussed, spacecraft simulators, THURIS, and recent optimization methods hold some promise as initial means to assist in the refinement of investigations of candidate tasks for future automation and robotics.

APPENDIX E

OVERVIEW OF AVAILABLE ADVANCED AUTOMATION TECHNOLOGY

The primary areas of advanced automation techology are in artificial intelligence (AI) and advanced computer interfaces. The main thrust of AI development for the Space Station is in knowledge-based systems, although other areas of interest exist. Advanced computer interfaces include speech recognition and synthesis, as well as more familiar technologies.

Artificial Intelligence

AI is a field of endeavor which seeks to use computers and electronic systems to emulate human mental processes. This field actually comprises a group of loosely related technologies whose primary commonality is that they support the emulation of a human capability. In some areas commercially used applications exist, while in others the technology is still restricted primarily to the laboratory. Many AI efforts, such as knowledge-based systems, are based upon relatively formal human reasoning processes; these efforts have been relatively successful in part because the reasoning methods are well understood. Other efforts, aimed at emulating such poorly understood human capabilities as cognition (e.g. machine vision systems), are less advanced.

The purpose of this appendix is neither to present a tutorial on AI nor present a taxonomy of intelligent systems applications; these may be found in Waterman (1986) and Waltz (1986), for example. Expanded discussion of NASA applications and technology development can be found in the *Space Station Freedom Program Capabilities for the Development and Application of Advanced Automation* (Bayer, 1989) and in the *Space Station Advanced Automation Final Report* (Friedland et al., 1988). Nonetheless, some description of the different technological areas comprising AI may be useful. The bulk of all AI applications fall into two categories, knowledge- based systems and cognitive systems.

Knowledge based systems are the most mature advanced automation technology. The term is derived from the fact that a major component of these systems is a base of symbolically encoded declarative and procedural knowledge; an inference engine manipulates this knowledge to perform the desired function. The knowledge may take the form of rules of thumb, heuristics, information describing various entities, etc.; it may further be based on a formal model of its domain, or it may be *ad hoc*. There are various approaches available for incorporation into knowledge based systems; these approaches are not mutually exclusive, and many hybrid systems exist. Expert systems are sometimes considered to differ from knowledge based systems in that they explicitly emulate human experts, but in this document the terms are used as synonyms.

The advantages of knowledge-based systems include their ability to handle problems which do not lend themselves readily to conventional computerization techniques, their ability to handle inexact data, and their ability to explain the reasoning by which a conclusion was reached. Automating the solution to a class of problems may result in lower cost operation, faster or more consistent decision-making, and exhaustive examination of possibilities that a human might overlook; and the resulting knowledge-based systems may have the further advantages of extending the availability of specialized expertise and facilitating the formal codification of expert knowledge. However, the knowledge-based system will generally have a relatively restricted domain compared to the human expert.

AI deals with the manipulation of symbols. In principle, many programming languages support symbol manipulation. Some AI researchers and system developers use general purpose procedural languages such as C and Pascal. However, two languages specific to AI are commonly used, LISP and Prolog. LISP has the advantage of great flexibility and wide applicability, but can present a significant programming challenge. Prolog is based upon a predicate calculus formulation which applies to some problems directly. OPS is a LISP-based production rule language which has been widely used among knowledge based system developers. Expert system shells (tools for building expert systems incorporating packaged inference engines, user interfaces, and development assists) such as KEE and ART are also widely used.

Intelligent applications can be fielded on almost any type of computer, but the applications are typically resource intensive and have been more successful on some architectures than others. In the early 1980s, a number of manufacturers introduced expensive dedicated AI workstations, which featured fast processors optimized for LISP, large real memories, efficient memory utilization, and tagged memory to support run time type checking. With the availability of inexpensive, powerful general purpose workstations, the reliance on specialized AI workstations has declined. Currently most applications are developed on workstations such as the Sun/4 and MicroVAX II and even on the current generation of personal computers.

Another area of research which is currently very active both inside and outside of the aerospace community and which may find significant applications in space systems for the future is artificial neural networks. These consist of large numbers of computing nodes, operating in parallel and generally arranged in layers, in a manner resembling the organization of the neurons in the human brain. Neural network systems are especially useful for cognition, an activity at which humans (and animals) excel but at which conventional computer systems have had only limited success. Neural networks may be simulated in software, but would most naturally be implemented in hardware. Development of neural network chips is on-going.

Advanced Computer Interfaces

Significant advances in the human-computer interface have been made in recent years, many associated with AI research. These include the routine use, on commercially available desktop computers and workstations, of graphical interfaces, pull-down menus, windows, and a "mouse" or other pointing/selection technique. Other efforts which have so far met with less widespread application are natural language processing, continuous speech recognition, speech synthesis and machine vision and image processing. Natural language interfaces have been successfully applied to restricted domains, such as control of robots or queries to databases, but natural language interpreters are still far from being able to handle the full range of expressions encountered in a language such as English. Speech synthesis is in widespread use commercially, but speech recognition systems at the present, generally handle only relatively small vocabularies and are subject to a significant number of errors; such systems are most apt to be used in an environment where only a small vocabulary is necessary and the operator's hands are busy. Machine vision and image processing systems have also achieved some successes in relatively restricted environments.

EXPERIENCE AND EVALUATION

A wide variety of artificial intelligence applications have been developed. While a great many of these are experimental or prototype systems, there are many applications in daily use. The bulk of these latter are expert systems, the most mature of the AI technologies. Automated systems are generally introduced for two reasons--to lower the cost of operations, either by using fewer people or by producing more with the same people and to improve the quality/consistency of performance.

Experience

The most promising technology for the near term is knowledge-based systems. A wide variety of prototype and fielded applications exist. Most fielded applications use a production rule knowledge representation, often in combination with frame based or semantic net representation schemes; applications based on a predicate calculus knowledge representation are less widely used, because of the strict world model of predicate calculus. Existing systems use both deep (model-based) and shallow (rule-based) knowledge; and depend on both exact and non-exact (fuzzy or probabilistic) approaches. Typical applications have included interpretation (monitoring and control), diagnosis (FDIR), prediction, planning/scheduling and design. A number of intelligent computer aided training systems have also been fielded. Distinctions are often made between knowledge-based and expert systems, e.g. Bayer et al. (1989) describe the difference as being that the expert systems explicitly emulate the behavior of human experts in solving a specific problem . However, in this document, the term expert system will be used broadly to include all knowledge-based systems.

Artificial neural networks are a promising research area which has applications to in many pattern matching tasks. While neural networks have been applied to the solution of mathematical problems such as the traveling salesman problem, their primary applications will probably be in such areas of cognition as speech and machine vision. However, many years of research may be necessary before the first practical applications of this technology are available; and the problems of the interpretation of vision or speech in natural settings are not addressed by this technology (Wasserman and Schartz, 1987).

Fielded/Knowledge-Based Systems

Although the existence of commercially available hardware suggests the existence in the field of applications using such technologies as speech recognition and machine vision, most of the available literature on fielded applications deals with expert systems. Turban (1988) estimates that between several hundred and several thousand such systems exist. The table below gives a small sample of these applications, taken from Turban (1988), Schutzer (1987), Waterman (1986) and other sources. Additionally, Feigenbaum et al. (1988) do an excellent job in describing many successful expert systems. These have been implemented by a variety of organizations, including many for-profit corporations and many corporations not usually involved in development of computer technology. In a few cases, expert systems have been marketed commercially, or embedded in conventional software products which are marketed commercially. Please note that only systems which had proceeded to at least to the field test stage have been included in this table.

Table E-1

Expert Systems In Business/Industry

System	Developer	Description
SMOKEY	Carnegie-Mellon/US Navy	Recommend corrective action for shipboard fires in real-time
Phosphorous Burden Advisor	FMC	Diagnoses flaws in a phosphorus producing process
DISPATCHER	Carnegie Group/DEC	Schedules dispatching of materials in production process
COMPASS	Intellicorp/GTE	Analyzes electronic repair logs to identify failures and suggest actions
Automated Cable Expert (ACE)	AT&T	Identifies and diagnoses faulty telephone network sections
SpinPro	Beckman Instruments	Advises users on effective use of centrifuge
Stratagene	Intelligenetics/Amoco	Advises on cloning experiments in molecular genetics
Regression Expert (REX)	AT&T	Intelligent front end to statistics package
Steamer	BBN/US Navy	Trainer on ships' steam plants for Navy personnel
A Cartographic Expert System (ACES)	TRW	Advises on feature placement
XCON	DEC/Carnegie Mellon	Advises on computer configuration
XSEL	DEC/Carnegie Mellon	Provides sales assistance in hardware selection/configuration
OPGEN	Hazeltime	Configures printed circuit boards
Yorktown Experimental System/MVS (YES/MVS)	IBM	Aids in Computer system operation
EXPLICIT	Quantum Development Corporation	Litigation support
DIPMETER ADVISER	Schlumberger, Ltd.	Interpretation of data from well logging devices
Process Diagnostic System (PDS)	Westinghouse	Diagnosis based on sensors
CASHVALUE	Heuros Ltd.	Capital projects planning
CELL Design Aid	Arthur Anderson & Co.	Computer integrated manufacturing planning
ISIS, ISIS II	Westinghouse	Decision making and economic analysis for automated factories (planning, scheduling, and maintenance)

Successful knowledge based system applications date from Dendral, a system for deducing chemical structure from mass spectrometer and nuclear magnetic resonance data, which was begun in 1964. Early applications included system for diagnosis of blood infections (MYCIN), a system for solving differential equations (Macsyma), geological exploration (Prospector successfully predicted a large mineral deposit location), a French offshore drilling platform expert system (Drilling Advisor), and pulmonary function evaluation (PUFF) In some cases, the systems have been implemented in functions which are critical from the perspective of the sponsor, such as DEC's XCON computer configuration expert system or American Express' Authorization Advisor. Expert systems have been implemented in military applications, where the potential consequences of late or wrong decisions are high. Military application include expert systems for diagnosis of faults and planning of maintenance for such complex hardware such as aircraft engines, planning of air transport loads, and battlefield planning. Other government agencies employing knowledge-based systems include the Internal Revenue Service, which is developing systems to aid in response to taxpayer queries and processing cases.

NASA has developed a number of knowledge-based system prototypes, some of which are shown in the table below. This table gives the names, sponsoring center, and a brief description for a sample of knowledge-based systems; please note that both prototype and operational systems have been included. Where available, the system hardware and software are also listed. Three of these have been used in Mission Control operations collectively called the Real-Time Data Systems (RTDS), one at the integrated communications (INCO) console, another to analyze mechanical problems, and the third, BOOSTER, to analyze propulsion system problems. These have been successful, and the Director of Mission Operation, Eugene F. Kranz (1989) has stated that the BOOSTER expert system paid for its own development cost by speeding resolution of one problem which delayed the launch of STS 26. An expert system has been implemented for planning radar tracking for Space Shuttle missions which saves one to two man-weeks per mission. Knowledge-based systems are also employed in planning Space Shuttle payload bay cabling and verifying on-board software (Morris, 1988).

Early knowledge based systems were very expensive to develop; such systems as MYCIN, DENDRAL, ACE and XCON were the result of many man-years of research and development. As the technology has become better understood, the costs of developing such systems has decreased, along with increases in the probable payback. Many users now attribute large cost savings to expert systems; Mahler (Computer World 1987) claimed an overall cost savings to I.E. DuPont de Nemours of $10 million in 1987--a 1500 percent return on investment--from a variety of expert system projects. Digital Equipment Corporation (DEC) is estimated to save over $40 million annually using expert systems for computer system configuration, order processing and other functions. The reasons for system implementation, where reported, often emphasize decision quality and consistency more than cost. While such systems generally appear to result in cost savings, the specifics are often not available; the table below gives a summary of the information which is available for fielded systems. This information comes from Friedland et al. (1988) and other sources.

The remainder of this section consists of fuller descriptions of several representative knowledge based system applications. Particular emphasis has been given to the actual experience with the fielded system, although prototype and experimental systems have been included to demonstrate the range of possible expert system applications. The intent of this section is obviously not to list all fielded systems, but rather to give an idea of the range of recent successful applications, with particular emphasis on those within NASA (other than XCON).

Table E-2
Knowledge-Based Systems in NASA

System	Center	Description
Thermal Expert System (TEXSYS)	ARC	Model and rule-based reasoning under uncertainty, monitoring and FDIR of Thermal Control System testbed
Automated Power Expert (APEX)	LeRC	Fault detection/diagnosis of Electric Power System, load planner and scheduler
Fault Recovery and Management Expert System (FRAMES)	MSFC	Power Management & Distribution system (PMAD) testbed monitoring/control/FDIR
Loads Priority List Management System (LPLMS) and Loads Enable Scheduler (LES)	MSFC	Development of load shedding lists and scheduling/rescheduling for PMAD testbed
Nickel-Cadmium Battery Expert System (NICBES)	MSFC	Fault diagnosis, system monitoring, system status/advice, decision support graphics for Hubble Space Telescope power test bed
Local Controller Fault Manager Expert System	JSC	Communications and Tracking (C&T) control and monitoring testbed
Central Processor Resource Manager Expert System	JSC	C&T control and monitoring testbed
INCO Expert System Project (IESP)	JSC	Responds to STS communications malfunctions and configuration problems
BOOSTER	JSC	Expert system for analyzing STS propulsion system problems
EMPRESS	KSC	Expert system for planning/scheduling the loading of horizontal payloads to orbiter
Spacecraft Health Automated Reasoning Prototype (SHARP)	JPL	Automatic fault detection and diagnosis of Voyager's Command Data System
Resource Allocation and Planning (RALPH)	JPL	Planning for radio antenna complexes & Helper associated computer facilities in support of deep space satellites

XCON

XCON (Barker and O'Connor, 1989) was the first knowledge based system to achieve routine use in industry; it is a production (rule based) system written in OPS5, the development of which was first fielded in 1981. Its function is to verify the technical correctness of system configuration orders. Prior to XCON, Digital Equipment Corp. was seriously impacted by the difficulty of generating correct system configurations because of the large number of discrete parts with complex interdependencies. A family of knowledge-based systems has grown around XCON including the fielded systems XSEL (which assists sales representatives in generating correct orders), XFL (which is used to generate computer room floor plans), and XCLUSTER (which assists in generating cluster configurations). XNET, a tool for planning local area networks, and SIZER, a tool to assist in computer installation sizing are in various stages of development. The XCON rule base consisted of 10,219 rules as of September 1988; XSEL, 3629; XFL, 1808; and XCLUSTER, 243. The estimated annual cost savings based on the use of all four systems is approximately $40 million, compared to a probable development cost in the $3-4 million neighborhood, although constant maintenance is required to handle new products, etc. Additional benefits in the form of more accurate order generation, smoothing of new product introduction, and reduction of customer complaints are more difficult to quantify.

Hubble Space Telescope Ground Support

Baseline ground support for the Hubble Space Telescope (HST), scheduled to be launched in March 1990, includes a number of knowledge-based systems (Cox, 1989). Telemetry Analysis Logic for Orbiting Spacecraft (TALOS) will provide automated monitoring, context sensitive evaluation and interpretation of telemetry data. TALOS will also perform some FDIR functions by prediction/identification of telemetry problems and recommendation of corrective action. The HST Operational Readiness Expert (HSTORE) will help assess operational readiness of the HST after its deployment by the Space Shuttle. The Nickel - Cadmium Battery Expert System (NICBES) monitors battery system state and performs fault diagnosis for the HST electrical power system test bed (Kirkwood and Weeks, 1986).

INCO Expert System Prototype (IESP)

The IESP (Muratore et al., 1988) was developed to assist Mission Control console personnel in the diagnosis and management of the Space Shuttle communications and data management systems. IESP is a rule based system implemented in CLIPS, a C-based expert system shell. The utility of IESP was successfully demonstrated during STS-26, and it has been in use since. The development cost was $880,000; and the projected savings, $400,000/ year due to the reduction of the staff requirements for full-time monitoring. IESP is also expected to reduce the time required to train INCO console operators, and improve the consistency of decision-making. The IESP led to other console expert systems including BOOSTER and Mechanical Systems.

Resource Allocation and Planning Helper (RALPH)

RALPH is an intelligent assistant for allocating/scheduling the resources of the antenna and computer resources of the Deep Space Network, using a combination of algorithmic and knowledge-based approaches. RALPH allowed the saving of 3.5 man-years per annum in the development of plans and planning meetings. In addition, previously infeasible long range planning is now being done, along with an increased emphasis on special studies.

An Intelligent Tutoring System for Satellite Operations (ITSSO)

The Intelligent Tutoring System for Satellite Operators has been implemented as a prototype intelligent, adaptive, embedded training system for satellite operators in a complex multifunctional ground control system at the Georgia Tech--Multi-Satellite Operations Control Center (Truszkowski, 1988). It has proven to be effective in training personnel for satellite operations.

Spacecraft Health Automated Reasoning Prototype (SHARP)

SHARP (Lawson and James, 1989) performs automated analysis of health and status analysis of the Voyager II probe and its ground data operations. SHARP utilizes both conventional and AI technologies to analyze telemetry data and identify and diagnose faults. Graphical displays communicate status information to the operator. SHARP was heavily used during the August 1989 Voyager II flyby of Neptune.

Nickel-Cadmium Battery Expert System (NICBES)

NICBES (Weeks, 1988) performs automated fault identification and diagnosis, system status and advice, and decision support graphics. It is interfaced with the Hubble Space Telescope electrical power system test bed, having first gone into operation in November 1986. NICBES was also found to be useful in providing quick snapshots of system operation.

Experience with Advanced Human-Computer Interfaces

Human -computer interfaces using graphics, icons, pull-down-menus, and a "mouse" or other pointing device are now readily available commercially. This technology is generally believed to support user efficiency by presenting information in a manner which is readily understood by the user and by making user commands simple to learn and execute: The extensive use of menus as a command mechanism is probably most useful for novice users for operations which the user will not be performing frequently. Frequently executed commands are often given a "hot key" alternative, to improve user speed/convenience. Speech synthesis systems are also in widespread use today in presenting information over the telephone or as an additional channel for critical information in information rich environments such as jet cockpits.

One human capability which developers have emulated with some success is speech recognition. One advantage offered by speech recognition is its potential for hands-free operation; another potential advantage is speed, speech being twice as fast as the average typist. Hardware is commercially available which will allow recognition of user speech, as long as the speech is clear and distinct. Such systems have limited vocabularies and generally deal with discrete words as opposed to continuous speech. The accuracy is highest and the vocabulary broadest for those systems which operate in a relatively noise free environment and are trained for each individual user; but accuracy may be affected by such factors as physiological changes which cause the users' speech to change. Early experimental systems (HEARSAY and HARPY) have demonstrated the ability to recognize continuous speech from individual users with 90 - 95 percent accuracy, although requiring extensive computer resources. A recent published test of a speech recognition system was conducted by Perdue and Rissanen (1986) at Fidelity Brokerage Services; in this experiment telephone customers were allowed to respond to computerized prompts either verbally or by pressing the appropriate buttons on a tone generating telephone. This system achieved 91 percent accuracy in nine-digit numeric responses given by non-specific users. Accuracy of 99 percent is attainable in user-specific systems if the vocabulary is small and reasonably distinct, such as the ten digits (Chrochiere and Flanagan, 1986). NASA has supported a number of studies aimed at the evaluation of speech recognition technology for use in space applications. Sheperd (1989) conducted a study using speech recognition to control a computer display, with significantly higher error rates than those cited above; however the bulk of the errors were incorrect recognitions of commands in extraneous speech. Bierschwale et al. (1989) have compared speech recognition to manual controls for video camera aiming/focussing; the speech recognition system was slower than the manual system but generated fewer errors. Speech recognition was found to be inefficient for control of continuous adjustments. Collectively these studies show that speech recognition can be reasonably reliable, as long as the command set is small, and reasonably distinct and the environment is free of extraneous speech; ambient or line noise (other then extraneous speech) is generally not a problem although it might be in some applications.

KNOWLEDGE-BASED SYSTEMS TECHNOLOGY OVERVIEW

Knowledge-based systems consist of a knowledge-base and an inference engine. The following paragraphs describe the major categories of knowledge based systems. The first four paragraphs describe the main forms of knowledge representation predicate calculus, productions, frames, and semantic nets. The next four sections describe the four main inference strategies. Finally a number of related architectures are described. Not only are different combinations of knowledge representation, inferencing strategy, and architecture possible (e.g. a production system using forward chaining and communicating via a blackboard), but different hybrid knowledge representations and inferencing strategies are possible (e.g. productions within a semantic net).

Predicate calculus: Predicate calculus is system of formal logic which predates digital computers by several hundred years. In such systems knowledge is represented by formal propositional statements called predicates. A collection of formal rules (*modus ponens* and *modus tolens*) exists for the derivation of new predicates from existing ones. A predicate calculus approach is used in such applications as automatic theorem provers.

Production systems: These systems are based upon the representation of knowledge as a series of *rules* or *productions* of the form

if (premise) then (assertion).

If the conditions in the premise are all satisfied then the assertion on the right hand side are applicable. The inference engine is responsible for searching the knowledge base for rules which can be triggered in this manner.

Frame based systems: These systems store knowledge about objects in abstract representations called *frames*. Groups of frames describing related objects are aggregated into classes in a hierarchical tree-like fashion. Objects (frames) may inherit knowledge from the classes of which they are members. Each piece of information in a frame is stored in a separate *slot*; this information may include procedures for handling certain conditions or implementing certain actions called *methods.*

Semantic nets: Semantic nets are similar to frame-based systems, except that more complex inheritance relationships are possible. For example an object may be a member of more than one distinct class. Thus the entire knowledge-base looks more like a network than a tree.

Inferencing techniques: Forward chaining is an inferencing technique which, derives new assertions from those which already exist, with the goal of ultimately arriving at some particular desired assertion. In backward chaining, a solution is derived by working backward from some desired assertion and planning a path for deriving this assertion from the existing knowledge. The choice of forward chaining or backward chaining will depend upon which approach is expected to lead most directly to the desired derivation. Generate and test, is an approach in which a set of alternative solutions are proposed via some appropriate scheme and tested.

Three types of reasoning may be used, deduction, induction and abduction. Deduction derives correct conclusions from given assertions via the rules of predicate calculus. Induction is the process of generalizing from existing assertions to some new possibly correct conclusions; formal mathematical induction guarantees the correctness of its conclusions. Abduction is the process hypothesizing assertions when the conclusions are known.

Model based systems: Knowledge-based systems normally reason about the behavior of some ideal or actual underlying objects. As such they may be based on two different types of knowledge--*deep* knowledge, which comprises a comprehensive model of the underlying system, and *shallow* knowledge, which is a set of *ad hoc* observations or rules with no comprehensive model. Systems may utilize both types of knowledge simultaneously.

Blackboard systems: Blackboard architectures allow a number of large knowledge-based systems to communicate internally using a *blackboard*, or shared communication area.

Fuzzy logic: Fuzzy logic (Zadeh, 1988) and the related fuzzy set theory (Zadeh, 1965) deal with concepts that are inherently imprecise. Fuzzy logic deals with assertions which may have a degree of truth (e.g. a very tall man); fuzzy set theory deals sets in which objects may have a degree of member ship (e.g. the set of all tall men). The degree of truth or degree of membership is usually expressed as a number between 0 and 1 inclusive, however this weight should not be confused with a probability value. Fuzzy logic may also be used outside of knowledge-based systems.

Neural networks: Neural networks are constructed from a large number of processors interconnected in a layered network, which mimics the interconnections of human neurons. Neural networks transform input patterns to appropriate output patterns, and as such are particularly suited for pattern recognition tasks. Often they are able to correctly recognize inputs which are similar but not identical to their target patterns. The training of neural networks is accomplished by successively altering the weights of the processor interconnections until the desired patterns are correctly recognized. This training may either be *supervised* training, in which weight change at each step is based on the difference between the current and desired output patterns; or it may be *unsupervised* training, in which the desired target pattern is not used in computing weights. Neural networks, like fuzzy logic, may be employed with systems other than knowledge-based systems.

APPENDIX F

OVERVIEW OF ROBOTICS TECHNOLOGY

AVAILABLE TECHNOLOGY

Robotics systems consist of physical robot components such as manipulators (arm), end effectors (hand), and actuators (muscles). The controller subsystem (computer) ties together all these components. In addition the controller controls the motion of the actuators, receives and utilizes data from any sensor that the robot may use, and supports the programming interface and input/output devices as necessary. At first glance, the problem of controlling actuators to achieve a specific motion or at a higher level of abstraction to perform a particular task may seem to be a simple exercise in trajectory planning. This simplified view, however is not appropriate because:

- Translation of real-world requirements into the kind of motion that the robot can perform involves complex coordinate transformations and is not always simple,

- The kinematics, i.e, the pure motion of the manipulator as a function of time without the consideration of forces, torques, frictions and other possible mechanical errors is distinct and different from the dynamics, i.e., the actual geometry of the manipulator motion. In general the difference between kinematics and dynamics grows larger during the task execution and depends strongly on complexity of the task and the task environment - the domain of operation. The difference between the kinematics and dynamics behavior -- i.e. where the robot thinks it is vs. where it actually is-- belongs to an important category of uncertainty that the robots will have to deal with.

- Uncertainties of non-geometric origin can also arise during operations. For example in the execution of a non-trivial task the selection and sequencing of an appropriate branch of a decision tree used in a deliberate planning exercise may have to be based on inaccurate sensor data and as a result be ambiguous or require computation times which are too long to be of any practical use.

Based on what has been said so far we may conclude that the application of robotics technology is promising only under circumstances where the inherent uncertainties can be isolated and dealt with effectively. Present day industrial robotics is a good example. In such applications implicit programming and advanced planning are used in a structured environment where errors in the operations are small and well understood. The success of such applications is guaranteed by increased sensor and manipulator accuracy, by using high tolerance and familiar objects, and by supplying parts at predetermined positions and orientations. In order to go beyond this capability, the robotics research initiated in the early to mid-80s concentrated on systems which use sensor data to extract particular features of an environment, and match these features to a data base of objects to determine the location and the orientation of the objects. These systems proved to work well in structured environments or in somewhat uncertain environments populated by well known objects. Because of their limited capability to acquire and use sensor data however, they are severely limited in their ability to resolve ambiguities, to identify spurious information, and to detect failures.

To address these limitations an extensive research effort is currently underway at universities (e.g., University of Rochester, University of Michigan, Brown, Stanford/SRI, CMU, MIT), government (e.g., JPL, NIST, Oak Ridge, Sandia) and many industry organizations. The current research is geared towards both advanced teleoperations and autonomous operations through novel architectures which allow acquisition and use of mutisensor data streams. Development of higher level, and task level programming languages which buffer low level operations such as sensor interactions and manipulators movements from the users are also the subject of current research. At the highest level of abstraction there is a resurgence of research interest in integrated robotics, AI, and perception research towards the type of semi-autonomous or autonomous operations which may be desired for future lunar and Mars missions. In such a system the execution of a given task may start with a deliberate plan, but allow modifications based on real time decisions which may be necessary to effectively deal with an unexpected situation faced during the task execution. To perceive the environment at the level of detail necessary for resolving real-time ambiguities the robot system should be capable of dealing with a variety of sensor data streams intelligently and efficiently.

NASA EXPERIENCE AND TECHNOLOGY STATUS

Early in the Space Station program NASA in response to a request by the U.S. Congress performed an assessment of the applications of the automation and robotics technology in Space Station operation. This assessment was based on NASA's past experience with the technology -- e.g., Mars Viking Lander and RMS - as well as the results of the following five studies:

1. Autonomous system assembly by Martin Marietta
2. Subsystems and mission ground support by Hughes
3. Space manufacturing by General Electric
4. Satellite servicing by TRW
5. Operator system interface by Boeing.

A report entitled "An Independent Study of Automation and Robotics for the National Space Program" (Automation and Robotics Panel, 1985) summarized the results of these five studies and noted considerable potential for robotics technology in the areas of assembly, inspection, satellite servicing, and manufacturing. New advances needed to perform the projected activities were defined. Recommendations presented in this report for the IOC phase are the basis for early capabilities and functionality planned for the systems presently being developed by the U.S. (Flight Telerobotic Servicer, the FTS), and as part of the international Space Station program, the Canadians (Mobile Remote Manipulator System, the MRMS) and the Japanese programs. Other studies which have been assisting in projecting required functionalities, likely capabilities, and technology requirements are Smith et al., "The Space Station Assembly Phase: FTS Feasibility", (1987), and Drews, "Telerobotic and EVA Joint Analysis System, TEJAS", (1989). The Smith study provides an unique man-machine automation tradeoff methodology which reduces EVA tasks down to equivalent robotic tasks, derives required technologies and conceptual designs, and then assesses the net benefits of replacing/augmenting EVA tasks with a teleoperated or supervised autonomous robotic counterpart. The technique also assesses the risks associated with incorporating new technology. A related component of the overqall tradeoff scheme, TEJAS, allows one to rapidly prototype EVA assembly/servicing tasks, reduce them to robotic primitives, and perform productivity savings projections/trades through the use of a relational database. (1987)NASA's robot technology program is based on two parallel paths, development, space qualification and operational integration of teleoperated manipulators (FTS, RMS, and

MRMS), and an extensive research program focussed on developing progressively more autonomy into the operational capabilities of manipulators.

The FTS, and to a lesser extent the MRMS and the RMS, have or are being developed with features designed to facilitate the future incorporation of automatic and autonomous capabilities as they are developed and demonstrated in the research programs, i.e.,. all three arms are programmable and the FTS utilizes a flexible hierarchical control architecture.

A report describing FTS evolution requirements is currently available in draft form (GSFC, 1989). The study showed that improvement in the performance of three functions, (path planning, non-contact alignment, and contact planning and control) would maximize the performance of the FTS for its most frequently required tasks. The report provides trade-off maps for each of the three functions which suggest the task elements for which the substitution of automated programs in place of human control would be technically practical and possible in the relatively near term. The report also includes an appendix which provides an overview of the long-term path to the nearly fully autonomous FTS of the future.

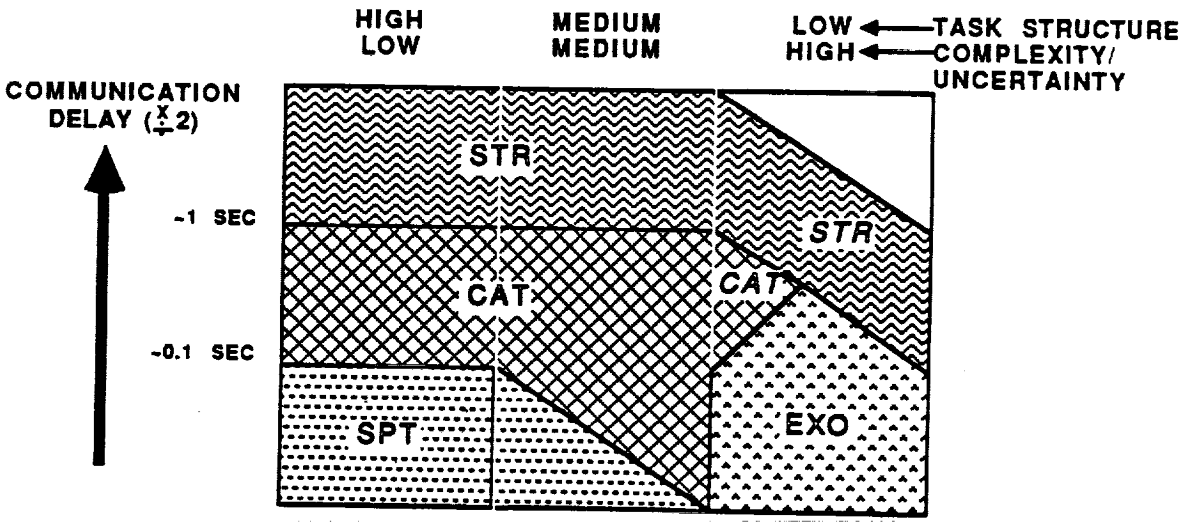
A current overview of the research path is presented in ADVANCES IN SPACE ROBOTICS (Varsi, 1989) a JPL study presented at the XXXXth congress of the IAF Oct 7-13, 1989. The report places the robotic research at JPL, other NASA laboratories and at universities in four categories:

- State of practice teleoperation (SPT)
- Anthropomorphic exoskeleton (EXO)
- Computer aided teleoperation (CAT)
- Supervised telerobotics (STR)

The figure below (Varsi, 1989) organizes these technical approaches to robot control into operational regimes defined by the communication delay required by the mission, and the relative complexity and uncertainty of the task structure. The chart indicates that pure teleoperation is limited to situations which have essentially no communication time delay operating in a highly structured environment with little task uncertainty and complexity. It also shows that both the CAT and the EXO control strategies are severely limited by the communication delay factor, leaving the future of missions with over one second time delay to the development of supervised telerobotic control systems which issue operator commands at an abstract task level. These operator commands would be implemented by automatic control functions, monitored and modified by local sensor information.

For the reason illustrated by the performance chart, the current robot research program is focused on developing the elements of a practical STR system, which Varsi (1989) notes requires two principal functions to be added to the hierarchical control structure of a telerobot:

- Machine vision subsystem to recalibrate or update the work-site information
- Task planning subsystem for sequencing macro-instructions and reasoning about the geometry of the work-site.



SPT = STATE OF PRACTICE TELEOPERATION

CAT = COMPUTER AIDED TELEOPERATION

EXO = ANTHROPOMORPHIC EXOSKELETON

STR = SUPERVISED TELEROBOTICS

Figure F-1. Control Technology for Space Robots

APPENDIX G

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APPENDIX I

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APPENDIX K

GLOSSARY

AALPS	Automated Air Load Planning System
AI	Artificial Intelligence
APEX	Automated Power Expert
APS	Astronaut Positioning System
A&R	Automation and Robotics
ARAMIS	Automation, Robotics, and Machine Intelligence Systems
ARC	Ames Research Center
ART	Automated Reasoning Tool
ATM	Apollo Telescope Mount
CAIT	Computer-Aided Instructional Trainer
CAP	Crew Activity Plan
CAT	Computer Aided Teleoperation
CMU	Carnegie-Mellon University
C&T	Communications and Tracking
DEC	Digital Equipment Corporation
DKC	Design Knowledge Capture
DMS	Data Management System
EVA	Extravehicular Activity
EDCO	Extended Duration Crew Operations
EPS	Electrical Power System
ES	Expert System
EXO	Anthropomorphic Exoskeleton
FCR	Flight Control Room
FDF	Flight Data File

FDIR	Fault Detection, Isolation, and Recovery used here to include Fault Diagnosis
FRAMES	Fault Recovery And Management Expert System
FTS	Flight Telerobotic Servicer
FY	Fiscal Year
GATES	Gate Assignment and Tracking System
GSFC	Goddard Space Flight Center
HQ	Headquarters
HDTV	High Definition Television
HST	Hubble Space Telescope
HSTORE	HST Operational Readiness Expert
ICAT	Intelligent Computer-Aided Training
ICE	Isolated and Confined Environments
IESP	INCO Expert System Project
INCO	Integrated Communications Officer
ITSSO	Intelligent Tutoring System for Satellite Operators
IVA	Intravehicular Activity
JEM	Japanese Experiment Module
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KBS	Knowledge-Based System
KEE	Knowledge Engineering Environment
KSC	Kennedy Space Center
LaRC	Langley Research Center
LeRC	Lewis Research Center
LES	Loads Enable Scheduler
LPLMS	Loads Priority List Management System
MALs	Malfunction Procedures

MCC	Mission Control Center
MIT	Massachusetts Institute of Technology
MOD	Mission Operations Directorate
MPSR	MultiPurpose Support Rooms
MRMS	Mobile Remote Manipulator System
MSD	Mission Support Directorate
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASREM	NASA/NBS Standard Reference Model
NICBES	Niceel-Cadmium Battery Expert System
NIST	National Institute Standards Technology
NRL	Naval Research Laboratory
OAST	Office of Aeronatics and Space Technology
OMS	Operations Management System
ORU	On-orbit Replacement Unit
OSF	Office of Space Flight
OSS	Office of Space Station
PAM/D	Payload Assist Module/Deploys
PC	Personal Computer
PI	Principal Investigator
PMAD	Power Management and Distribution
PMS	Platform Management System
POCC	Payload Operations Control Center
POIC	Payload Operations Integration Center
RALPH	Resource Allocation and Planning Helper
RMS	Remote Manipulator System
RTDS	Real-Time Data Systems

SHARP	Spacecraft Health Automated Reasoing Prototype
SIM	Simulation
SL	Spacelab
SLS	Spacelab Simulator
SMS	Shuttle Mission Simulator
SOC	Space Operations Center
SPDM	Special Purpose Dexterous Manipulator
SPT	State of Practice Teleoperation
SRI	Stanford Research Institute
SSC	Stennis Space Center
SSCC	Space Station Control Center
SSE	Software Support Environment
SSFP	Space Station Freedom Program
SSHPS	Space Station Human Productivity Study
SSM/PMAD	Space Station Module (hab/lab) PMAD
STR	Supervised Telerobotics
STS	Space Transportation System
TALOS	Telemetry Analysis Logic for Orbiting Spacecraft
TCS	Thermal Control System
TEXSYS	Thermal Expert System
THURIS	The Human Role in Space Study
TMIS	Technical Management Information System
U.S.	United States
VLSI	Very Large Scale Integration