NASA SPACE STATION AUTOMATION: AI-BASED TECHNOLOGY REVIEW

EXECUTIVE SUMMARY

March 1985 (Revised March 26, 1985)

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CONTENTS

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I INTRODUCTION AND SUMMARY

A Introduction

As part of the enabling legislation for the space station, Congress requested that NASA establish an Advanced Technology Advisory Committee (ATAC). ATAC was to identify promising automation and robotic technology for the space station, and make recommendations that would comprise an integral part of its definition and preliminary design contract. These recommendations were to be given to Congress by April 1, 1985. NASA established the Space Station Automation Study (SSAS) as a source of informed technical guidance for ATAC in the use of autonomous systems to implement space station functions. Such systems are expected to provide U.S. industry with vital automation capabilities.

The SSAS was conducted by a concept design team and a technology team. Each member of the concept design team examined particular topics relevant to the space station to determine how the required functions could be automated. The corporate members of that team and the topics they reported on were (1) TRW (satellite servicing), (2) GE (space manufacturing), (3) Hughes (subsystem autonomy), (4) Martin-Marietta (autonomous systems and assembly), and (5) Boeing (man-machine interface). The role of SRI, as the technology team, was to utilize the automation concepts postulated by the first four concept teams to determine what research and development would be required in artificial intelligence (AI) and computers to attain the capabilities implied by these concepts.*

The goals of the SRI study were (1) to provide guidance with respect to the state of the art in artificial-intelligence (AI)-based technologies; (2) review the results of the concept design contractors to determine the AI capabilities required by the designs, (3) delineate a series of demonstrations that would indicate the existence of these capabilities; and (4) develop a research-and-development plan leading to such demonstrations. As a separate issue, advanced techniques for the space station's information system were also to be investigated.

The methodology used in the SRI study consists of the following steps:

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*Our role was not to determine the optimal mix of man and machine in the space station This topic is covered in "The Human Role in Space, THURIS," a study by McDonnell Douglas Astronautics Company, MDC H1295, October 1984.

(1) Examine automation concepts prepared by the concept design contractors and determine needed automation capabilities.

(2) Derive sequences of demonstrations leading to the desired automation capabilities.

(3) Derive research and development plans leading to technology for carrying out these demonstrations.

We first reviewed the material provided by the concept design contractors and identified the implied automation capabilities required. After determining the latter, we then postulated a series of demonstrations that would verify the existence of these capabilities. Finally, for each of the AI-based technologies, the relevant research and development to carry out the demonstrations are indicated.

B.   Summary

The research and development projects in automation technology described in this report can yield the following essential advantages of crew safety, productivity, increased autonomy, and augmented capability that will ensure successful, maximally efficient operation of the space station. Many of the research projects also have extremely promising potential for innovative results that can be applied directly to terrestrial automation.

- Crew safety Increased astronaut safety through a reduced need for EVA, and the ability to deal safely with malfunctions that cause hazardous conditions in the vicinity of the failed equipment.

- Productivity Increased astronaut productivity through greater dexterity (compared with suit gloves), reduced space-suit maintenance and EVA overhead (prebreathing time, need for a backup crew member, etc.); less time spent by crew and mission specialists in performing routine housekeeping and station operation tasks such as monitoring, maintenance, and malfunction handling; and a smaller support team needed to provide services to "paying customers."

- Space station autonomy. Decreased cost of ground mission support and increased mission versatility.

- Augmented Capability. Telepresence systems, robots, and perhaps even robot supply tenders could be left in geosynchronous orbit for extended periods to service satellites. Such servicing could also be carried out by remote control from earth, relieving

4

the space station crew of control tasks. There will also be the ability to sense, identify, and correct malfunctions either instantly or very quickly. Even the fastest possible human response to onboard subsystem failure—e.g., requiring crew members going into EVA to prebreathe oxygen, get into a suit, egress, and move to the problem area—may be too time-consuming to cope effectively with serious emergencies.

While the purpose of this study was to propose demonstrations and R&D that would indicate the technology needed, we did not estimate the funding levels necessary However, in this respect, it should be noted that DARPA's Strategic Computing Program (SCP) commitment totals approximately $300 million over the next three years, and that the needs of space station automation identified by the concept contractors are at least equivalent to the tasks comprising the SCP. Thus, if NASA is to derive maximum benefit from space station automation, an investment of at least $100 million per year in research and development is certainly not unreasonable. In particular, if the space station is to serve as a driving force for industrial automation, it is essential that substantial funding be provided for research in advanced automation, especially robotics and artificial intelligence, rather than concentrating exclusively on more immediate engineering issues. We summarize here what is said regarding the need for NASA support for the various automation technology disciplines, taking into account research now being done under other auspices.

1. Teleoperation/Robotics

Although research in automation technology is being carried out by DARPA and other agencies, the special needs of space and the concomitant motivation for focusing on a different set of objectives are compelling NASA to initiate projects that are relevant to its purposes and that utilize the available resources and accumulated experience of the scientific community. Specifically, there are unique environmental problems (zero gravity, vacuum, etc.) not found on earth. In addition, for space telepresence equipment to evolve smoothly towards greater autonomy, it must be built with more quality than an industrial robot, yet also be very dexterous. The combining of these two criteria is something new. No equipment on the market meets both requirements very well, and certainly none has been designed from the standpoint of weight minimization and space qualification.

For the greatest possible effect on the progress of the space station, NASA research in telepresence carried out at the various NASA centers should be expanded and coordinated. In particular, intensive early research and development are needed on *telepresence*—with emphasis on slave equipment hardware, work station design, and related software. A sufficiently vigorous

effort would produce space-qualified equipment with useful levels of dexterity—and do so in time to meet the contractors' schedules for their automation concepts.

2. *Sensing*

NASA-sponsored sensor research should concentrate on research and development not included in the DARPA program, i.e., visual and tactile sensors leading to the transition from teleoperation to more automated operation of robot arms. A basic goal of the research should be to develop algorithms and techniques that will achieve automatic interpretation of complex objects under variable lighting conditions. Such a capability is essential for directing manipulator arms and effectors in the execution of a task. A CAD data base often plays a key role in making this kind of interpretation possible. Mobile robots should be able to determine their location by means of easily read fiducial points distributed throughout the space station. Finally, NASA should encourage the development of tactile sensors and algorithms for interpreting the tactile data, since it is specifically this capability that will be needed for sophisticated object manipulation.

3. *Expert Systems*

In examining space station applications, it is evident that a high return on research investment, in terms of safety and effective utilization of ground and spacecraft crew, is to be found in automation of the operation, maintenance and control of space station subsystems and manufacturing processes. The crucial characteristic of these applications is that the domain is dynamic—i.e., it involves reasoning about the effects of sequences of actions and tests that can change the state of the world over time. Moreover, because various subsystems will be operating simultaneously, it is important that the representation be sufficiently rich to enable reasoning about concurrency and subsystem interaction, and that efficient procedures for automatic scheduling and synchronization be developed.

Very little research is being done in this area. Consequently, without NASA support it is unlikely that the technology necessary for automating space station operations could be developed before the end of this century. Furthermore, most of the research issues that arise in representing and reasoning about these applications are also of critical importance in developing intelligent robots. Thus, through concentration on generic formalisms, schemes for representation and reasoning can be devised that would be eminently suitable for both areas of application. In addition, such generic research would produce major benefits for terrestrial applications, both military and civilian. Space qualification of new expert systems and reverification of existing ones when changes in other subsystems have been made are also important.

4   *Planning*

Planning in DARPA's SCP concentrates mainly on navigation issues and will have very little influence on the more general forms of task planning required for the space station   In particular, the navigation of robotic devices is radically different in the space station environment, requiring reasoning about a dynamic world cluttered with moving objects, rather than the planning of routes in a relatively static domain that consists of varied terrain, enemy positions, etc. General robotic tasks involving spatial/geometric reasoning (such as repairing a satellite) are somewhat related to the DARPA/Air Force Intelligent Task Automation projects, and there is some research of that type being done in industry.   It may be possible to adapt some of these results to the specialized requirements of NASA   There is no significant multiagent research being done in the DARPA projects, yet this topic is of critical relevance to many space station tasks in which multiple robots or persons are engaged.   Finally, there is very little in the DARPA projects that is concerned with planning to realize goals or perform tasks in nonnavigation activities—nothing, in fact, dealing with repair, construction, or material transfer, all of which are essential for such space station operations as satellite servicing, construction of assemblies, orbiting maneuvering vehicle operations, and transfer of fuels.

5.   *Computers*

Most automation in the space station will require the existence of a new generation of computers   An important impact will be exerted on computer technology by the SCP support in three broad areas: (1) signal processing, (2) symbolic processing, and (3) multi-function machines. The goal in signal processing is to build a system capable of executing one billion or more operations per second by 1986, and one trillion operations per second by 1990. The symbolic processor research and development is aimed at applications in vision, natural language, and expert systems. New optical recording techniques will provide multigigabyte, erasable storage.

Exploitation of such new technology and the need to meet the multiple requirements of the space station for computer reliability and performance will place considerable stress on current technology.   It will require architecture that allows rapid integration of new techniques in a way that preserves system integrity and satisfies ever-increasing requirements for performance.   The hostile natural environment necessitates a computer design of extraordinary reliability. An integrated model of system data, as well as new approaches to data management and retrieval, must be provided to deal with masses of data of different types.

The Space Station Information System (SSIS) application and operating-system software can currently be designed so as to evolve into more distributed-

processing configurations when they become feasible. These design techniques should be employed in the initial SSIS system. The greatest challenge will be to integrate these techniques with new ones that are emerging from current research, so as to achieve all of the required goals simultaneously. Thus, the SSIS requires new research approaches, new architectural techniques, and better computer system engineering. In our view, the computer research topics that will yield the most benefit are a unified hierarchical-distributed architecture, software engineering approaches that support higher levels of programming abstraction, an intelligent data system that supports a unified model of multitype data, the application of expert system techniques to system integrity, and hierarchical fault analysis and recovery.

6. *Man-Machine Interface*

The incorporation of techniques for automated, but human-supervised, control of large, complex, high-risk systems such as the space station is based on the rationale that this mode of control will provide greater efficiency and reliability than would be otherwise obtainable. However, research is needed on how to display integrated dynamic-system relationships in a way that is understandable and accessible to the human, and how best to allow the operator to tell the computer, in a flexible and natural manner, what is desired and why.

The operator's cognitive process must be aided by computer-based knowledge structures and planning models. Results of DARPA's natural-language and speech research should be utilized for more effective man-machine communication, particularly in situations such as EVA where voice input/output has very special advantages.

It will also be important to develop techniques for coordinating the efforts of the different people involved in supervising the same system. This research should be coordinated between NASA and the various DoD agencies, since all are faced with a similar problem.

C.   Conclusions

The challenge of space station automation will inspire advances in AI-based technology, acting as a spur to integrate and focus the combined efforts of diverse disciplines. These accomplishments will make the space station more effective and provide U.S. industry with vital automation skills for the future. Because the space environment brings with it problems not encountered on earth, and because the very survival of the crew depends upon the reliability of the space station, it is essential that NASA ensure its strong support of purposefully directed AI-based technology research.

II ANALYSIS OF TECHNOLOGY NEEDS

To obtain a clear picture of scheduling considerations and time constraints, we examined the SSAS contractor reports as well as other contractor documents dealing with space station automation. In our analysis of these sources, it became evident to us that the following applications are of particular interest (with the first two highest in priority):

(1) Satellite Servicing. The capability of servicing diverse satellites can result in substantial savings and greater scientific return because of extended life for many missions, such as the Gamma-Ray Observatory (GRO), the Space Telescope (ST), and the Space Infrared Telescope Facility (SIRTF). In addition, the research results can be transferred to terrestrial automation.

(2) Onboard Monitoring and Diagnosis. Monitoring-and-diagnosis systems will be required for the space station because of its complexity and anticipated evolution. Such systems would ease demands on the crew, freeing its members for other activities, and would reduce the need for ground operations support in this area. The technology developed would contribute to industrial applications on earth.

(3) Space Manufacturing. There will be a need for teleoperation/robotics dedicated to the task of maintaining space manufacturing equipment. Also necessary will be expert systems that can supervise quality control, operate the production system, and diagnose equipment failures.

(4) Assembly of Space Structures. Automated means of unloading and moving structural elements from the space shuttle will be required. Automation can also play a role in assembly of the structures.

The major AI-based subdisciplines for these applications are teleoperation/robotics for object manipulation; expert systems to aid in monitoring, diagnosis, and maintenance; automatic planning to schedule space station resources and determine which actions should be performed by autonomous robotic devices; a data management system; and man-machine interface. The contractors' consensus as to when some of this technology will be

needed is as follows·

Teleoperation/Robotics/Sensors

- <u>1990</u>. Telepresence with stereo vision and force reflection; an effective arm with a simple but fairly dexterous gripper.

- <u>1993</u> Same as above, but with a highly dexterous multifingered gripper, perhaps with its own force reflection capability.

- <u>1993-1995</u>. Telepresence with supervisory control capability. Able to computer-enhance sensory feedback for the operator and automatically execute simple "trained" procedures that might involve sensory guidance

- <u>2000-2005</u>. Autonomous robots with self-contained vision, planning, and control. Able to perceive and manipulate objects, and move about the space station to carry out the crew's orders.

Expert Systems

- <u>1991-1992</u> Monitoring-and-diagnosis systems for selected space station functions—capable of determining when trouble occurs, identifying the problem, and suggesting corrective actions.

- <u>1993-1995</u>. More complex monitoring-and-diagnosis systems that can deal with interactions among systems as well as with more subtle problems.

- <u>2000-2005</u> Space manufacturing system that is capable of quality/process control and maintenance of the equipment.

Planning

- <u>1993-1995</u> Planning routines capable of expanding an operator's high-level instructions into lower-level detailed actions for an adaptive robot to carry out

- <u>1995-2000</u>. Planning complex maintenance and repair operations for space station subsystems and manufacturing equipment.

- <u>2000-2005</u>. Planning for autonomous robots that can navigate from one location to another and work cooperatively with other robots

III DEVELOPING A RESEARCH AND DEVELOPMENT PLAN

Any NASA plan for research and development in automation technologies should take into account the relevant activities of other funding agencies. These are described briefly below, and are further discussed in the various AI topic areas.

DARPA's SCP is a major effort[*] that will provide significant research results in expert systems, computer vision, natural language, and advanced computer architectures.

DARPA's Engineering Applications Office is in the early stages of planning a new initiative with respect to modular, repairable robots, expert systems for automated repair, and design for easy repairability. The results of this effort could be very important to NASA, particularly for satellite servicing.

DARPA's Intelligent Task Automation (ITA) project, a joint industry-university research effort in cooperation with the U.S. Air Force, has the goal of reducing to a minimum the software effort needed to enable a robot to assemble and inspect a given product. Pertinent research includes 3-D vision, supported by CAD models of object shapes, and multisensory integration. The ITA project is directly relevant to the robotics aspect of space automation systems, as described in this report.

Various expert-system projects, relating to the maintenance of equipment or as aids to human decision-making, are being carried out by the Department of Defense (DoD). Other military research in automation is being conducted under the following auspices:

- *U.S. Army* Ground-mobile systems for handling large items, such as shells and fuel drums. There is little interest in dexterous manipulation for equipment repair.

- *U.S. Navy.* The development of autonomous underwater mobile systems is only somewhat applicable to space station robotics.

- *U.S. Air Force.* Manufacturing technology to reduce costs,

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[*] The plan provides for $50M in FY84, $95M in FY85, and $150M in FY86

including the Integrated Computer-Aided Manufacturing (ICAM) project, and ITA project in conjunction with DARPA. The most likely contribution to space station automation will be CAD-based fusion of visual and tactile sensory information.

Other sources of research include the following:

- *National Bureau of Standards (NBS)*. The NBS has a project that is comparable in scope to the U.S. Air Force's ICAM program.

- *National Science Foundation (NSF)*. The NSF funds basic research on many important core topics for automation, but cannot support projects at the level of effort needed by NASA.

- *University*. Universities have provided significant contributions to automation technology. However, their primary mission is to educate students -- a constantly fluctuating resource that makes it very difficult for academic institutions to carry out highly organized, tightly scheduled multiyear programs.

- *Commercial*. Commercial firms focus on immediate and generally low-technology solutions to their most urgent manufacturing problems, often applying innovative techniques developed previously at universities. Most of the larger corporations have recently established in-house research groups concentrating on advanced robotics and artificial intelligence. These will begin to bear fruit in the next two to five years; a few may even rival academic centers in performance. Nonetheless, because these technologies will be critical for its very survival, industry will jealously guard its proprietary interests.

In the following sections we discuss various automation technologies and their implications for the space station. We then describe the demonstrations that indicate the needed capabilities, the research and development required for them, and the timing of the demonstrations as well as of the R&D projects.

IV DESIGN FOR AUTOMATION

In designing for automation, one identifies and provides specific physical and functional accommodations* that must be included as part of the initial operational capability (IOC) of the space station. Their purpose is to simplify the operation, diagnosis, and repair of space station equipment, as well as to make it easier to automate these tasks. Another major consideration is to provide for increased *future* automation of the space station and, with this in mind, to avoid limiting NASA's options by unwise, premature design choices; flexibility and the potential for growth in power and scope are crucial factors. The key accommodations are for the computing requirements of expert and planning systems and for making the space station infrastructure and equipment compatible with and repairable by teleoperation/robotics.

A.   Accommodations for Expert and Planning Systems

We envision four types of computer systems as necessary to support the variety of expert and planning systems needed for the space station:

(1) Astronaut work stations with graphics that have both conventional- and symbolic-processor capability.

(2) Space-qualified symbolic processors connected via a network interface to system data bases.

(3) Space-qualified symbolic processors connected via high-speed interfaces to sensors, switches, and other essential monitoring and control points of equipment and subsystems.

(4) Portable symbolic-processing systems that require no interface with any subsystem or equipment.

Accommodation must be made for the first three systems by providing access to pertinent space station data bases and by requiring that subsystems make sensor and control points available.

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*Sometimes called "hooks" (software design features) and "scars" (hardware design features)

13

B   Accommodations for Automation

Setting up a design data base for all equipment on the space station (including automation equipment) is an important accommodation suggested by most of the contractors.   Thus, in developing space station systems and equipment, it is critically necessary that information about these systems be incorporated in a system data base. Such information should include CAD/CAM specifications, structural and functional descriptions, and as much design information as possible. Operating and maintenance procedures should also be in the data base, including annotations describing the purpose of every routine and of each step within each routine.

Other accommodational concepts fall into the categories of (1) design of the automation equipment itself and (2) design of other space station equipment:

Design of Automation Equipment

- Modular, self-repairable manipulators, capable of being assembled manually, automatically, or by teleoperation to create different sizes and configurations of arms to serve different purposes.

- Redundant components in the rotating joints of manipulators for greater reliability, to deal with the problem that rotating joints are inherently unreliable in space.

- Digital communication networks with excess capacity connecting space station equipment with computers that also have excess capacity

- A family of general-purpose equipment connectors (GPEC) in different sizes that would provide sturdy mechanical attachment and support, power, and access to the space station data network. These could not only be distributed over the space station's structure, but could also be built into onboard equipment.

Design of Other Space Station Equipment

- Intrinsic GPECs to connect to the space station and other equipment.

- Simple hard points or holes that teleoperator/robotic equipment could grasp to stabilize itself with respect to a satellite or a work area on the space station. They could also be used as "footholds" for walking along a space structure

- Design for easy location, identification, handling, and servicing by imprecise automation equipment operating in zero gravity.

C.   Demonstrations

The Space Operations Mechanism Testbed at the NASA Marshall Space Flight Center (MSFC) will have a pivotal role in matching the appropriate technology with evolving space station requirements, and evaluating alternative mechanisms in an integrated manner. The following demonstrations indicate a capability of designing equipment so that it can be handled and repaired by automated devices:

- A data base organization that can be expanded to handle information that may be necessary for future space station operation, including information about the organization, contents, and access methods of the data base itself.

- A prototype data base that can describe the structure, method of operation, and maintenance procedures for (1) simple mechanisms constructed mainly from rigid parts, (2) electronic equipment, (3) complex electromechanical-hydraulic equipment, and (4) space station subsystems.

- A methodology for verifying that a piece of equipment can be serviced and repaired successfully by astronauts in EVA, by teleoperation, and by robots.

- A family of mutually compatible, space-qualified, general-purpose, modular sensors, effectors, controls, and connective elements for the rapid construction of specialized devices, including teleoperators and robots, by other teleoperators and robots, or by humans.

V TELEOPERATION AND ROBOTICS

Teleoperation and robotics reflect a broad spectrum of important automation concepts for the space station—from very low to very high levels of autonomy.

- *Teleoperation (TO)* is remote manual control of equipment that is capable of sensing, manipulation, and/or mobility.

- *Telepresence (TP)* is teleoperation in which feedback of visual, tactile, auditory, or other sensory information from the remote work site gives the operator illusion of being there, so that better, more precise control can be exercised.*

- *Supervisory control (SC)* or *augmented teleoperation (AT)* is a mixture of manual and automatic control modes. As the amount of automatic control increases, it begins to approximate adaptive robotics.

- *Adaptive robotics (AR)* is full automatic control of the equipment by a computer in accordance with a program that makes it react in predetermined ways to data from sensors that report external conditions

- *Intelligent robotics (IR)* is adaptive robotics in which AI-based reasoning and planning programs develop the detailed control steps, either to carry out high-level instructions from people or to respond creatively to unforseen conditions and events during a mission.

Space station automation for servicing, manufacturing, and construction tasks should evolve in the direction of increasing autonomy. It should start at the telepresence level, rather than teleoperation, because modern microprocessor technology can provide a great deal of additional function for a very small weight

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* In this report, we assume that NASA will want to take advantage of the benefits of advanced telepresence methods wherever practical Therefore, we use the latter term in place of teleoperation or teleoperation/telepresence to encourage the reader to think about space station automation in the manner thereby suggested.

17

penalty. It should evolve from telepresence through supervisory control and adaptive robotics to the long-term goal of intelligent robots.

The intelligent-robot stage of evolution will probably take place in two steps. Initially, AI software will generate robot control programs for "unintelligent" adaptive robots to execute. This would be an "off-line" process that would at first probably involve close interaction with a person through a sophisticated workstation environment. Later, a more closely coupled mode will develop in which AI software, perhaps on board, operates the robot(s) directly, interacting only minimally with people to obtain task assignments. For the sake of simplicity, we do not distinguish between these two steps in this report.

Simulation of teleoperator and robot activity will play an important role in most stages of this evolution. It will first be used to make remote control easier in the presence of moderate (e.g., one-second) communication delays between master controller and slave arm, caused by both buffer accumulation delays and distance. For example, as an operator moves the master control of a manipulator, a computer will display a synthesized picture of the arm moving in response and without delay. This *predictive display* will allow the operator to move the arm more smoothly and rapidly, without waiting for television images to arrive from the remote equipment. When an operator is steering a mobile robot remotely, the predictive display might show the path that the robot will travel during the round-trip communication delay time. The same simulation technology will also be useful later in advanced work stations needed for ground and space station crew programming of adaptive robots and other automation systems. The crew will not require extensive training in formal computer programming languages, but will operate a simulation of the robot or other automation system to illustrate the procedure to be carried out. Finally, the ability to simulate the activity of a robot performing a task will be absolutely vital for automatic planning of robot activity by artificial-intelligence techniques. The simulation will allow the planning program to evaluate different action sequences to find a feasible or even optimal procedure for accomplishing a task.

A.   Space Station Applications

The most important initial motivation for teleoperation/robotics automation is to enhance *crew safety* by reducing the need for extravehicular activities (EVA). Another motivation is to increase *capability* by making possible some activities that are now impractical because of long communication delays encountered when servicing satellites in lunar, planetary, and solar orbits. A third motivation is to improve the *productivity* of ground and space station personnel. Such automation will improve productivity by eliminating the overhead costs in each EVA that is avoided, thus reducing the need for constant

operator attention in remote operations and decreasing astronaut fatigue by replacing muscles with machinery.

Fully automatic adaptive and intelligent robots will increase capabilities still further. They will enable continuous construction and repair where communication paths have execessive delays, are too intermittent, or are unavailable to support supervisory control—e.g., in polar, lunar, and planetary orbits. They will also increase productivity, since one person on the ground or on the space station can direct and supervise many robots working simultaneously on different tasks.

The concepts developed by the contractors are concerned with automating the following space station activities:

- *Manufacturing in Space (GE)*. Use of dexterous manipulators to transfer semiconductor material between automatic-fabrication stations for the production of gallium arsenide (GaAs) integrated circuits; periodic servicing of production equipment (e.g., cleaning, replenishment of consumables); periodic rebuilding of crystal-growing furnaces.

- *Satellite Servicing (TRW)*. Use of dexterous manipulators for routine servicing of satellites, such as exchanging orbital replaceable units (ORU) and refueling, as well as more difficult "Solar Max"-type repairs.

- *Construction of Large Structures in Space (Martin-Marietta)*. Use of "crane" manipulators like the orbiter's remote manipulator system (RMS) to unstow modular elements (e.g., beams), and to help astronauts in EVA assemble them into structures; use of such devices to transport astronauts around a structure in "cherry picker" mode.

The first two automation concepts, manufacturing and satellite service, require the most advanced equipment and control because they involve the precise manipulation of small objects.

B.   Research Funding

DARPA is not interested in teleoperation or the special problems posed by a zero-gravity environment; its principal emphasis is on the development of aids to human decision-making and on automatic navigation for autonomous land-mobile robots. The DARPA Autonomous Land Vehicle (ALV) project encompasses a considerable amount of vision research dealing with terrestrial scenes, particularly

roads.

NASA research in telepresence, which is being supported at Office of Aeronautics and Space Technology (OAST) and carried out at the various NASA centers, must be expanded and coordinated if it is to have an impact on the space station. Intensive early research-and-development work on *telepresence* is imperative—in particular, on slave equipment hardware, work station design, and support software. A vigorous effort is necessary to provide space-qualified equipment with useful dexterity in time to be "in sync" with the contractors' schedules for implementing their automation concepts. Furthermore, any shortfalls are likely to delay NASA in attaining the high-payoff robotic capabilities that are its ultimate objective. Note that, in most of the research programs described below, we propose a set of early across-the-board "benchmark" demonstrations for approximately 1987. These demonstrations would have the following purposes: (1) to make sure that the most advanced automation technologies available are identified so they can be adapted to IOC; (2) to educate the space station community in general about these new technologies; (3) to obtain an accurate picture regarding deficiencies in performance of the various technologies, so that NASA and Congress can best direct available resources to research-and-development programs planned for 1988-1995.

C.   Demonstrations

Certain demonstrations should be conducted, either separately or in combination, to show that the contractor's telepresence and robotic concepts are feasible. Some could be performed first on the ground, later in the orbiter bay, still later in "cherry picker" mode on the end of the RMS, and finally by a free flyer. Most concepts can be adequately demonstrated initially in a 1-G environment. A few require simulated weightlessness, as provided by a neutral-buoyancy tank such as the one at MSFC. A "frictionless" flat floor with air bearings, such as those at MSFC, Stanford, and other research centers, could also be used for some demonstrations. In all cases, proof of concept will require a demonstration in actual orbit for proper testing under conditions of weightlessness and, where appropriate, in a vacuum. The planned NASA facility Space Missions for Automation and Robotic Technologies (SMART), for example, could support many of these orbital demonstrations.[*]

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[*] SMART is a multiflight shuttle and space station automation/robotics test facility for the evaluation of advanced robotics, automation, telepresence techniques, and real-time operational concepts. The facility, which can be carried in either the shuttle or the space station, will validate robotic and automation applications

The demonstrations will exhibit increasing degrees of autonomy. For example, such a progression should include (1) simple telepresence; (2) telepresence interspersed with automatic control for routine portions of a task, so as to reduce operator fatigue or accelerate performance; (3) adaptive robotics, using preprogrammed, sensor-controlled actions; and (4) "intelligent" robotics, using automatic planning and expert systems to decide how best to carry out crew requests. The simplest of these methods, telepresence, would be sufficient to demonstrate the feasibility of applying the contractors' concepts to IOC. Higher levels of autonomy could be demonstrated later as the enabling technologies mature.

Mobility will be an important capability for many automation systems. The most important modes of locomotion for use on the space station include rail transport, crawling, and free flight. Rail transport is simple and need not expend consumables, but the rails add weight in proportion to the size of the space station, can become blocked, and allow only limited motion. Crawling need not expend consumables, carries a constant weight penalty for any size station, and allows free motion over the surface and within structures, but requires relatively complicated equipment Free flight carries a constant weight penalty and allows the most freedom of motion, but has the disadvantages of moderately complicated equipment, fuel and reaction mass consumption, and possible plume impingement problems. Free flight will be necessary for capturing satellites, servicing co-orbiting platforms, and inspecting large, delicate tension structures such as mesh antennas. For free flight within pressurized station modules, aerodynamic propulsion methods (e.g., ducted fans) are possible.

We suggest the following set of mission-specific demonstrations They are listed in an approximate order of increasing difficulty within each group

Manipulator Repair

- This demonstration should be done by astronauts in EVA, as well as by telepresence or other automated methods; its purpose would be to show that people are capable of repairing automation equipment in an emergency.

Satellite Servicing

- Exchange orbital-replaceable modules in a satellite.

- Mate and uncouple representative connectors used on spacecraft.

- Operate simple mechanisms (e.g., latches, cranks, slides, control handles).

- Transfer fluids to and from a satellite (cryogens might be featured in a separate demonstration of this type).

- Remove and install typical fasteners used on satellites (e.g., screws, bolts, nuts, clips).

- Handle nonrigid satellite materials (e.g., insulation blankets, foils, fabric, wires, hoses, springs, seals).

- Rigidly attach a telepresence/robotic system to a work area on the space station (from which the system might work on a docked satellite).

- Rigidly attach a telepresence/robotic system to a free-flying but nonrotating satellite.

- Dock with, grapple, and despin a free-flying satellite.

Manufacturing of GaAs Integrated Circuits

- Transfer wafer carriers between units of automatic fabrication equipment

- Service fabrication equipment

- Rebuild the crystal-growing furnace.

Orbital Construction of Large Structures in Space*

- Move along the surface of a structure being constructed. Initially simple rail or cable transport mechanisms would suffice. Free flyers and/or crawlers could be introduced later.

- Unstow structural members and convey to EVA astronauts

- Join structural members with special mechanical connectors

- Install equipment on structure (e.g., cables, lights, docking rings).

Some of these demonstrations will require progress in "conventional" technologies such as process control, as well as robotics or artificial intelligence.

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*Construction demonstrations would necessarily involve small but representative subsections of actual structures

For example, to transfer cryogens automatically, NASA will need zero-gravity instrumentation that can measure the quantity transferred. None exists at present. One could probably identify hundreds of similar gaps that must be filled for the space station. However, they lie outside the scope of this report, and we have assumed that the needed technology will be available at the proper time.

Figure 1 lists a schedule for demonstrating those foregoing activities that would concur with the automation schedules proposed by the contractors.

D. Research and Development

Most of these early demonstrations would probably have to take place on the ground, even though the later demonstrations of mature technologies may be conducted in orbit. Some demonstrations would also necessarily be rather rudimentary, because the particular technology they feature will still be at a very early stage of development over the next several years. The research projects[*] are grouped into (1) ground-based telepresence experiments, (2) telepresence in orbit, (3) supervisory control in orbit, (4) adaptive robotics in orbit, and (5) intelligent robotics in orbit. The goals of these projects are given below; L indicates the availability of results from laboratory demonstrations, while R indicates readiness to be incorporated into fully operational systems:

(1) Ground-based Telepresence Experiments, L=1986

- *High-Quality Force-Reflecting Manipulators.* A pair of teleoperated arms with force reflection.

- *Simple Force-Reflecting Gripper.* A simple parallel-jawed gripper of appropriate size and sensitivity.

- *Prototype Master Controls.* Controls for both slave arms and hands.

- *High-Quality Visual Feedback.* Probably color, stereo, high-resolution television.

(2) Telepresence in Orbit

- *Space-Qualified Slave Equipment, L=1989.* Mainly the manipulators, sensors, and transportation devices for use outside the spacecraft, together with any associated electronics.

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[*] Sensing is treated separately in Chapter VI below.

V TELEOPERATION AND ROBOTICS

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Ground:   D --- "Dry lab"     Orbit:   E --- EVA
          N --- Neutral-               T --- Telepresence
                buoyancy               S --- Supervisory control
                tank                   A --- Adaptive robotics
                                       X --- Intelligent robotics


                                    |   |   |   |   |   |
Manipulator repair  ..................|..N.|...T|S.A.X....|....|..
                                    |   |   |   |   |   |
SATELLITE SERVICING                 |   |   |   |   |   |
                                    |   |   |   |   |   |
Modules, connectors; mechanisms  .....|D.T.S.A..|....X....|....|
                                    |   |   |   |   |   |
Fluid transfer; fasteners; nonrigid ..|.D..T.S.A|....X....|....|..
                                    |   |   |   |   |   |
Attach to despun satellite ...........|.N..|.T..|S.A.X....|....|..
                                    |   |   |   |   |   |
Attach to space station  .............|.N..|....|T.S.A.X..|....|..
                                    |   |   |   |   |   |
Despin and dock with satellite  ......|....N...T|..S.A.X..|....|..
                                    |   |   |   |   |   |
GaAs IC MANUFACTURING               |   |   |   |   |   |
                                    |   |   |   |   |   |
Transfer product  ....................|.D..|....|T.S.A....|X...|..
                                    |   |   |   |   |   |
Service equipment  ...................|.D..|....|T.S.A....|X...|..
                                    |   |   |   |   |   |
Rebuild furnace  .....................|.D..|....|T...S.A..|X...|..
                                    |   |   |   |   |   |
ORBITAL CONSTRUCTION                |   |   |   |   |   |
                                    |   |   |   |   |   |
Mobility .............................|.N..T S..|A...X....|....|..
                                    |   |   |   |   |   |
Unstow and present  ..................|.N..|.T.S|..A.X....|.. .|..
                                    |   |   |   |   |   |
Join members  ........................|.N..|...T|S.A.X....|....|..
                                    |   |   |   |   |   |
Install equipment  ...................|...N|...T|..S.A.X..|....|..
                                    |   |   |   |   |   |
                         YEARS  85   90   95   00   05   10
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Figure 1: Schedule of Mission-Specific TP/Robotics Demonstrations

- *Master Controllers for Use in Space, L=1989.* Mainly the telepresence master controls, displays, and associated electronics for use within space station modules.

- *Stable Dynamics, L=1989.* Servo-control algorithms for manipulators on resilient mountings.

- *Dexterous Gripper, L=1986, R=1992.* Probably a gripper with several many-jointed fingers, similar to the human hand.

- *Gripper Master Control, L=1986, R=1994.* A device that allows intuitive control of the dexterous slave gripper.

- *Helmet Display, L=1986, R=1994.* A light, compact heads-up display suitable for use in or on a space suit helmet.

(3) Supervisory Control

- *Voice Interaction, L=1986, R=1990.* Simple voice-input equipment for controlling equipment and asking for information.

- *Procedural Programming, L=1986, R=1992.* "Training" of simple automatic procedures by means of a combination of telepresence master control actions, voice input, graphic interaction, or other "intuitive" methods

- *Kinesthetic Cueing, L=1986, R=1992.* Simulation of external forces acting on the slave manipulators to help an operator move and position the arms more accurately.

- *Coordinate Transformations, L=1986, R=1992.* The computer solves kinematic equations rapidly in real time to map motions and forces between the master and slave reference frames.

- *Computer-Augmented Displays, L=1986, R=1995* Television displays of the work area augmented by computer-generated graphics or image processing to facilitate human operation of the equipment.

(4) Adaptive Robotics

- *CAD-based Visual Perception, L=1986, R=1990.* Use of three-dimensional CAD models to aid in location, identification, and inspection of sensed objects.

- *Tactile Arrays, L=1986, R=1990.* High-resolution arrays of pressure sensors, suitable for use on the fingertips of manipulator hands.

- *CAD-based Tactile Perception, L=1986, R=1990.* Same as CAD-based visual perception, but for tactile array and force reflection data.

- *Textual Programming Method, L=1986, R=1990.* A method for describing complex teleoperator procedures.

- *CAD Work Area Data Base, L=1986, R=1990.* A three-dimensional geometric model of space station equipment, based on an unambiguous solid modeling technique such as constructive solid geometry.

- *Multisensory Integration, L=1986, R=1992.* Integration of information from visual, tactile, navigation, and other sensors.

(5) Intelligent Robotics

- Intelligent robotics will require substantial research in sensory interpretation, expert systems, and automatic planning These topics are discussed in Chapters VI-VIII.

VI SENSING

We discuss here sensing related to teleoperation and robotics. The sensing process in this case consists of converting the relevant object properties into a signal, then transforming this signal into the information required to plan and execute a robotic function. Processing is often divided into *preprocessing* (improving the signal) and *interpreting* (analyzing the improved signal and extracting the required information). Various sensing modes—visual, tactile, acoustic, etc.— can be employed to suit different situations, and information from different sensors can be combined for a more comprehensive situational assessment. Some model of the operating environment and its relation to the sensor is necessary for any evaluative analysis. The more autonomous a robotic system is, the more difficult the assessments it must make and the more elaborate the models it requires.

A.   Space Station Applications

The performance of servicing, construction, and manufacturing tasks by teleoperation in the same or less time than is possible by EVA presupposes a high degree of dexterity that can be achieved only with good visual and tactile sensing. The same sensory inputs will be needed in the autonomous mode to operate robot arms with equal dexterity. Machine vision will be easiest to apply in those space station activities in which the appearance of the work area is highly predictable. For example, it would probably be easy to guide the RMS grapple automatically to mate with a standard NASA docking probe, since the probe has a target designed to indicate any misalignment visually. A complex, cluttered environment such as an orbital construction site, however, would pose many still unresolved problems in computer image "understanding."

Force reflection from the manipulator hand to a teleoperator master control is one kind of tactile sensing that increases the operator's dexterity. The same information will be needed by a computer to make the gripper exert the forces and torques required for a task, and to ensure its proper compliance in response to external stimuli so that it will operate mechanisms and assemble components without jamming. To handle small parts well, both teleoperation and robotic systems will have to sense not only that they are holding them, but also just where a part is in the fingers, how it is oriented, and (to identify it) what shape and size it is. To do this, we shall need small "fingertip" sensors that can measure pressure distributions with high spatial resolution over a planar region extending about one inch on either side. Simple proximity sensing (an elementary

27

kind of range sensing) will also be useful—mainly to help avoid collisions between manipulators and other objects, but also to locate objects where vision or tactile sensing is impractical.

B   Research Funding

The Autonomous Land Vehicle (ALV) program of the DARPA SCP has a strong vision component. The functional objectives for the vision system are to model and recognize terrain and objects, to recognize and match landmarks with maps, and eventually to carry out reconnaissance in a dynamically changing environment. The most significant technology resulting from this effort will be generic scene-understanding capability, plus the integration of sensors and automatic planning systems. However, the results in this area may not be entirely applicable to NASA's space environment problems because the ALV requires *passive* sensing methods, while the space station can (and should) use *active* sensing, special markings, and reflectors to simplify interpretation.

If the results of the vision research supported by DARPA's ALV program are made available, they could of course be utilized in NASA's sensor demonstrations We have therefore concentrated on research and development that are not part of the DARPA program—namely visual and tactile sensors that represent a transitional technology from teleoperation to more automated operation of robot arms A basic goal of the research is to develop algorithms and techniques that will make possible the automatic understanding of complex objects under variable lighting conditions. Such a capability is essential for directing manipulator arms and effectors in the execution of a task. A CAD data base often plays a key role in achieving this level of understanding.

C.   Research and Development

The chronology of sensor research and development given below is based on the teleoperation/robotics demonstrations described in Chapter V. The following research topics require NASA funding; the dates signify when results are expected to be required

- Incorporation of model-based visual analysis, requiring integration of the visual-analysis system with a three-dimensional CAD data base (1987).

- Force and torque sensing (1988).

- Proximity sensing (e g , using capacitance, dielectric phenomena, structured light, or—in pressurized areas—acoustic effects) (1988).

- Tactile sensing involving the development of sensors and analysis of sensor signals (1989).

- Analysis of visual and range data for rapid "understanding" of three-dimensional objects (1989).

- Integration of visual, tactile, and range sensors of the same, or mixed, modality (1992).

VII EXPERT SYSTEMS

VII EXPERT SYSTEMS

The term *expert systems* was originally used to denote systems that utilize a significant amount of expert information about a particular domain to solve problems in that domain. Because of the important role of knowledge in such systems, they have also been called *knowledge-based* systems. However, the first term has since been applied to so many diverse systems that its original meaning has been largely lost. There are essentially two uses of the term that need to be differentiated.

First, the term is often used to describe any system constructed with special kinds of "expert system" programming languages and tools. Development of such languages is better regarded as an area of programming methodology or software engineering and, indeed, has made a significant contribution to these fields. However, it is very important to realize that such languages can be used for a variety of programming tasks apart from the construction of systems that emulate expert reasoning Consequently, it is misleading to call any system developed in this manner an "expert system." Nevertheless, influenced by the considerable weight of accepted usage, we shall continue to call such languages (together with their supporting environments) "expert-system programming tools."

The second use of the term "expert systems" is to denote systems that "reason" about a problem in much the same way humans do. Some of the features distinguishing these systems from standard application programs are the following:

(1) Each contains a data base of knowledge represented in a relatively natural form that allows some sort of reasoning to be carried out. The knowledge representations are usually symbolic, reflecting the qualitative nature of much human reasoning

(2) The representation of knowledge is such that changes to the knowledge base do not require extensive system modifications. Thus, the systems are extensible, degrade "gracefully" rather than catastrophically as elements are removed, and can evolve without extensive rewriting. Such evolutionary capability is essential for space station automation

(3) The systems are often highly reactive—that is, the choice of

31

actions to be performed next depends primarily on the current situation, rather than on the fixed control structure. This is particularly important for space station applications, as the software systems must be flexible enough to respond rapidly to environmental changes.

(4) Many systems can retrace the reasoning sequence employed and explain what was done at each step and why. This explanatory capability enables the user to accept or reject the system's conclusions if he disagrees with its reasoning.

(5) Many of these systems can apply their reasoning processes to incomplete, uncertain, or inaccurate data.

Expert systems have been highly productive in a large number of areas, including design, interpretation and diagnosis, prediction and induction, and monitoring and control. However, any premature enthusiasm over the apparent success of these systems needs to be tempered by the following observations.

First, very few such systems have been developed beyond the experimental testing stage. Although such testing is essential in establishing the soundness of the basic design, there can still arise serious technical problems in getting the system to work in a real environment.

Second, most of the expert systems developed to date cannot easily be generalized to handle problem domains other than the ones they were specifically designed for. In other words, they are application programs that were designed and constructed for one particular application.

Third, the kinds of knowledge that existing systems can represent are particularly simple. This does not mean that the systems are not useful, but it does mean that the application of expert systems to more complex domains will require a significant amount of research in knowledge representation.

While the available expert system programming tools are well suited to developing expert systems that require relatively simple knowledge representations, it is not at all clear that they are useful in handling the more powerful and expressive knowledge formalisms needed for more complex problem domains. Indeed, they can actually hinder development in these areas. It is usually better to build the more complex formalisms upon a more basic programming language, such as LISP or Prolog.

A   Space Station Applications

Some application areas of expert systems in the space station are:

- <u>Maintenance and Repair</u>. Expert systems are important in manufacturing and satellite servicing for carrying out routine tests, noting possible deviance, and flagging abnormal transient operation before a hard failure occurs. In addition, expert systems will be needed to isolate and diagnose faults, as well as to indicate methods of handling malfunctions.

- <u>Expert Process Controller</u>. In manufacturing, expert systems are required for quality assurance (interpreting process deficiencies), process control (suggesting processing corrections to attain better results), and equipment maintenance (isolating equipment faults and initiating corrective action).

- <u>Subsystem Monitoring and Control</u>. Expert systems can be applied to subsystems, such as the power subsystem, to monitor and control complex operations and make difficult decisions. Maintenance of life support systems, operation and servicing of experiments, onboard mission control, and automation of traffic control could also be handled by expert systems.

- <u>Intelligent Autonomous Robots</u>. An expert system could guide the scheduling of the construction and assembly of large space structures, the servicing of satellites, deployment of payloads, OMV/OTV operations, and the transfer of cryogenic fluids. Eventually, as effector and perception capabilities are developed, these processes could be automated and handled in their entirety by autonomous robots

- <u>Astronaut's Associate</u> An expert system could act as an astronaut advisor to aid in the use of a complex program or complicated item of equipment. The advisor could suggest parameter values, the meaning of certain system responses, and sequences of control actions.

In many of these areas, there will be some subclasses of problem that can be solved by constructing simple expert systems that use relatively elementary knowledge representation schemes. Commercially available expert system programming tools may be adequate for creating such systems, while the deeper problems of some applications would at least be indicated as targets for further resolution. Furthermore, there are some applications, such as monitoring and

control, for which current tools could be used advantageously, even though the resulting systems might not reflect any expert reasoning at all or provide any useful explanatory capabilities

However, by far the most important means of enabling automation of space station applications is to pursue a well-focused research plan for investigating the critical issues involved in knowledge representation and reasoning. Unless this is done, it is difficult to see any possibility of automating space station functions; furthermore, expert systems will find useful application only in a few relatively simple tasks

B   Research Funding

The DARPA SCP will have a major influence on expert system development. DARPA believes that the most time-consuming portion of the process of constructing an expert system is the expert's articulation of his knowledge, and its subsequent satisfactory formulation in a suitable knowledge-representation language.   The SCP therefore places particular emphasis on knowledge acquisition and representation

The Pilot's Associate portion of the DARPA SCP program also will contribute to the development of expert systems. The Pilot's Associate would use an extensive knowledge base of information concerning such items as aircraft systems, tactics and strategy, and navigation. The three aspects of this project that could be relevant to the space station are the interface with the pilot, the organization of multiple interacting expert systems and knowledge bases, and the high-speed processors used to support these.

There is a great deal of industrial activity in the development of expert systems for practical use. In addition, several NASA centers have developed such expert systems for dealing with pressure control and environmental control system malfunctions, and electric power distribution. Most of these applications utilize the results of expert systems research conducted at universities during the past decade.

Our examination of space station applications has made it evident to us that the highest return on research investment is to be found in automation of the operation, maintenance and control of space station subsystems and manufacturing processes. The crucial characteristic of these applications is that the domain is dynamic—i.e., it involves reasoning about the effects of sequences of actions and tests that can change the state of the world. Moreover, because various subsystems will be operating simultaneously, it is important that the representation be sufficiently rich to enable reasoning about concurrency and

subsystem interaction, and that efficient procedures for automatic scheduling and synchronization be developed.

Very little research is being done in this area. Consequently, without NASA support it is unlikely that the technology necessary for automating space station operations could be developed before the end of this century. Furthermore, most of the research issues that arise in representing and reasoning about these applications are also of critical importance in developing intelligent robots. Thus, through concentration on generic formalisms, schemes for representation and reasoning can be devised that would be eminently suitable for both areas of application. In addition, such generic research would produce major benefits for terrestrial applications, both military and civilian.

As discussed elsewhere in this report, it is important that the space station systems possess the potential for evolutionary growth. To achieve this, as well as to satisfy the real-time requirements of operating and control systems, a distributed architecture containing multiple expert systems must be employed. Since no existing expert system can meet these needs, considerable research will be needed to solve the related technical and theoretical problems.

Researchers developing symbolic processors can benefit from DARPA's research effort, adapting any useful results to the needs of the space station. Reasoning about uncertainty, a common feature of many current expert systems, plays a relatively small part in most space station applications. Work in this area, therefore, can be left principally to DARPA and industry. On the other hand, research on qualitative reasoning and on knowledge formalisms that are capable of representing structure, function and mechanism will be vital to the long-term needs of space station automation. But this more essential research can be deferred until later in the program, thus enabling it to benefit also from similar work being conducted by DARPA.

C.   Demonstrations

The following demonstrations would verify that the necessary capabilities are available; the proposed schedule is given in Figure 1. These demonstrations can start with ground simulations; they would next proceed to actual implementation—first on the shuttle, then on the space station itself.

Near-term (1985-1992)

- Information retrieval from a data base that describes the structure and functionality of major systems in formal or semiformal language.

35

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Demonstrate data base of structures....|.X..|....|....|....|....|....|
                                        |    |    |    |    |    |    |
Demonstrate data base of procedures....|.X..|....|....|....|....|....|
                                        |    |    |    |    |    |    |
Fault isolation of single subsystem....|...X.|....|....|....|....|....|
                                        |    |    |    |    |    |    |
Fault isolation using                   |    |    |    |    |    |    |
   distributed expert system............|...X|....|....|....|....|....|
                                        |    |    |    |    |    |    |
Fault isolation of multiple             |    |    |    |    |    |    |
   interacting subsystems...............|....|X...|....|....|....|....|
                                        |    |    |    |    |    |    |
Real-time fault isolation...............|....|.X..|....|....|....|....|
                                        |    |    |    |    |    |    |
Control of single manufacturing         |    |    |    |    |    |    |
   process or experiment................|....|X...|....|....|....|....|
                                        |    |    |    |    |    |    |
Space-borne processor...................|...X|....|....|....|....|....|
                                        |    |    |    |    |    |    |
Operation of subsystem when substeps    |    |    |    |    |    |    |
   of operational procedures fail.......|....|...X|....|....|....|....|
                                        |    |    |    |    |    |    |
Operation of subsystem when major       |    |    |    |    |    |    |
   operational procedures fail..........|....|....|..X.|....|....|....|
                                        |    |    |    |    |    |    |
Operation of multiple subsystems        |    |    |    |    |    |    |
   when operational procedures fail.....|....|....|....|X...|....|....|
                                        |    |    |    |    |    |    |
Automatic verification techniques.......|....|....|.X..|....|....|....|
                                        |    |    |    |    |    |    |
Operation of manufacturing systems......|....|....|.X..|....|....|....|
                                        |    |    |    |    |    |    |
Advanced expert system                  |    |    |    |    |    |    |
   able to run many major subsystems....|....|....|....|X...|....|....|
                                        |    |    |    |    |    |    |
Advanced expert system able to deal     |    |    |    |    |    |    |
   with major unanticipated failure.....|....|....|....|..X.|....|....|
                                        |    |    |    |    |    |    |
System that can learn by experience....|....|....|....|....|....|.X..|
                                        |    |    |    |    |    |    |
                            YEARS  85   90   95   00   05   10
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Figure 2: Schedule of Expert Systems Demonstrations

36

- Information retrieval from a data base describing maintenance and operating procedures of major systems in formal or semiformal language, including information as to purpose of the procedures and their component steps.

- A system capable of fault isolation of a single subsystem, using standard maintenance procedures.

- Same as the preceding, but using distributed expert-system architecture with the aim of improving real-time performance and evolutionary potential.

- A system capable of fault isolation of multiple interacting subsystems, using standard maintenance procedures.

- Same as the preceding, but operating under real-time constraints and allowing for data errors.

- A system for control of a single manufacturing process or a single experiment.

- A spaceborne processor particularly suited to mechanization of expert systems—e.g., able to handle parallel processing.

Medium-term (1993-2000)

- An expert system capable of solving problems in an isolated subsystem when some substeps of a standard maintenance procedure are inapplicable.

- An expert system capable of fault diagnosis and recovery in an isolated subsystem when a major portion of some standard maintenance procedure is inapplicable.

- Same as the preceding, but involving multiple interacting subsystems.

- Automatic-verification techniques for guaranteeing that an expert system is "safe," i.e., cannot harm the subsystems that it controls.

- An expert system of medium-level complexity for use in manufacturing, capable of limited quality control, production control, and maintenance and fault diagnosis of a manufacturing process.

37

<u>Long-term</u> (2001-2010)

- An advanced expert system that can run many major subsystems, maintain and control experiments and manufacturing processes, schedule tasks, and interact with intelligent robots.

- An advanced expert system that can cope with an unanticipated major system failure (like the one that occurred during Apollo 13).

- An expert system that can improve its own maintenance skills—i.e., "learn" from experience.

D.   Research and Development

To accomplish the sequence of demonstrations described above, the following research topics would require NASA funding:

<u>Near-term</u> (1985-1992)

- Techniques for representing and reasoning about procedural knowledge, particularly in conformance with the NASA style of describing operational procedures.

- Representation of actions and events; causality; reasoning about the effects of sequences of actions.

- Techniques for ensuring consistency of the knowledge base over time (truth maintenance, frame problem).

- Techniques for distributed systems; communication protocols; reasoning about the knowledge bases of other systems (mutual belief); communicating to exchange information.

- Techniques and representations suitable for reasoning about the reasoning process.

- Techniques for reasoning about concurrency and about interactions among subsystems; synchronization of processes.

- Techniques for reasoning about inconsistent information and data errors.

- Interactive techniques for verifying the correctness of expert

systems.

- Space qualification of symbolic processors and development of special parallel architectures for expert systems.

- Fast theorem provers and rapid data base access and updating for supporting real-time reasoning.

- Delineation of the CAD data base and representation of maintenance procedures for expert maintenance systems; development of formal languages to represent this type of information.

Medium-term (1993-2000)

- Knowledge representation and reasoning techniques for dealing with the structure and function of physical mechanisms.

- Reasoning about deadlock, cooperation, and communication among multiple expert systems.

- Integration of qualitative and quantitative reasoning.

- Reasoning about geometric properties of objects and continuous time (as opposed to discrete time).

Long-term (2001-2010)

- Fully automatic techniques for verifying the correctness of expert systems.

- Representation and reasoning for utilizing commonsense knowledge.

- Learning from past examples and reasoning by analogy.

VIII   AUTOMATIC PLANNING

We encounter two types of planning problems in the space station: (1) scheduling predefined activities, and (2) the planning of tasks. In the scheduling problem, one begins with a set of known activities, conditions to be satisfied, and goals to be achieved. The problem is to schedule such activities to make the best use of resources and satisfy the goals as fully as possible, while coordinating these activities with other concurrent functions of the space station. An example of this is the construction of flight crew activity plans.

In task planning, the goals to be achieved are given, but the actions required to achieve them are not. A task planner must select appropriate actions and incorporate them into a plan for fulfilling the given goals. During execution of the plan, replanning may be necessary if unexpected situations are encountered. Task planning is required, for example, in deciding how to move from one location to another, in determining what actions are necessary to repair a failed component, or in enabling autonomous robots to carry out operations in conjunction with the crew or with other robots.

Task-planning systems can logically be divided into the following classes:

- Planning by a Single Controller. Given certain specific goals, the planner synthesizes a plan for control of a single agent, or of multiple agents under a single controller. This plan is created by determining which actions achieve the goals and in what sequence the actions should be performed. For example, a plan might be generated for repairing a piece of equipment by using a single arm or several arms—under a single controller in either case.

- Planning by Independent Agents. Same as the preceding, except that now each agent creates plans independently. An example of this would be planning by multiple independent robots to assemble a space structure, or carrying out different tasks on the same piece of equipment.

- Geometry-based Spatial Planning. This planning involves reasoning about time and space—e.g., how to assemble/disassemble a piece of equipment, how to construct a space structure, and how to plan a path from one location to another on the space station.

41

A   Space Station Applications

AI-based planning systems will reduce manpower requirements, expedite activity planning for the space station, and, in the long run, produce better plans. Such systems will be needed for scheduling the servicing of both manufacturing operations and onboard experiments. Automatic planning of manipulator movement will be necessary for shifting from teleoperator to autonomous robot systems, while automatic navigational planning will be necessary for mobile robot systems. Automatic planning will also be required for constructing maintenance and repair procedures. Some specific applications of planning to the space station are.

- Astronaut and Experiment Scheduling. Scheduling crew activities and coordinating experiments.

- Power Distribution. Replanning the power load distribution as needed

- Servicing   Planning the servicing sequences to be used in the maintenance of equipment.

- Process Planning   Planning the processing operations of a manufacturing unit.

- Mission Planning. Scheduling space station operations and planning missions.

- Maintenance Planning. Synthesizing procedures for fault diagnosis and repair.

- Adaptive Teleoperation. Planning the sub-movements required by a robot arm and effectors, based on high level requirements specified by the person.

- Construction   Planning the construction of large space structures.

- Autonomous Robots. Planning the movements of an autonomous robot, taking into account the actions of other agents, human and robotic.

Automated planning systems will first deal with scheduling, and these can be available in time for space station implementation. Planning systems for simple assembly and disassembly, based on the use of CAD databases, may be available prior to IOC. They can be tested in the space station environment, but

probably will not come into common use until several years after IOC. In task planning, interactive systems that allow the astronaut to supervise and optimize the plans being developed offer the best prospect for the near future. The most sophisticated automatic planning will involve operation of autonomous robots and planning maintenance and repair tasks.

B.   Research Funding

The autonomous land vehicle (ALV) portion of the DARPA SCP has a strong automatic-planning component that emphasizes route planning using stored terrain and other map information. The results of the ALV automatic-planning research may be applicable, in part, to navigational planning for robotic devices that move in a semiautonomous fashion around and in the vicinity of the space station. However, the navigation of robotic devices poses a radically different problem in the space station environment. It requires reasoning about a very dynamic world with moving objects, rather than planning routes in a relatively static domain consisting of varied terrain, enemy positions, and the like.

Since planning in DARPA's SCP concentrates mainly on navigational issues, it will have very little effect on the more general problems of task planning required for the space station. Planning for robotic tasks involving spatial/geometric reasoning (such as repairing a satellite) will benefit from research being conducted under the DARPA/Air Force Intelligent Task Automation program, which deals with automatic assembly. There is also research of this type being done in industry. It may be possible to adapt some of these results to the specialized requirements of NASA.

There is no significant multiagent research being done in the DARPA projects, yet this topic is of critical relevance to many space station tasks in which multiple robots or persons are engaged. Similarly, there is very little in the DARPA projects that is concerned with planning to realize goals or perform general tasks such as repair, construction, or material transport, all of which are essential for space station operations such as satellite servicing, construction of assemblies, OMV operations, and transfer of fuels.

C.   Demonstrations

The following demonstrations would confirm the availability of the respective automatic-planning capabilities needed for the space station. They can first be conducted on the ground, then in space. The schedule is shown in Figure 3:

```
Scheduling of crew activities..........|X...|....|....| ...|....|
                                       |    |    |    |    |    |
Interactive planning of disassembly    |    |    |    |    |    |
  and assembly, using a CAD data base..|..X.|....|....|....|....|
                                       |    |    |    |    |    |
Automatic planning for                 |    |    |    |    |    |
  a repair operation...................|....|X...|....|....|....|
                                       |    |    |    |    |    |
Scheduling of SS operations............|....|.X..|....|....|....|
                                       |    |    |    |    |    |
Planning for traffic in SS vicinity....|....|..X.|....|....|....|
                                       |    |    |    |    |    |
Plan construction for correcting       |    |    |    |    |    |
  single system malfunction............|....|..X.|....|....|....|
                                       |    |    |    |    |    |
Automatic disassembly and assembly     |    |    |    |    |    |
  planning, using a CAD data base......|....|...X|....|....|....|
                                       |    |    |    |    |    |
Planning for a two-arm                 |    |    |    |    |    |
  repair task.........................|....|....X....|....|....|
                                       |    |    |    |    |    |
Planning a procedure for               |    |    |    |    |    |
  nonstandard malfunction..............|....|....|.X..|....|....|
                                       |    |    |    |    |    |
Interactive planning of activities     |    |    |    |    |    |
  for mobile robots....................|....|....|....X....|....|
                                       |    |    |    |    |    |
Autonomous planning of robotic         |    |    |    |    |    |
  activity.............................|....|....|....|.X..|....|
                                       |    |    |    |    |    |
Synthesis of maintenance and           |    |    |    |    |    |
  operational procedures...............|....|....|....|...X|....|
                                       |    |    |    |    |    |
Learning from experience...............|....|....|....|....|.X..|
                                       |    |    |    |    |    |
                          YEARS  85   90   95   00   05   10
```

Figure 3: Schedule of Planning Demonstrations

Near-term (1985-1992)

- Interactive scheduling of crew activities.

- Interactive planning of disassembly and assembly, using a CAD data base.

- Automatic planning for a repair operation.

Medium-term (1993-2000)

- Scheduling of space station activities and utilization of resources.

- Planning for traffic in the vicinity of the space station (involving OMV, OTV, EVA, and STS movements).

- Construction plans to correct single subsystem malfunctions using knowledge of system structure and function.

- Automatic disassembly and assembly planning, using a CAD data base.

- Multiple-agent planning for a two-arm repair task.

- Synthesis of procedures for correcting malfunctions not handled by standard procedures.

- Interactive planning of activity for mobile robots.

Long-term (2001-2010)

- Autonomous planning of robotic activity.

- Synthesis of maintenance and operational procedures, taking into account crew safety, integrity of the space station, and expert engineering knowledge.

- Construction of new plans based on analagous previous solutions.

D   Research and Development

The following research and development will be required for the demonstrations. Specific space station planning problems in scheduling, subsystem operation, and robotics should be used as a focus for the research.

VIII AUTOMATIC PLANNING

Near-term (1985-1992)

- Representation of actions and of resource constraints so as to produce a scheduling system capable of effective user interaction.

- Formalisms for representing and reasoning about a wide class of actions and objects.

- Techniques for maintaining the consistency of data bases over time

- Planning under uncertainty and construction of conditional plans.

- Monitoring plan execution and replanning on plan failure.

- Reasoning about concurrency and synchronization of activities.

- Representation and reasoning about simple objects using geometric information (e.g., contact constraints, attachment points, CAD models, etc.).

Medium-term (1993-2000)

- Representation of actions and of resource constraints so that scheduling systems can be interfaced with automatic-planning systems

- Complex scheduling involving cooperation, conflict, time-space constraints, and coordination with other schedulers.

- Planning systems capable of synthesizing plans involving iteration, recursion, and other control mechanisms.

- Reasoning about systems of multiple agents involving beliefs of agents, interagent coordination, and communication.

- Plan synthesis for complex tasks requiring reasoning about 3-D spatial relationships among objects and temporal relationships among activities

- Reasoning about part mating and disassembly and maneuvering of complex objects in a cluttered environment.

<u>Long-term</u> <u>(2001-2010)</u>

- Reasoning about continuous (rather than discrete) time, and rates of change of system parameters.

- Reasoning about the function and operation of complex physical mechanisms and processes (qualitative reasoning about physcial systems).

- Reasoning by analogy for use in planning systems.

IX SPACE STATION INFORMATION SYSTEM

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The Space Station Information System (SSIS), also known as the Space Station Data System (SSDS), provides data management, computer process control, and an interface with the crew, terrestrial users, and space station subsystems. The stringent requirements for reliability and performance will place new demands on computer technology. New hardware and software techniques, as well as innovative architectural approaches, will be necessary to accommodate many high-performance heterogeneous functions, especially to provide for system growth and evolution. For example, the objective of largely automated system control implies the need for intelligent interfaces to relieve the crew from the burden of process integration; the hostile natural environment demands an extraordinary capability for fault tolerance and recovery; the astronaut's need for rapid, unforeseeable access to masses of data requires a new methodology for integrating and retrieving such information whenever necessary and without delay.

To some extent, techniques exist to accomplish many of these tasks individually, but the integration of techniques to meet all the requirements with reasonable efficiency, and in a way that allows for future evolution, is a very great challenge indeed.

A.   Space Station Applications

The Space Station Information System must provide online interactive support for a very broad range of computing functions, such as the following.

- **Support for Man-Machine Cooperation.** The SSIS must be strongly astronaut-centered, providing the crew with powerful interfaces for decision-making and control, a high level of machine intelligence to extend their reasoning and command capabilities, and high-quality, meaningful graphic displays.

- **Process Control.** Individual control functions for the many onboard processes will be similar to the common earth-based process control functions, but the number of systems and the complexity of their interactions will demand new more advanced automation to assist the crew, more sophisticated parallel processing, and improved techniques for fault tolerant design.

49

- **Data Base Management.** The SSIS will manage a very large volume of data, perhaps on the order of 10^{15} bytes, both archival and dynamic. The SSIS data management system must be more than just a collection of files; to support the astronaut in real-time problem solving, it must be an integrated collection of data bases from which any complex property about the state of the space station can be derived instantaneously. This requires compatible networking of all of the constituent data bases, as well as the use of a powerful query language to permit the retrieval of information (especially in emergencies) in combinations not always anticipated beforehand.

- **Support for Artificial-Intelligence Computations.** As indicated in other chapters, expert systems will have an important role in the space station—e.g., for planning, for scheduling, and for servicing of certain robotic functions. There is a corresponding need of such techniques within the SSIS itself for intelligent extension of system functions such as maintenance, security, and human command. (For example, we recommend a capability, appropriately called the "Astronaut's Associate," to aid the astronaut in using the SSIS and meet his personal informational needs—e.g., planning and scheduling.)

B.   SSIS Attributes

To satisfy the foregoing application requirements, the SSIS must be endowed with certain attributes. Among these are the following:

- **High Performance.** The SSIS must provide sufficient processing power to meet the requirements for throughput, response speed, and satisfaction of real-time constraints. In addition, storage capacity must be available for station operations, transmissions to earth, and for maintenance information. Many computations will be limited to serving the needs of individual station subsystems, but some will deal with multiple subsystems and with station-wide processes.

- **User support.** The SSIS architecture should be user-oriented in its organization and access to data. The astronaut must be provided with a uniform view of system data and functions that hides the individual characteristics of subsystems. Graphic and intelligent aids should be provided to help him define his informational and command needs according to his own frame of

reference.

- **Amenability to VLSI.** The SSIS architecture must facilitate incorporation of VLSI technology so as to obtain its benefits in speed, size, and power. Because inexpensive hardware will increase the feasibility of a distributed system and of more powerful fault-tolerance techniques, this has special significance for system evolution.

- **Distribution of Function.** Some combination of distributed processing and centralized processing will be essential to meet requirements for fault tolerance and evolvability. Techniques exist for designing application and system software so that they may be moved incrementally from centralized to distributed hardware configurations. Use of these techniques will prevent the initial hardware configuration from inhibiting evolution that will enable future requirements for growth, performance, and reliability to be met.

- **Hardware Reliability.** Service must be maintained and critical data must be protected in the event of any component failure, and with a minimum of human intervention. The present state of the art in fault-tolerant computing is not yet capable of coping with the multiple simultaneous faults and unanticipated fault modes that may be encountered in the harsh environment of space. It is particularly deficient in preserving data and process integrity under conditions of major equipment failure.

- **Security, Privacy, and Integrity.** The SSIS will be shared by users who want their data protected against unauthorized access, modification, or other abuse. Another matter of serious concern will be the integrity of the SSIS itself and its vulnerability to possible penetration through such stratagems as covert use of the ground link or the implementation of improper, "alien", functions in onboard subsystems.

- **Evolvability and Growth.** The SSIS will change significantly during its lifetime to meet new requirements and utilize the latest technology. Changes will include new subsystems and new kinds of data bases. Changes in scale may call for a degree of expandability available only in distributed systems. Data structures and logical processing initially based on conventional designs may be replaced later by AI-based techniques.

51

- **Software Development and Modifications.** The cost of space-qualified software may well comprise a significant portion of the space station program's budget. Major advances in software technology—e.g., very-high-level languages and intelligent software workbenches—that can drastically reduce the expense of ground-based software development will be essential. Software techniques of a different kind, such as application-specific program generation, will also be needed to support onboard programming.

- **Accommodation of Emergencies.** Emergencies will require creative reaction by the astronaut. For example, in the event of a major loss of computing power, the crew may need to marshall significant computational potential from those resources that remain available in order to carry out some critical computation. This capability will require powerful system-diagnostic functions (both algorithmic and heuristic) and well-designed man-machine human interfaces. Portable computers may play a role here.

For each of these attributes, there is a significant body of research results that gives promise of initial solutions in the near term; better solutions must await additional research. However, we emphasize that no existing information system concept embraces *all* the attributes listed   While the goal of providing them offers a significant technical challenge, the most acute and essential need is for a system architecture that addresses all requirements in a fully integrated manner.

C.   SSIS Design

Physical View of the Computer System

There are three possible generic approaches to the SSIS: centralized, distributed, and hybrid. Of these, we strongly favor the hybrid approach. However, it is extremely important to distinguish between physical structure and functional structure. It would be a mistake to design software systems so that they exploit the particular features of the initial hardware complement to achieve optimal economy and performance, but at the possible sacrifice of future system evolvability   Software mechanisms are available that would simplify use of the same software on different physical configurations; examples include message-based module communication; centralized directories of objects by name, location and access authorization; and tagging of multiple attribute descriptors to individual data items. The use of such mechanisms, even within strictly centralized hardware configurations, makes it possible to distribute software physically with relative ease. (Communication delays may affect performance, but

this may be compensated for in the future by higher hardware speeds).

Logical View of the Computer System

We have argued for the mutual independence of hardware and software structures to allow substantial system evolution. We believe that there is great benefit, for both evolution and reliability, in logical organizations comprised of a hierarchical ordering of functions, ordered from the *abstract* to the *concrete*. Such an organization for the SSIS is given in Figure 4.

Layer	Name	Principal Functions
5	Man-Machine Interface	Multimedia display of information; instructions in support of application programs
4	Astronaut's Associate	Planning, status monitoring, explaining; specialized languages in support of multiagent, distributed expert systems
3	Intelligent System Agents	Specialized expert systems for management of the SSIS, e.g., maintenance, configuration management
2	Distributed Operating System	Management of communication among computing elements; management of redundancy to achieve fault tolerance; scheduling of resources to optimize performance; security management
1	Physical Resources	Computing elements and their local operating systems

Figure 4: Logical Organization of the SSIS

In the initial SSIS, the layers would use conventional, algorithmic programming, augmented by rudimentary expert systems. As the technology advances, additional capability would be introduced at each layer, especially in the area of expert systems. Within this framework, it is meaningful to consider hierarchies in relation to different aspects of the SSIS, e.g., fault tolerance, security, life-criticality, evolvability, and modifiability. Distributing these functions over multiple levels encourages logical simplicity and efficiency.

A particular benefit of the hierarchical approach is that it provides standard interfaces for sharing resources and functions in a distributed system. For example, if all machines in the SSIS assume the same functionality at their file-system levels, it will be easy to have a logically unified, system-wide file system, as demonstrated by the UNIX-United system.

A Unified, Intelligent Data System

Space station computations will be very data intensive, and the data collected and stored will have many forms and logical structures. This diversity and volume could place a heavy burden on the crew, both in remembering the particular data structures and in finding the data that are relevant to a particular operational problem. We recommend development of a unified data model that will hide the particularities of individual data structures, and supporting functions that allow the crew to define the data they need in terms of the operations to be performed. A second recommendation is to incorporate into the data bases some additional logical capability to provide background services for monitoring and controlling station operations. For example, continuously active monitors can observe changes in data that imply the need for crew attention, thus relieving the crew of the burden of requesting such checks. Such service can be generalized, so that the data base becomes an active model of the station, as well as a cooperating agent in station management.

Software Technology

Software costs and quality have been recognized as crucial to the success of the space station program. Modern software engineering practice obviously must be applied to the development of station software, but even the best current practice will not avoid the substantial cost of high-quality programs, and will not provide adequate flexibility. Significant advances will require a step upward in the level of abstraction employed in software design, e.g., in the form of higher-level programming languages. Such languages not only can greatly improve software verification, but can lead to the building of libraries of reusable, parameterized designs, which can help to reduce development costs.

Designers of the initial software should aim for a high degree of modularity

and information "hiding" in their designs, features that are encouraged (but not guaranteed) by the Ada language. Another practice that will yield long-term benefits is the maintenance of a documented history of design decisions, to guide future modifications of the software.

A second challenge is support for the crew in solving unanticipated operational problems. An intelligent aid would help the astronaut define his problem, explain the program that has been generated, and assist in checking its operation Simple forms of application-specific program generators are available in current practice. Intelligent assistance is a major research objective.

IOC Design Techniques to Permit System Growth

We recommend that the following techniques and mechanisms be applied in the initial system design to facilitate future growth and obtain higher levels of automation.

Software Mechanisms to Aid in Evolution Toward Robust, Distributed Systems

- **Name and Authoritization Manager.** Provide a directory of all system objects, giving their locations and authorized users.

- **Intermodule Communication.** Provide interface data representations and protocols to support communication among software modules.

- **Data Tagging.** Provide packages of descriptive information associated with all intermodular data, e.g., location, time of origin, and priority. This will ensure the system attributes of reliability, security, and real-time performance.

- **Interface Standards.** Define standard interface functions for system support in communication, data access, and error handling, to encourage data sharing, system growth and relocation of modules.

- **Intelligent Data Management.** Provide modular data management units, employ data structures that are not rigidly bound to specific hardware features, and provide support for *demon* (change detector) functions.

Immediate Measures for Software Development

- **Modern software methods.** Use techniques such as modularity, hierarchy, specification, parameterization, logical synchronization, and design libraries that encourage simplicity and generality of abstractions.

- **Maintain a design knowledge base.** Document the reasoning behind design decisions, and the history of the design, test, and evaluation of the system.

- **Graphic input and output.** Provide logically accessible display data structures

D.   Research and Development

Measures such as the foregoing will aid in system growth. However, significant progress in computing power and autonomy will require advanced techniques that are presently unavailable. We recommend research efforts directed toward the following objectives:

(1) **Distributed Processing.** Improved techniques for programming and synchronizing concurrent processes, for recovery of service and preservation of data after system breakdowns, and for unified structures and mechanisms for fault tolerance, security, and safety.

(2) **Data Management.** Techniques for consolidating multiple data models, for satisfying logical constraints among data items, and for providing intelligent assistance in defining required data.

(3) **Software Development.** Very-high-level languages to support specification, validation, and reusable software designs; application-oriented software generators to support solution of operational problems by astronauts.

(4) **Fault Testing and Diagnosis.** Design techniques and test methods for multilevel systems (networks, computers, chips), and knowledge-based techniques to extend standard diagnostic programs to cover unusual fault conditions, e.g., correlated and unanticipated faults.

Of these, Items 1 and 2 are most important to the ultimate success of the

space station and would yield the greatest return in future computing power and user convenience Item 3 is indeed crucial, but research being done elsewhere is pursuing similar objective. NASA should therefore monitor progress in advanced software methodology to ascertain the merits of a major investment. While there is current research in advanced fault-diagnosis techniques, the possibility of unusual fault modes and of a lack of maintenance personnel in the space station may justify NASA investment in knowledge-based techniques for fault diagnosis.

X MAN-MACHINE INTERFACE

X MAN-MACHINE INTERFACE

The space station is an example of *supervisory control* in which the crew interacts via a computer with a complex and semiautomatic process, setting initial conditions for, intermittently adjusting, and receiving information from a computer that closes a control loop through external sensors, effectors, and the task environment. There are two main topics that arise in the design of such *man-machine interaction* subsystems: (1) the technology of the input/output devices, and (2) the human factors problems that arise in making effective use of these devices The first of these involves equipment such as displays, keyboards, light pens, joysticks, graphical input tablets, printers, and speech input/output devices. The latter is concerned with improving collaboration between the human and the computer.

A.   Space Station Applications

Some of the space station activities requiring man-machine interactions are real-time command and control; passive and active monitoring; information storage and retrieval, computational support; process planning and scheduling, recovering from failure; control of experiments and of manufacturing processes; and communication The conventional equipment that must be provided for interaction includes the spectrum of displays and input/output devices indicated above. In our discussion, we will stress the less conventional use of natural language, both spoken and typed. Many applications can be found for natural-language technology on the space station:

- in EVA when the use of keyboard is impractical

- in repair tasks when the hands of the astronaut are occupied

- in control of complex systems, such as onboard manufacturing operations

- in information retrieval, where natural language input/output avoids the need to learn special formal query languages

However, supervisory control entails much more than the provision of suitable equipment, since human factors problems will arise as automation is introduced into the space station. Such problems are likely to occur in the following situations (1) the astronaut has overall responsibility for control of a

system that, under normal operating conditions, requires only occasional adjustment of system parameters to maintain satisfactory performance; (2) the major task of the astronaut is to assume control in case of a failure or malfunction, (3) important participation occurs infrequently and at unpredictable times; (4) the time constraints associated with participation can be very short, of the order of a few seconds or minutes; (5) the values and costs associated with astronaut decisions can be very large; and (6) good performance requires the rapid assimilation of large quantities of information and the execution of relatively complex inference procedures.

B.   Demonstrations

The development of an advanced teleoperation work station requires that considerable thought and effort be devoted to the human-factors aspect of the man-machine interface. Many of the important considerations were discussed above in the teleoperation/robotics chapter. Our focus here is on natural-language and speech demonstrations. The following demonstrations would indicate the existence of the needed capabilities·

Near-term (1985-1992)

- Natural-language access to data bases, with speaker-dependent voice input for a vocabulary of 1000 words.

- Natural-language control of a complex system, such as a factory.

- A simple acquisition facility for an expert system that uses natural language.

- Useful recovery facilities for handling common grammatical errors

Medium-term (1993-2000)

- Natural language control of a complex system, including the ability to engage in extended dialogue.

- Speaker-independent voice input for a vocabulary of 1000 words.

- Speaker-dependent voice input for a vocabulary of 10000 words.

C.   Research and Development

Research results in speech and natural language will be available from other sources, such as the DARPA SCP, to satisfy the needs of the above demonstrations. For example, positive contributions can be expected in the following areas of investigation: speaker-dependent speech recognition; syntactic analysis and parsing with speech input; semantic representation of sentences; models of dialogue, including recognizing and reasoning about the system user's knowledge and plans. NASA research-and-development efforts in language and speech should extend the foregoing efforts by concentrating on the special problems found in the space environment. Some of the development may be appropriate for the Space Station Program Office.

Concerning research in solving the human factors problems of supervisory control, the Committee on Human Factors, established under the auspices of the Office of Naval Research, the Air Force Office of Scientific Research, the Army Research Institute, and NASA, identifies objectives and makes recommendations for basic research needs in support of human-factors-engineering applications. In the committee's 1983 report,[*] the following note of caution was sounded: *The human-factors aspects of supervisory control have been neglected. Without further research, they may well become the bottleneck and the most vulnerable or most sensitive aspect of these systems.* If these problems are to be resolved, the following research topics are among those that must be investigated as comprehensively and expeditiously as possible.

- How to display integrated-dynamic-system relationships in a way that is understandable and accessible.

- How to provide the operator with means of telling the system in a natural manner what is desired and why.

- How to aid the operator's cognitive process by computer-based knowledge structures.

- How to coordinate multiple operators controlling the same system.

- How best to learn from experience in a large, complex, interactive system.

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[*] "Research Needs for Human Factors," National Academy Press, (National Academy of Sciences), Washington, D C , 1983

A later workshop[†], concludes that

Researchers can contribute to the design process by first understanding it, then providing designers with information gained from research in a form that is useful to them. This implies a greater need for communication between designers and researchers.

Thus, close collaboration between human-factors researchers and the designers of the space station will be essential for dealing with such problems.

[†]"Research and Modeling of Supervisory Control Behavior," Committee on Human Factors, National Academy Press, 1984

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