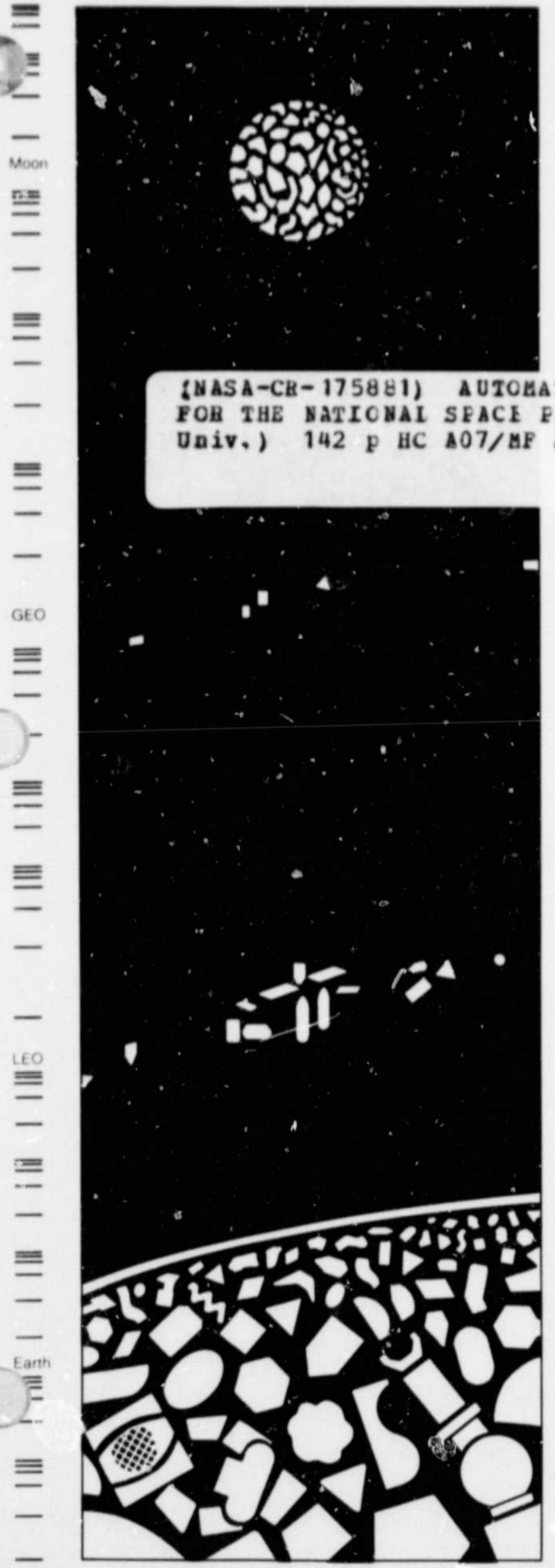

Automation & Robotics

for
The National Space Program

Automation & Robotics Panel

California Space Institute
University of California

25 February 1985

NASA Grant NAGW629
Cal Space Report CSI/85-01

NASA
National Aeronautics
and Space Administration

An
Independent
Study
of

Automation and Robotics

for

The National Space Program

by the

Automation and Robotics Panel

Administered by

California Space Institute
University of California

NASA Grant NAGW629
Cal Space Report CSI/85-01

25 February 1985

Automation and robotics has already begun to transform Earth industry. It can make the Space Station a tool for the growth of human presence and industry in Earth orbit, on the moon, and beyond.

Cover by:
Dennis Davidson
Art Director
California Space Institute

Preface

ORGANIZATION OF THE STUDY

In April 1984, the staff of the Senate Appropriations Committee and NASA agreed to establish a *Congressionally-sponsored study* to produce an automation report for the Space Station Program. Four groups contributed to the overall effort. NASA Headquarters was chosen to manage the study.

A special NASA team (the Advanced Technology Advisory Committee - ATAC) was to prepare a report on the automation study to guide the Phase B contractors. The ATAC report was to be submitted to the Congress by April 1, 1985.

To provide insight into practical applications, the Level A Space Station Program Office at NASA Headquarters organized a design team composed of five major aerospace corporations. They were charged with a six-month examination of how advanced automation and robotics could be used in actual Space Station subsystems. The design areas and contractors chosen were

Operator-Systems Interface (Boeing)

Space Manufacturing (General Electric)

Subsystems and Mission Ground Support (Hughes Aircraft Co.)

Autonomous Systems and Assembly (Martin Marietta)

Satellite Servicing (TRW Systems)

Level A also selected SRI International to form a technology team to review and assess the design concepts. This team provided assessments of the advanced automation and technology needs as determined by the mission contractors, and assisted the contractors with the integration of these technologies into the conceptual designs. In addition, SRI will provide an overall technology plan for the Space Station to be completed on March 1, 1985.

Finally, at the request of NASA, and with the agreement of Congress, the California Space Institute organized and administered the *Automation and Robotics Panel* (ARP) which conducted the *independent study*. The Panel was asked to provide guidance on the application of advanced automation and robotics to the Initial Operational Capability (IOC) program, and how the Space Station program could evolve to accept advances in these fields. Guidance was also requested on how the Space Station program might help advance automation and robotics capabilities for the nation as a whole. This report is the result of that work.

Dr. David R. Criswell organized and directed the ARP. The subpanel chairmen (indicated in the membership list by chapter responsibility) assisted in Panel member selection and supervised preparation of the report. Specialists in the fields of automation, computer science, robotics, industrial development, and aerospace engineering from industry, universities, and the government constituted the full Automation and Robotics Panel (see membership list). Members were encouraged to consider and contribute to all sections of the report. Many others active in government, industry, and university research provided additional review activity, attended key meetings, and submitted position papers to ARP. They are recognized in the beginning of this report.

NASA and the California Space Institute (Cal Space) formed a steering committee. Dr. Robert A. Frosch, Vice President of Research for General Motors Corporation and a previous Administrator of NASA, agreed to head the steering committee and maintain liaison with Congress and NASA. Prof. James Arnold and Dr. Charles A. Rosen were both on the steering committee and participated extensively in ARP. Dr. Rosen is the founder of automation and robotics research at the Stanford Research Institute (now SRI International) and is active in the development of several new advanced technologies critical to automation and robotics. Dr. Arnold is the director of the California Space Institute, a multi-campus research unit of the University of California, headquartered at the University of California, San Diego, on the campus of the Scripps Institute of Oceanography.

Special care was taken to coordinate ARP with NASA, the five design contractors, and SRI International. Key personnel in the Space Station Level A Office at NASA Headquarters were invited to attend all major meetings of ARP. The chairman of ATAC and the Chief Scientist of the Space Station program were full members of ARP. Members of ATAC's Intercenter Working Group were invited to participate in major ARP meetings. At least two senior employees of the design contractors and SRI were also invited to attend all major ARP meetings. Dr. Criswell attended the eight meetings of NASA with the design and technology teams, as well as the coordination meetings of ATAC's Intercenter Working Group. Results of these meetings were distributed to ARP members. Both SRI and the design team members reserved modest allocations of manpower to assist ARP in specific work requests. All major ARP documentation was available to NASA, the design teams, SRI, and other interested groups. Senior staff members of Science Applications International Corporation (SAIC) worked with Cal Space as ARP members in the development of technical materials, attended the design team meetings, prepared documentation and helped with the special projects.

ACKNOWLEDGMENTS

Many individuals and organizations contributed to the success of the Congressionally mandated automation and robotics study. The Cal Space Automation and Robotics Panel is deeply appreciative of the support and involvement received from Congress, NASA, and the five design contractors and SRI. The University of Texas cooperated with Cal Space in seeking some Panel members and hosting a work session. Many other organizations and individuals contributed their technical knowledge by participating in selected ARP meetings, submitting written comments, and reviewing various drafts. These individuals and organizations are recognized in the following section.

The California Space Institute is grateful for the extensive support provided to ARP by the Panel members, and the staff members of SAIC for their additional documentation efforts. The many ARP report drafts could not have been produced without long hours of work by the ARP support staff.

Membership

Automation and Robotics Panel Steering Committee

The Steering Committee provided top level advice on Panel membership, guidance to NASA and the Panel, and liaison with the Congress.

Dr. Robert A. Frosch (Chairman)
Vice President, GM Research Laboratories
General Motors Corporation
Warren, MI 48090

Professor James R. Arnold
Director, California Space Institute
University of California, San Diego
La Jolla, CA 92093

Dr. Charles A. Rosen
Machine Intelligence, Inc.
330 Potrero Avenue
Sunnyvale, CA 94086

Dr. David R. Criswell
Senior Technical Advisor and Program Director
California Space Institute
University of California, San Diego
La Jolla, CA 92093

Automation and Robotics Panel Members

The Automation and Robotics Panel members provided professional expertise in the wide range of topics encompassed by the fields of automation and robotics. They worked to identify major opportunities for applying new technologies and hardware to the planning of the Space Station, associated systems, and NASA's support operations. They also identified and explored those NASA activities with large potential impact on the national economy, either directly or by example. Members attended major meetings, authored report sections and reviewed the various drafts. Subpanel chairmen are indicated by chapter number.

Dr. James R. Arnold*	California Space Inst.
Dr. Robert Cannon	Stanford Univ. (Chapter 2)
Dr. Rodger Cliff	DARPA
Mr. Aaron Cohen	NASA Johnson Space Center
Dr. David R. Criswell	California Space Inst. (Chapter 6)
Dr. Doyle Evans	Los Alamos National Lab.
Dr. Sidney Firstman	Tech. Applications Lab., Georgia Tech.
Mr. Harold K. Forsen	Bechtel Group, Inc.
Alternate: Dr. Charles Cook	
Dr. Owen Garriott	NASA Johnson Space Center
Dr. David E. Groce	SAIC
Mr. Robert Hambright	Southwest Research Institute
Dr. Hugh Hudson	Univ. California, San Diego
Dr. Demetrius Jelatis	Sargent Industries
Dr. Michael Knasel	SAIC
Dr. Gene Konecci	Univ. Texas, Austin
Dr. Peter B. Linhart	AT&T Bell Labs.
Dr. Sanjay Mittal	Xerox PARC
Dr. Marvin Minsky	Mass. Inst. Tech.
Mr. John Niehoff	SAIC
Alternate: Dr. Harvey Feingold	
Dr. Roger Perkins	Los Alamos National Lab.
Dr. Marc Raibert	Carnegie-Mellon Univ.
Mr. Martin L. Reiss	United States Senate, staff
Dr. Charles A. Rosen*	Machine Intelligence, Inc.
Mr. Carl Ruoff	Jet Propulsion Lab.
Dr. Jack Schwartz	New York Univ.
Dr. Scott A. Starks	Univ. Texas, Arlington (Chapter 3)
Dr. Terry Triffet	Univ. Arizona (Chapter 4)
Dr. Richard Volz	Univ. Michigan (Chapter 7)
Dr. Bruce West	La Jolla Institute
Dr. Theodore J. Williams	Purdue Univ. (Chapter 5)
Dr. Michael J. Wiskerchen	Stanford Univ.

*Member of Steering Committee

Contributing Participants

Several individuals assisted the Panel extensively.

Dr. Anne Beuter	Univ. Southern California
Dr. G. David Brin	California Space Inst. (Report Editor)
Dr. Richard Emmerson	Criterion, Inc.
Dr. James C. Fox	KMS Fusion, Inc.
Mr. Blake Hannaford	Univ. California Berkeley
Dr. M. Hyson	Consultant
Dr. George Kozmetsky	Univ. Texas, Austin (Panel Advisor)
Dr. Lance A. Leventhal	Emulative Systems (Report Editor)
Dr. Alex Marusak	Los Alamos National Lab.
Mr. David S. McFalls, II	Southwest Research Inst.
Dr. David Nitzan	SRI International
Mr. John C. Oldson	California Space Inst. (ARP Technical Manager)
Mr. Robert Pierce	SAIC
Dr. Frank Sinden	AT&T Bell Labs
Dr. L. Stark	Univ. California Berkeley
Dr. Martin O. Stern	California Space Inst.
Mr. David Stuart	MIT Space Systems Lab.
Dr. Randolph Ware	Univ. Colorado
Dr. Jack Wilson	Robot Systems International
Mr. Harry Wolbers	McDonnell Douglas

NASA and ATAC Liaison

These NASA personnel have assignments directly with the NASA Space Station Office or the Space Station Advanced Technology Advisory Committee (ATAC).

Dr. Victor Anselmo	NASA Headquarters
Mr. Aaron Cohen ATAC Chairman	NASA Johnson Space Center
Dr. Jon D. Erickson	NASA Johnson Space Center
Dr. Owen Garriott	NASA Johnson Space Center
Mr. Jon Haussler	NASA Marshall SFC
Mr. Daniel Herman Chief Engineer - Space Station Program	NASA Headquarters
Dr. Ron Larsen	NASA OAST
Dr. Henry Lum	NASA Ames Research Center
Dr. Jane Malin	NASA Johnson Space Center
Dr. Al Meintel	NASA Langley Research Center
Dr. Tom Pendleton	NASA Johnson Space Center
Mr. Robert Stachle	Jet Propulsion Lab.
Ms. Claire Wolfe	NASA Ames Research Center

Support Staff (California Space Institute)

Ms. Colleen Hauck ARP Program Coordinator	Ms. Susan Hope
Ms. Beth Di Julio	Mrs. Florence Kirchner
Ms. Marie Felthouse	Ms. Teri Patterson

Contractor Participants

The firms involved in collateral studies of Space Station A&R supported attendance by key personnel at the major Panel meetings. Results of the contractor studies were distributed to the Panel.

Dr. Oscar Firschein	SRI International
Ms. Britta Gross	Hughes Aircraft
Mr. Ray Hallett	General Electric
Dr. Donald Kugath	General Electric
Mr. Hans Meissinger	TRW
Mr. Paul Meyer	Boeing
Mr. Richard Spencer	Martin Marietta Corp.
Ms. Amy Toussaint	Boeing
Mr. Donald Waltz	TRW
Mr. James T. Yonemoto	Hughes Aircraft

Study Reviewers, Advisors, Observers and Other Contributors

Dr. John A. Alic	Office of Technology Assessment
Mr. George Butler	McDonnell Douglas
Dr. Ronald D. Christman	Los Alamos National Lab
Ms. Paula Criswell	Emulative Systems (Tech. Editor)
Dr J. Dray	Office of Technology Assessment
Dr Grahme Fischer	Grumman Aerospace
Dr. Jack Foidl	TRW
Mr. Willis M. Hawkins	Lockheed Corp.
Dr. John Helly	The Aerospace Group
Dr. Ralph Kuiper	Lockheed
Dr. N. Metropolis	Los Alamos National Lab.
Dr. Al Meyers	SAIC
Dr. George Mueller	Santa Barbara, California
Dr. Ardell W. Nease	Rockwell International
Dr. Stewart Nozette	Univ. Texas, Austin (U.T. Coordinator)
Dr. S. H. Philipson	Jet Propulsion Lab.
Dr. Roy Radner	AT&T Bell Labs.
Mr. M. Simon	General Dynamics Corp.
Dr. Paul Smolensky	Univ. California, San Diego
Dr. J. Solem	Los Alamos National Lab.
Dr. Harry Sonnemann	NASA Headquarters
Dr. Byron Tapley	Univ. of Texas, Austin
Dr. J. Torre-Bueno	American Innovation Inc.
Dr. R. Williamson	Office of Technology Assessment
Dr. Lofti Zadeh	Univ. of California, Berkeley

Foreword

The Transformational Frontier--A Historical Perspective

We are now passing through what appears to be the greatest evolutionary jump in human potential in history. In the last 40 years there have been revolutions in molecular biology, in jet airplane and rocket transport, in nuclear and solar power, in the management of the environment, in the weapons that have changed the face of war, and in the way that television is transforming our lives and cultural interactions around the world. Microelectronics and cybernetics are bringing us new powers in communications, data handling, learning and problem solving, and automation and robotics, and we are now seeing the beginnings of artificial intelligence. And, of course, in the last 25 years, the move into space has suddenly lifted human prospects into a new dimension.

In just a single human generation the achievements in each of these fields have expanded our powers by orders of magnitude--a transformation more rapid than any comparable jump in the history of life on Earth. If we represent this planet's 4 billion years of life by the 500 foot height of the Washington Monument, then the 4 million years of human existence are the the last six inches of the top block, and the 4000 years of recorded history are only a layer of paint on the block. But this jump we speak of, to a new kind of future in just a few decades, would be like a thin film of moisture atop the paint.

We may cross this hazardous moment in history to become a richer, healthier, more powerful and coordinated global species, expanding into space. It is a tremendous prospect. The uniting of so many powerful changes has created a take-off point in evolution--one whose future is almost impossible to predict.

Space as a Focus for Dramatic Change

What may be particularly significant in all these dramatic changes is how they contribute to finding ways of working and living in space. This new realm, so different from the one we evolved in, is one that we humans can begin to inhabit, with special problems and special benefits.

Space has no weather or friction, thus vast light structures undergo little stress and can be shaped or moved in new ways. For example, automatic factories, powered by sunlight, might operate continuously and unattended for years, doing integrated chemical processing of asteroidal or lunar materials. Dangerous experiments might be carried out more safely in space laboratories. The design and maintenance of balanced ecological systems for space habitats might be important not only for the occupation of space but also for learning about and preserving ecological systems on Earth.

Large satellite or Moon-based solar power stations, providing energy for space and perhaps for Earth, could transform our approach to space and create another evolutionary watershed, joining our already bustling satellite communications industry as a focus of profit. Eventually, lunar and other resources may even be "harvested" by self-replicating, autonomous machines, opening up vast new sources of wealth.

Development and Diversity

Such benefits from space are probably not achievable through either early and exaggerated enthusiasms or by too narrow a focus on one or two big programs. Rather, a careful approach combining vision, diversity, and practicality will work best.

The areas of greatest growth potential today are probably molecular genetics, artificial intelligence, and the development of space. (Note that these are at the frontiers, respectively, of the three basic levels of human organization, the gene, the brain, and the social organism.) Each of these has opened a vast and uncharted ocean of possibilities whose limits we cannot foresee. Space requires a heavier commitment of complex organization and long-range planning than either of the other two. Nevertheless, our approach to space, like our approach to genetics and artificial intelligence, should be as varied and imaginative as possible if we are to realize its full potential. In new growth fields of this kind, the essence is to explore the widest possible range of variations and combinations, to permit early and effective evaluation.

The history of technology has many examples of premature closures, and they have often been disastrous in the competitive world of business. Edison himself delayed the efficient distribution of electric power for a long time by his insistence on direct-current generators. In the 1960s, the great Mohole project for drilling completely through the earth's crust was finally replaced by the less expensive Glomar Challenger method of taking many smaller cores from the sea beds, and the findings revolutionized geology.

In the space program, such considerations would seem to favor further emphasis on automation and robotics to augment human-centered systems. Such tools can amplify greatly the powers of human beings and the different kinds of equipment and studies that can be controlled, monitored, and manipulated. These advanced tools are important in life support of humans and to assist human operators in emergencies, in diagnosis, and repairs. Automated equipment, telerobots for human-controlled manipulation at a distance, and general purpose robots can offer enormous flexibility, because they frequently require no more than a change of control program, when priorities change or new possibilities open. And advances in artificial intelligence can be incorporated into a prepared and well-developed program of automation and robotics (A&R), to provide new aids in pattern perception, expert-systems analysis, inference, and reasoning.

These are, of course, the reasons for the 1984 Congressional mandate that NASA vigorously pursue advancing A&R technologies. This report is a particularly valuable step in that direction. Only through as wide-ranging an exploration as possible, adapting to new findings and using the most advanced new technologies, can we be reasonably sure of avoiding the worst pitfalls, and of finding keys to the most rapid evolution. This is what A&R and advances in intelligence can add to the central national and human programs, to make a joint optimum of technical and human systems working together.

The Space Station will not be a place or a workshop so much as a *new tool*, a center for the makers of new tools, and a place to develop and demonstrate these tools. Space Stations, and eventually a space system consisting of many stations and components reaching out to the moon's orbit and beyond, will not only return direct benefits to us on Earth. They will also begin to open up another kind of destiny, developing a whole new dimension of human existence.

John Platt
Cambridge, Massachusetts

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* California Space Institute - A-021 - UCSD - La Jolla, CA 92093 (Available at cost).

Chapter 1

EXECUTIVE SUMMARY

1.1 INTRODUCTION

PUBLIC LAW 98-371 OF THE 98th CONGRESS, DATED JULY 18, 1984, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION RESEARCH AND DEVELOPMENT, 98 STAT. 1227, RESEARCH AND PROGRAM MANAGEMENT REPORT states:

> "*Provided further*, that the Administrator shall establish an Advanced Technology Advisory Committee in conjunction with NASA's Space Station program and that the Committee shall prepare a report by April 1, 1985,
>
> *identifying specific space station systems which*
>
> *advance automation and robotics technologies,*
>
> *not in use in existing spacecraft, and*
>
> *that the development of such systems shall be estimated to cost no less than 10 per centum of the total space station costs.*" (emphasis added)

The United States Congress has taken a keen interest in how the National Aeronautics and Space Administration will manage the design, construction, operation, and evolution of the Space Station. This interest is driven by an awareness of the spectacular advances being made in electronics, computers, industrial automation, robotics, knowledge engineering, and related fields. Vital new industries and advances toward future possibilities are being created daily. The pace is accelerating, and there seem to be few acknowledged limits to these developments.

Congress became convinced that the Space Station program should not only incorporate these advances, but should also use this opportunity to stimulate national development. Demonstrations and applications of advanced technologies associated with the Space Station program will automatically receive high public and technical visibility.

The Committee on Appropriations (Department of Housing and Urban Development - Independent Agencies) recommended these responses by the National Aeronautics and Space Administration in Report 98-506 of the 98th Congress - 2nd Session (Calendar No. 967) to the challenges of advanced automation and robotics (page 65):

> "...the Senate bill requires...a NASA automation report. This report and the *ongoing NASA-sponsored automation study* are expected to be completed no later than April 1, 1985.
>
> The Committee also expects the contractors (i.e., Space Station Contractors) to devote a significant portion of their effort pursuing the study of automation and robotics technologies identified in the mandated report *with the objective of advancing the state of the art in these technologies and increasing their terrestrial application.*
>
> The Committee acknowledges the need to pursue a manned space station, however, the Committee believes that NASA needs to pursue the areas of automation and robotics more vigorously. Consequently, the bill language is intended to assure that *such advanced technologies are indeed made an integral part of the planning and development for a manned space station.*" (emphasis added)

1.2 FINDINGS OF THE PANEL

The Automation and Robotics Panel (ARP) concludes that Congress was correct in its initial judgement: *NASA can indeed significantly improve the effectiveness and reduce the cost of Space Station operations through the use of advanced automation and robotics. Capabilities in A&R will be accelerated, leading to broad national benefits.*

All major systems and most subsystems of the Space Station can be advanced over implementations in existing spacecraft (including ground support). Capabilities and efficiencies will expand if the program is designed, *from the beginning,* to accept and absorb future advances in automation and robotics. By establishing a strong technical base early, the Space Station will be able to accomplish an ever wider range of missions, and do them better and at lower cost than if only limited use is made of advancing technologies.

NASA can be challenged to move from Earth-based, human-intensive control of space operations toward highly mechanized systems located in and largely controlled from space. As they become available, advanced automation and robotics can be steadily incorporated into the Space Station to make it capable of autonomous operations for increasing periods. Transfer of control from ground to space can result in economies of operation.

Making this come true will require that *NASA make the necessary major investments to advance the technology base.* This can be accomplished through a complementary, multileveled approach. NASA can *lead* in the development of space-unique technologies, the Agency can *leverage* terrestrial technologies adaptable to the space environment, and it can learn how to *exploit* off-the-shelf technologies by providing the proper environments in space. Careful analysis must be used to determine the correct level for each development.

This is an important issue, because NASA cannot lead in all areas of technology. The Space Station program must, of course, utilize many components designed exclusively for space; special techniques and hardware will require a vigorous technology advancement and demonstration program continuously pushing the state of the art. However, in many domains the program can simply adapt techniques developed for terrestrial applications. Commercial organizations on Earth, such as communications companies, large chemical refineries, and computer centers at national laboratories, are currently more sophisticated in many areas of technology than is NASA. The more the Station draws on terrestrially developed technology and procedures, the faster the nation's presence will expand profitably into space.

Automation and Robotics (A&R) applies to many other activities of NASA besides the Space Station. Extensive interaction should be fostered between the Office of Space Science and Applications (OSSA) and A&R. Future explorations of the moon, asteroids and other bodies might lead to permanent automated centers near or on the object being studied. These centers could be upgraded regularly via small packets on relatively inexpensive flights from low-Earth orbit. A permanent center could support wide-ranging local exploration via probes, reusable orbital transfer vehicles, or *in-situ* propellant production. In all of this, OSSA could make efficient use of advances made elsewhere, especially in the Space Station program. Closer to home, advanced A&R can provide terrestrial scientists with far greater access to orbital facilities, can decrease unit costs, and permit more extensive experiments.

The Office of Aeronautics and Space Technology (OAST) is also active in automation, e.g., in developing highly reliable electronic controls for aircraft. The Office of Space Flight, using the Space Transportation System operations, or components on board the shuttle in space, can advance Space Station planning with efforts in A&R.

Most important, humans can progress to increasingly higher-level tasks as automated systems take over routine jobs. Such achievements require fundamental knowledge of how to organize exceedingly complex, even somewhat "self-aware" systems. NASA Space Station programs can demonstrate complex service functions in "smart" computer systems or extend the electronic reach of humans.

The Space Station can demonstrate technologies that soon will have new applications on Earth. These technologies will be used, for example, in non-invasive monitors of human health, and in helping the elderly or handicapped. Demonstration of new capabilities in the unforgiving environment of space will educate a wide audience. NASA has a record of achieving progressively more demanding goals in full public view. ARP concludes that the Space Station program can be related even more intimately to the mainstreams of American life and technology than were past space activities.

At the same time, NASA can learn to take advantage in space of the increasingly complex devices now becoming part of everyday life.

The entire Agency, and certainly the Space Station Program Office, could take advantage of currently available techniques in office and industrial automation. For instance, the Space Station request for proposals states specifically that engineering design data must be submitted in electronic (computer usable) form. Far greater advances can be anticipated as we learn to "electronically" conduct complex activities. NASA's openness, the nature of its missions and the technological interests of its personnel all contribute to its suitability for demonstrating advanced automation in service activities.

A permanent Space Station program can expedite the smooth growth of our presence and capabilities from Earth to space, also supporting people whose efforts are directed to non-Space Station tasks. As a wider spectrum of people and tasks are moved out to orbit, it will become clear that the Space Station program is not just an end in itself. There will be benefits far beyond the initial concept of living quarters and a workshop in low-Earth orbit.

The "Space Station program" will never mean the same thing to all people. It should be considered as part of a continuum in time, space, and society. It is building and evolving the first major tools for people to use for creative work beyond the Earth. To achieve the program's varied ends, the Automation and Robotics Panel offers its recommendations in the next section, based on the findings of its study.

1.3 RECOMMENDATIONS

The following compilation of the Panel's major recommendations is supported and expanded by accompanying exhibits and discussion.

Design the IOC Space Station (Initial Operational Capability) to accommodate major evolution and growth in its use of Automation and Robotics

Recommendations

1. NASA's goal should be to achieve, in stages, a very high level of Space Station automation by the year 2010. This level will
   a) greatly enhance effectiveness and productivity, and reduce operational costs.
   b) allow astronauts to perform duties primarily involving decision-making, supervision, and creative investigation.
2. The IOC Space Station should be designed to emphasize its capability to grow and evolve, accepting new advances with minimum retrofit. This will allow incorporation of the best and highest level of automation available at a given time, at minimum cost.

   This emphasis, established from the beginning, will be particularly important in accepting the technologies and concepts listed in Exhibit A.

3. Phase B contractors should be graded on how well they achieve Recommendation 2 (above). Selection of contractors for phases C and D should be based substantially on how well they address the goals in Recommendation 2.
4. From the beginning, NASA should search actively for and allow for breakthroughs that might surpass even current predictions of what is likely by the year 2010.

Exhibit A

Technologies and Concepts Important to Growth and Evolution of the Space Station

- Natural and efficient man/machine interfaces (e.g., voice and speech comprehension, heads-up displays, supervisory control of robots).
- Robot accommodations (e.g., standard fastenings, bar codes).
- Advanced robot capabilities (e.g., perception, manipulation, judgment, mobility).
- Standard high capacity, redundant, fault-tolerant internal and external communications networks.
- Modularity concepts that facilitate system evolution.
- Standard computer languages.
- Problem-oriented user languages.
- Comprehensive simulation for operational planning and decision making (including parts and system status, scenario testing).
- Integrated computer aided engineering and some on-site fabrication capability.
- Systems that are tolerant and protective of personnel.
- Expert systems and dynamic databases conducive to growth.
- Continuously improved computer systems, including parallel processing, and high speed circuitry.
- Methods for identifying, evaluating, projecting, and displaying effects of rapidly evolving technologies.
- Self evaluating, self repairing life-support and utilities systems with reduced dependence on Earth provisioning.
- Operational policy that utilizes astronauts in increasingly higher levels of creative activity, liberating them from routine functions.

Implement advances in Automation and Robotics throughout the Initial Operational Capability (IOC) Space Station

Recommendations

5. IOC should feature the attributes in Exhibit B, especially including
    a) Selected designs featuring modularity, reserve capacity, flexibility, and standard protocols.
    b) Excess information storage and channel capacity.
    c) Suitable environments for movement, operation, and recognition by robots.
6. Automation and robotics milestones should be demonstrated before IOC. Exhibit C shows suggested pre-IOC demonstrations and milestones along a hypothetical time line.
7. Control should be shifted as much as possible from Earth to a space-based operations center to reduce costs through automation while increasing station autonomy.

Exhibit B

Features of the IOC

- New ways of promoting the use of state-of-the-art A&R hardware to allow use of evolutionary design of computer and robotics systems.
- A flexible Earth-based computing/network test-bed for developing initial and later generation space station information management systems.
- Selected designs featuring modularity, reserve capacity, flexibility, and standard protocols.
- Initial devices and structures that allow for ease of operation, recognition, and movement by robots; this includes standardized markings (e.g., bar codes), color codes, connectors and other fastenings, and computer/network interfaces.
- Initial use of expert systems for selected tasks such as utilities analysis, fault isolation, environmental monitoring, information retrieval, and astronaut briefing.
- Provisions for obtaining and representing knowledge derived from experience for use in later, more competent expert systems.
- An initial network design and hierarchical computing system that allows for increasing decentralization.
- Selected initial and increasing use of autonomous robots.
- Deliberate accommodation, testing, and use of equipment and procedures developed in terrestrial applications for non-critical functions.

Exhibit C

Suggested pre-IOC A&R Demonstrations and Milestones*

	Near-Term: To 1988		Mid-Term: 1989 to 1992 (IOC)	
General		Flight-test some common "off-the-shelf" hardware (e.g., memory drives) to develop simpler flight qualification standards	Demonstrate dexterous end effectors and tools	
Robot Hardware	Terrestrial demos in simulated space environment - Semi-autonomous Space Station assembly - Automated inspection - Autonomous "go-fer"	Begin flight demos in shuttle Complete telerobot compatibility standards for Space Station design	Continue flight of terrestrially demonstrated hardware Demonstrate techniques for in-space parts adaptation/fabrication	"Scars" for hardware implementations after IOC
Sensors	Develop sensors & low level perception systems to support specific requirements of Space Station		Develop special-purpose hardware for sensory data processing	
Controls and Man/Machine Interfaces	Identify A&R human factors concerns	Develop and demonstrate force feedback for Shuttle Remote Manipulator System	Demonstrate robotic control systems pertinent to space environment - Micro-g manipulation - Flexible arms - Execution monitoring with real-time simulation	Demonstrate limited speech control operator interface Demonstrate multi-arm telerobots and robots for internal & EVA applications
Artificial Intelligence and Knowledge Engineering	Lab demos of space applicable early expert systems - Utilities monitor - Life Support System monitor - Data storage/access - Astronaut briefing	Accommodate in space and on the ground CAD databases, describing and integrating Station components from all contractors	Flight demos of early expert systems Demonstrate flexible dynamic simulation using CAD database	Demonstrate† expert system applications to - Crew activity planning - Communications monitoring -Fault isolation

* Discussed in Section 2.6

† Development should start immediately.

Apply Automation and Robotics (A&R) funds to advance the technology base, meeting Space Station needs

Recommendations

8. Resources for research and demonstrations must be carefully allocated for technology advancement in
   a) areas in which NASA must *lead.*
   b) areas in which NASA must interact with and vigorously *leverage* outside developments.
   c) areas in which NASA should *exploit* progress made by industry and other outside communities, devoting in-house effort primarily to intelligent purchase and space-qualification of off-the-shelf technologies.

   A proposed list of such technologies is presented in Exhibit D. Exhibit E depicts an approximate initial distribution of suggested funding. More discussion of these issues is given in Section 1.4 and Chapters 3 and 4.

9. The Panel recommends that a long-range technology advancement and demonstration program (distinct from engineering development and deployment activities) of significant size be funded to ensure that *needed* A&R technologies are developed for both the IOC and beyond.
   a) A baseline program of technology advancement and demonstration should reach approximately $190M annual funding well before IOC, e.g., by 1990. A minimally effective program serving some of the A&R technology needs of the Space Station must reach approximately $100M annual funding by 1990.
   b) Approximately 85% of this budget should be applied to the technology advancement program, and 15% to timely demonstrations of new capabilities emerging from that program.

   Exhibit F summarizes the Panel's recommendation for program funding to best enhance Space Station capabilities both at IOC and afterwards.

10. NASA must sustain a continuous, aggressive A&R technology program at all phases, considered as a national goal, but targeted at the needs of both pre- and post-IOC, regardless of any delay in the IOC program itself, or other disruption in funding.

Exhibit D

Automation and Robotics Technology Advancement Program

Class	Man/Machine-Robotics	Information Management	Communication & Mechanical Infrastructure
NASA must *lead**	Space Manipulators Materials Handling Technologies Robot Mobility in Space Man/Machine Interfaces	Expert System Mission & Payload Control, Planning & Directing "Smart" Simulations Fault-Tolerant, Reliable Software Tools CAE Standards Software Language Standards Automation Design for Integrating Technology	Lightweight Structure & Assembly Spare Parts & Repair Technology Fluids Transfer Technologies
NASA applies *leverage*	Robot Sensors/Integration Reconfigurable & Repairable Robots High-Level Robot Programming Language	Space-Related Custom Hardware Communications Networks Distributed Large-Scale Databases CAD-Directed Programming Knowledge-Based System Development Sensing Algorithms Real-Time Systems Facility "Seed" Funding	New Fabrication Technologies
NASA can *exploit* (examples)	Terrestrial Robots and Manipulators Lightweight Motors	Computer Architecture Chip Technologies Speech Technologies	Local Area Networking Display Technologies High Bandwith Technologies Communication Technologies

* Programs specified for "NASA must *lead*" logically contain technologies in which "NASA applies *leverage*" and "NASA can *exploit*." For clarity, program designations were placed only at the highest level; with time, programs may change level.

Exhibit E

Automation and Robotics Technology Program Cost Summary*

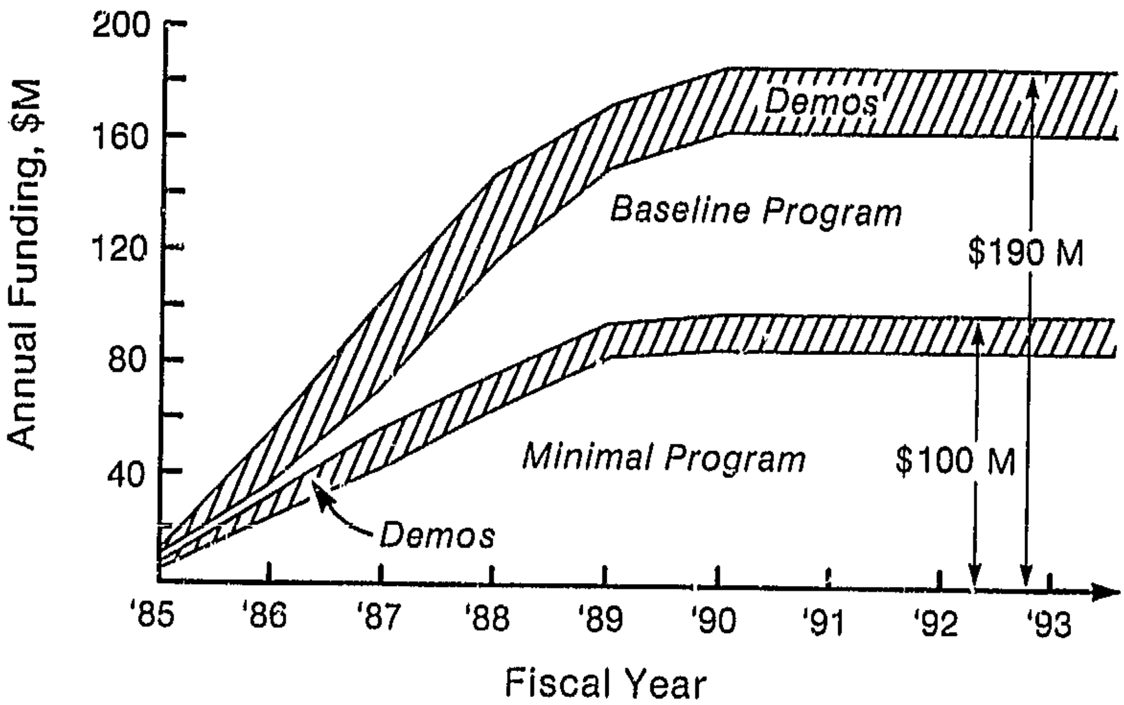
	Annual Funding Levels ($M/yr) *Baseline Program*	
	Research	*Demos*
NASA Leads:		
Man/Machine-Robotics	51	10
Information Management	26	4
NASA Applies Leverage:		
Man/Machine-Robotics	25	4
Information Management	31	7
NASA Exploits (Buys):		
Man/Machine-Robotics	< 1	< 1
Information Management	4	< 1
Infrastructure Technical Adjustment†	23	5
Program Totals	160	30
Combined Elements	190	

* After 1990 on Exhibit F

† "Man/Machine-Robotics" elements are addressed in Chapter 3. "Information Management" applications are covered in Chapter 4. "Infrastructure Technology Adjustment" is a category of expenditure dealing with *integration* of various technologies into overall station design. Part of the latter can be thought of as *exploiting* and space-qualifying Earth-derived technologies.

Exhibit F

A&R Technology Advancement Program Funding Guidelines



Establish management structures that ensure rapid, ongoing advancement of Automation and Robotics (A&R)

Recommendations

11. Establish management structures in NASA to ensure that
    a) the needed A&R technology advancements occur unimpeded by Space Station operational or budgetary problems.
    b) there is a strong linkage between the technology advancement program and Space Station A&R implementation activities.
    c) the goals for Space Station A&R technology advancement reflect a consideration of broader applications (including terrestrial).
    d) the A&R technology advancement and implementation activities have visibility and accountability to the highest levels of NASA and to Congress.

12. Without presuming to recommend a specific organizational structure, the Panel further suggests strongly that NASA accomplish Recommendation 11 by providing
    a) an organization, managed outside the Office of Space Station, to lead the A&R technology advancement activity.
    b) the A&R technology advancement activity with a line item at no lower than a first level breakout of an Associate Administrator's budget.
    c) a second organization, administered within the Office of Space Station, charged with promoting smooth flow of capabilities from the A&R advancement activity to Space Station operation, and with conducting required prototyping and testing activities.

13. Create an external review panel consisting of experts from universities, industry, and government to
    a) conduct in-depth review of NASA A&R activities.
    b) advise NASA.
    c) present annual reports to Congress.

Promote interactions among and benefits to national communities

Recommendations

14. Establish mechanisms for vigorous interactions among the national research and development communities (e.g., through joint participations in critical technology development programs, national conferences, interactive networks, and data exchanges). Keep abreast of A&R advances made by, for instance, industry, DARPA, NBS, and foreign groups.
15. Actively promote dissemination of NASA advances in automation and robotics for the general benefit of the nation by employing a vigorous NASA program of technology exchange. Facilitate both Earth and space-based applications.
16. Use advanced automation and robotics to increase the capabilities and improve the efficiency of NASA's operations, both space- and ground-based. Consider these activities as a focus for learning more about the management of modern, complex programs. This recommendation applies throughout the Agency, not only to the Space Station.
17. Establish incentive schemes to encourage new participants to become involved in NASA programs.

1.4 DEVELOPING THE TECHNOLOGY BASE

How can we be sure to develop the technology base for advanced automation and robotics that the Space Station program will need? The process involves four steps:

Step 1 - Provide the advancing technology base.

Step 2 - Conduct early demonstrations (ground and flight) of key new capabilities.

Step 3 - Develop and test prototypes.

Step 4 - Achieve operational implementation

It is clear that the scope of effort at each succeeding step narrows, beginning from a broad range of key technologies in the applied technology program and proceeding to specific systems at the implementation phase. The ARP recommendations primarily encompass Steps 1 and 2. These stages in the total A&R development process will need to draw sharply upon NASA centers, university laboratories, and industrial research programs.

In addressing the budget required to provide a solid technical base for Space Station A&R, the ARP focused on the period between now and IOC, i.e., 1985-92. It is equally important, however, that funding for this program, in place at IOC, be maintained in subsequent years to continue to advance the technology base for evolving Space Station needs.

To achieve the objectives summarized in Section 1.3, the Panel makes the following specific recommendations concerning funding:

a) A solid baseline program of both technology advancement and key demonstrations would need to reach an annual funding level of $190M well before IOC, e.g., by 1990.

b) A minimally effective program to support the A&R technology needs of the Space Station, before and after IOC, must reach $100M by 1990.

c) If the baseline program cannot be supported, ARP has developed fallback priorities in the recommended technology advancement program. This will maintain well balanced efforts in the most critical technology areas even in the event of constrained funding.

Representative annual funding in 1990 for the *baseline* and *minimal* programs required to support advancement and demonstration of key automation and robotics technologies is summarized in Exhibits E and F. Details are given in Chapter 3 (Exhibit G) and Chapter 4 (Exhibit H).

ARP members who manage private and government A&R programs estimated the professional labor (man-years per year) required for the *baseline* and *minimal* programs. The various programs will require different labor skills and development support. These factors were accounted for in estimating the annual program costs in Exhibits E and F. Demonstrations were costed separately. Then the order of fallback from *baseline* to *minimal* program was specified.

Clearly, NASA cannot, and should not try (as it did in the mid-1960s) to lead in nearly every advanced technology. Major efforts to develop NASA in-house and contractor expertise should focus on particular areas, especially those areas of automation and robotics in which Space Station needs simply will not be met without intensive NASA-supported efforts. In these fields, NASA must *lead.*

In many areas, vigorous developments by industry, defense and university communities will advance technologies. NASA *can leverage* these developments and apply them in space. Carefully chosen interventions could have dramatic effects. To do this, NASA must have high level, in-house expertise in these selected areas.

Finally, there will be many areas in which NASA should *exploit* available technology. These are fields in which industry is already forging far ahead, developing and mass-producing rugged, sophisticated hardware and systems that might function well in a space environment. NASA must establish enough in-house expertise in these areas to evaluate off-the-shelf technologies, develop more efficient space-qualification standards, and make these systems available to users in the Space Station program. In areas that NASA must generally *lead*, NASA should also *leverage* and *exploit* component systems available from other sources. With continuing imaginative approaches, NASA and its contractors can maximize the range of new technologies that do not have to go through Steps 2 and 3 or even more than a minimal check at Step 1.

Exhibit D presents distribution of proposed technology efforts along these lines of emphasis. They are broken down among Man/Machine-Robotics applications, Information Management applications, and Infrastructure Technologies specific to Space Station. Man/Machine-Robotics applications are the topic of Chapter 3, Robotic Systems. Information Management applications are covered in Chapter 4, Computer Science and Knowledge Engineering. Infrastructure Technologies addresses Space Station unique applications, each of which integrates several of the technologies included in both Chapters 3 and 4. While discussion of these applications is premature, given the current embryonic stage of the Space Station design, they must be identified as part of the total research program.

The *government procurement cycle* is now itself a serious impediment to Space Station use of advanced technology. It is complex, difficult, slow, and especially troublesome for prototype devices and development contracts. Smaller companies, often the leaders in automation and robotics, frequently decline to enter the process at all. In fast-moving areas, the procurement cycle can take longer than a technology's generation time, and itself guarantees obsolescence in the installed hardware.

Some parts of the government use simpler, more rapid procedures. Given the congressional view (which we share) that this technology is a matter of national urgency, there is a strong case for authorizing NASA to use such procedures for certain types of Space Station technologies.

It is essential that NASA sustain an aggressive A&R technology program at all phases, targeted at needs both before and after IOC. In the event of delays in IOC, automation and robotics will actually *increase* in importance, representing probably the best avenues toward recovery of lost time and opportunities. This important effort is vital to the success of the Space Station and the consequent A&R benefits to our nation. Disruptions in funding must not sidetrack NASA from a continuing pursuit of the stated A&R program objectives.

1.5 ENSURING ADVANCEMENT AND IMPLEMENTATION

The previous section has pointed out that to achieve the A&R implementation necessary to make most effective use of the Space Station, there must be several levels of substantial A&R activity within NASA. Two fundamental characteristics distinguish these levels: the degree of innovative risk involved, and the time frame in which the work is conducted. There is large variation in these characteristics as one progresses through the four stages identified above. At Step 1, the technological risk is fairly high; only a fraction of the approaches investigated will ultimately lead to operational devices. The time frame can be very long, 10 to 20 years in many cases; technology advancement work begun now will be principally directed toward post-IOC implementation. On the other hand, activities at Step 4 have high public visibility, must involve low risk, and must meet rigid time schedules.

The risk and time-frame characteristics of the activities could lead to strongly conflicting goals at various organizational levels within NASA. Experience in many different programs has shown that long-range advancement is often compromised by short-term solutions to immediate problems. Conversely, persons dedicated to technology advancement propose ideas but often have no means of reducing them to practice.

Recommendation 11 sets forth operating principles designed to resolve such conflicts to the Space Station's best advantage. The Panel recognizes there are a number of possible management structures for accomplishing the desired long-term goals. The ARP feels that managers required to deal with these conflicting goals must be accountable to higher authorities. This concept is represented in Recommendation 12, the Panel's preferred characterization of the mechanism for implementing Recommendation 11.

A separate A&R technology advancement organization (see Recommendation 12a) will focus A&R activities, allow implementation of long-range planning, and introduce new ideas for automation and robotics in space. Separation of this organization from the Office of Space Station reduces the possibility that A&R advancement funds will be used to cover unexpected Space Station delays or costs. It will also provide the freedom to pursue new ideas outside the daily pressures of implementation details and deadlines. The appearance of the A&R technology advancement budget as a line item (see Recommendation 12b) at a high level will provide visibility and accountability for the program. This is consistent with the level at which the activity was initiated, and also provides a degree of security against the use of its budget for other purposes.

The establishment of a second organization, this one within the Office of Space Station, will promote the smooth flow of new capabilities from demonstrations to operational status. This organization would have principal responsibility for Step 3, described above, but would work closely with the A&R technology advancement activity to perform the concept demonstrations of Step 2. It should have a major, but not dominant, voice in setting goals for and monitoring the A&R technology advancement activity. It should also select, develop, and promote the best ideas for use in the Space Station.

Finally, the ARP recommends that an external review panel be established to periodically conduct in-depth reviews and make recommendations to both NASA and Congress. It can help NASA maintain a top quality focused A&R program by promoting awareness of external A&R activities, and can be a strong voice of advocacy to Congress on A&R matters.

1.6 ORGANIZATION OF THE REPORT

The chapters are organized as follows:

Chapter 2 (Designing for Growth in Automation) suggests methods for promoting continual growth in Space Station automation and robotics. It emphasizes IOC design criteria that will allow for ever-increasing levels of automation. These include

- Providing abundant onboard computing power, storage facilities, and databases.
- Introducing expert systems early and continually adding to their functions.
- Identifying routine functions and planning for their gradual automation.
- Allowing for onboard control and simulation of Space Station processes through the use of CAD/CAM methods.
- Use of standard connections, fittings, and markings that automated systems can utilize or recognize.
- Allowing for robot mobility and capabilities in the design of distribution networks, structures, assembly methods, markings, and by other means.
- Separating upgradable functions into replaceable modules, micro-modules, or boxes.
- Developing a replaceable automation module that includes robots and facilities for controlling both them and other automated systems.

This chapter also summarizes the required technology advancement programs and presents example pre-IOC technology demonstration projects.

Chapter 3 (Robotics) describes the required technology advancement in robotics. It explains the need for improved human-machine interfaces, manipulators (teleoperators) and sensors, and their combination with Earth-developed robot technology into hybrid systems. It presents typical applications and scenarios in the areas of

- Assembly and construction.
- Materials handling.
- Satellite servicing and manipulation.
- Inspection and monitoring.
- Repair.
- Manufacturing.
- Experiment control.

Major research subjects in this area include end effectors and mechanization, control systems, telepresence and human factors, robot perception, manipulation in zero-gravity, operation planning using CAD/CAM databases, and robot self-diagnosis and repair.

Chapter 4 (Computer Science and Knowledge Engineering) presents the needed research base in computer science, artificial intelligence, and applied mathematics. It emphasizes

- The need for a hierarchical computer network that allows for both central control and distributed processing.
- Introduction of specialized machines for both signal and symbolic processing.
- The importance of developing adequate database standards and methods for accessing and transporting data.
- The need for improving tools and facilities for designing, developing, testing, and maintaining expert systems.
- Significant pre-IOC demonstration projects for expert systems.

It describes methods for developing these systems in a way that is largely machine-independent, distributed, and based on standard languages, interfaces, and communications techniques.

Chapter 5 (Interactions with Private and Government Sectors) explains the effects of Space Station automation and robotics on both private and governmental institutions. It describes ways to

- Obtain effective contributions from private industry, laboratories, and academia.
- Use private sector developments in the Space Station.
- Promote use of the Station by industry, other U.S. government agencies, universities and research institutions, and foreign governments.
- Use Station automation and robotics technology advancement externally.

Chapter 6 (Broader Opportunities) explains why the Station will be a continuum in time, space and society. Since it will be in operation for many years and will be used in a variety of projects, autonomy, flexibility, capacity for growth, and ease of use and operation will all be key factors. Extensive implementation of automation and robotics can help

- Provide autonomous operation without extensive ground support, and allow much better recycling and leveraged use of materials.
- Serve deep-space missions and lunar activities, and open opportunities to use new resources.
- Maintain basic Space Station core functions despite crew changes.
- Make space accessible to a much wider range of people.
- Help automate NASA operations and demonstrate advanced service automation to the nation.
- Provide the basic ability to take advantage of major technological breakthroughs.

Chapter 7 (Advancement and Implementation) contains organizational recommendations for meeting Congressional goals for Space Station automation and robotics. It emphasizes the need for

- An independent entity in NASA with responsibility for automation and robotics technology advancement and transfer.
- An organization within the Office of Space Station that ensures the actual implementation of automation and robotics systems.
- An external review panel of experts who establish goals and priorities and review progress.

1.7 CONCLUSION

On a daily basis, space is becoming increasingly intertwined with the life of every American. The Space Station is a major step toward the creation of a set of tools that will permanently sustain people beyond Earth and allow them to work in bold new ways for the benefit of all.

The space program is growing dramatically, both technologically and in the *scale* with which we do things. For example (with the exception of Skylab), the total mass of all manned capsules and landers previously flown by the United States is less than seven shuttles could carry to orbit. The Space Station will continue this revolution in scale.

Rapid physical growth is being increasingly augmented by developments in electronics. Advances in communications, computers, and robotics can increasingly leverage the capabilities of people, especially in space.

The Space Station can provide a permanent presence and sustain rapid growth off Earth during a short period in which America effectively has no major competitors. A central purpose of this report is to help design a program that will enable the nation to take advantage of this special time in history. Automation and robotics, applied vigorously now, can deeply map our human endeavors into near space, onto the moon, and beyond.

Chapter 2

DESIGNING FOR GROWTH IN AUTOMATION

2.0 SUMMARY

This chapter explains how achievement of a high level of automation throughout the Space Station's history will require an early, consistent design commitment. Robots and expert systems must be introduced as early as possible and their functions must be expanded continuously. Most important, Initial Operational Capability (IOC) design must *foster* increased automation by providing an appropriate infrastructure. Upgradable systems must be separated into replaceable units or modules to promote a regular schedule of changes, and designers must always look for ways to automate functions.

The ultimate goal should be for crew members to operate exclusively in a supervisory capacity or do advanced work.

To promote ever-increasing levels of automation, Station design should

- Consider robot mobility and the capabilities of robots and expert systems in planning internal and external structures, distribution networks, and assembly methods.
- Provide ample onboard computing power and storage, databases, control functions, and simulation facilities.
- Use standard fastenings, fittings, labels, color codes, computer network interfaces, and markings that automated systems can utilize or recognize.
- Provide a distributed network of sensors from which automated systems can derive data.
- Use standard but extensible formats for data communications.
- Provide reserve bandwidth in cabling and networking.
- Distribute computing power to promote expansion and avoid single points of failure or capacity over utilization.
- Include a comprehensive design database, covering geometry, connections, mechanisms, and equipment.

Just as important as the initial design philosophy is a commitment to a dedicated, sustained NASA program for *advancing* specific areas of *fundamental technology* in automation and robotics (A&R). This is essential if we are ever to realize the great cost savings and productivity improvements that Space Station automation could produce. While the advancement program must interact vigorously and systematically with the Office of Space Station (OSS), its resources must be dedicated to technology advancement and protected by budget structure and by a separate reporting line.

2.1 INTRODUCTION

Attention and resources must be devoted to *technology advancement* in automation and robotics. Then (and only then) will America's Space Station (*circa* 2000-2010)

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provide its services at high efficiency and low cost, at levels difficult to imagine today.

The Congressional mandate is a crucial and farsighted first initiative. But two more steps are equally essential in our view, or the promise will go unfulfilled and the Space Station of 2010 will remain a costly, labor-intensive operation. These two steps are to

1. *Require consideration of future automation in IOC Space Station designs.* NASA should require that designs for the IOC Space Station, *circa* 1992, (employing only a current state-of-the-art level of automation) demonstrate a capability to grow, in every aspect and at minimum retrofit cost, to the level of automation *possible* by the year 2010.

2. *Provide dedicated management of technology development resources in automation and robotics.* NASA should establish a separate organization to advance automation and robotics technology.* This organization should manage expenditure of all funding that the Act earmarks for development in this area. Systematic, vigorous interaction with the Office of Space Station should be required. For example, a high Space Station program official might be part of an A&R technology steering committee.

It is essential that resources be fully dedicated to *fundamental technology advancement*, to develop leverage for the future Space Station.

2.1.1 Designing for Higher Levels of Automation

The first step is that the IOC Space Station (the operation of which will be primarily a manual activity) must be designed to evolve and accept increasing levels of automation and autonomy.

It is clear that to achieve IOC, in say, 1992, the initial Space Station design will need to be frozen only a few years from now, with a level of automation not much higher than today's state of the art. The great benefits of cost-saving will come later, as automation emerges from the R&D community and from large commercial development enterprises. But the Space Station will benefit only if the IOC has the infrastructure to accept new developments. The National Research Council (NRC 1985) has examined the challenges to development of the Space Station, illustrating some of these issues.

The proposed modular nature of the Space Station meshes readily with this infrastructure, but much thought, commitment, and a design-review discipline is necessary to make it a reality.

We must first try to imagine the level and form of automation in 2010. This is the basis for specifying the details of design for growth of the IOC Space Station. It is the major task of this chapter.

Section 2.2 describes the benefits of a highly automated Space Station, with astronauts in a high-level management role. It outlines how the nature of the man-machine team could evolve during the next three decades.

* There should also be an organization dedicated to providing specific automation subsystems for implementation and operational deployment in the Space Station. See Chapter 7 for further details on recommendations regarding these two A&R organizations.

Section 2.3 examines the kinds of capabilities that could be operational by 2010 if the proper fundamental technology advancement work begins in 1985.

Section 2.4 suggests a first compilation of 1992 IOC design features that would help ensure that the Space Station can grow continually and smoothly toward the level of automation described in sections 2.2 and 2.3. Without such planning, prohibitively expensive retrofitting would be necessary.

Section 2.5 outlines specific areas requiring technology advancement efforts to provide the base for developing the Space Station.

2.1.2 Assuring Development of New Technology

The automation and robotics effort is designed primarily to benefit the Space Station. However, there are important reasons for maintaining a degree of separation between them. We believe that NASA must establish a dedicated organizational unit to manage the funding of *fundamental* automation and robotics technology for the Space Station. This funding could exert significant leverage on the nation's technology development community--but only if it is dedicated to *advancing* pivotal basic technology. A fraction could be used for selected in-house work. The bulk would fund industrial and university laboratories.

The technology advancement program should, of course, be coupled closely with the long-range needs of the Space Station. One way of accomplishing this might be a joint steering committee in which a high Space Station program official would play an important role. Strong working-level interactions should also be structured carefully.

The goals should always be useful devices and systems, not pure research. There is a danger at the opposite "applied" extreme, however. If the automation and robotics funds were allocated at the discretion of and by the OSS, they would surely (and with understandable motivation) be used to help meet pressing IOC requirements--albeit in the name of automation. This would hamper fundamental advances in automation, and the future Space Station would have little more automation than today's state of the art allows--far short of what it could have. Thus we believe that independence from direct OSS management is critical. Chapter 7 covers this topic in more detail.

2.2 THE IMPORTANCE OF DESIGNING FOR FUTURE HIGH AUTOMATION

In the first 25 years of the Space Age, we have seen rapid evolution from the earliest simple, small orbital payloads into large, highly sophisticated manned and automated space facilities. Continuing problems in the design and development of these facilities are the long lead times required, the lengthy lifetime of payload operations themselves, and the added expense and risk of last minute attempts to include the latest technological innovations. As a result, space payloads typically use technology some 10 years behind corresponding ground facilities. For the Space Station, which is intended for permanent habitation for, say, 10 or 20 years, beginning in about 1992, we must find a better way.

Concurrent with, and as a result of our rapidly advancing sophistication and capabilities in communications, electronics, and automation, the role of the space-flight crew member has also changed. Mercury and Gemini involved relatively simple tasks and used almost total onboard manual control. In Apollo and Skylab, substantially greater reliance on computer technology was possible, and a much closer interaction with ground investigators enhanced the value of scientific data return. Currently, with the shuttle and Spacelab, the degree of interaction has become quite high, with ground and space investigators operating essentially as a single team. Where appropriate, research team members themselves fly in space to operate the hardware they helped design.

The roles of the flight crew have also become more specialized, as their numbers have increased from a few to 7 or 8 in the shuttle. The majority of the crew members now devote most of their time to payload related activity. The role of the *payload specialist* includes control of teleoperators (the remote manipulator system is an early device), deployment of satellites or platforms, set-up of experiments for (semi-) automatic operation, evaluation of data quality to assure satisfactory performance, participation as test subjects, repair and maintenance of space hardware, interpretation of experiment performance, and selection of operating modes based upon real-time evaluation of the results.

These trends of payload complexity will grow even more pronounced in the developing Space Station. A major challenge in Space Station design will be to provide for many modes of operation. Crew will operate either autonomously or in concert with ground-based colleagues. The combined team will use the latest technological innovations such as nearly full-time, wide-bandwidth downlink data, television, and voice coverage for *payload-related* activities. The earliest Space Station designs will have to allow expansion and modernization of communications and control. Likewise, as teleoperators become more expert and proficient, the Space Station must be able to support their introduction and increasing use.

In contrast to the astronaut involvement in payload activities, the routine and repetitive *housekeeping* tasks should be taken over totally by onboard computer-automated control. Thus, by 2010, humans should be operating purely in a high-level, payload-oriented supervisory role.

As time passes, the jobs done by the human crew will change. One example might be materials processing or space industrial activities. Initial payloads will be human operated, but later systems will feature high levels of automation, freeing people to work on the next technological cutting edge. Substantial economics will ensue from automated support systems that allow control over both normal operations and extreme conditions. For example, life support systems that recycle vital elements will sharply decrease the cost of space operations by increasing autonomy from Earth re-supply. However, the control of such systems will be more complex and require more automation than does the control of more traditional systems.

The following chapters of this report describe the capabilities we believe will be required up to the year 2010. The Space Station's designers must ensure the incorporation of the necessary *growth potential.*

2.3 SPACE STATION 2010: AUTOMATION THAT COULD BE

As a first approximation, let us assume that, by the year 2010, the amount of onboard computing capacity will be so large as to put no limit, *per se*, on the number and complexity of computational functions performed onboard the Space Station and companion systems.

Similarly, *as a first approximation*, let us assume that, by 2010, robots will be capable of near-human performance. Moreover, they will be available in various forms, outfitted with a variety of manipulators and end effectors. Some will be capable of crawling, stepping along structures, or propelling themselves through space.

The 2010 Space Station should contain a computer system capable of maintaining the Station, even to the extent of dealing with many kinds of emergency repairs. In the following sections, we discuss various stages or levels of such abilities.

2.3.1 Station Simulation: The Decision Making Process

An important onboard facility would be a computer simulation capable, at any time, of modeling the entire Space Station and its environment in great detail, looking ahead of real-time under current or hypothetical conditions.

The initial building block for this capability is an onboard library of schematics and computer aided design (CAD) representations of every part, tool, and machine aboard the station. This library would be updated constantly. It might be stored on optical disk. It would keep track of the age, wear, expected lifetime, and current status of every part. Doing an annual inventory might be as simple as using a light pen to brush hundreds of exposed bar codes. In the short term, this library/inventory/simulator would allow the crew to know the status and availability of all parts.

Later, CAD images of parts might be used on a small scale to produce replacements on-site, helping to make the Station less dependent on Earth supply. Updated designs might be sent to the Station as *data*, rather than as physical parts. This capability, of course, assumes the enforcement of standard CAD protocols for Space Station contractors to allow representation of all components in the same database. The physical configuration of the Station should anticipate addition of fabrication or computer aided manufacturing (CAM) capability.

The next, more sophisticated step would be to use the library as the basis for developing the complete *Station simulator*. This would have access to a physical database containing information about nearly every plate, beam, fastener, wire, article of clothing, etc., their conditions, locations and velocities, temperatures, currents, and so forth. Sensor devices would monitor key conditions continuously. For others, the values would be estimated by simulations and common-sense reasoning.

Finally, the Station simulator should be able to predict what will happen if, say, a certain beam or tether is removed. The results should go beyond the assumption of a single future scenario. Instead, a semi-intelligent program must explore the extremes of plausible scenarios so that the simulator can quickly find worst cases. To do this requires problem-solving programs with a high level of understanding; they might have to reason backwards, for example, by first envisioning an undesirable configuration and searching to find a sequence of events that could produce it. Once such a sequence is discovered, perturbations can be explored to discover the boundaries for such conditions and determine if a warning should be issued.

By the year 2000, we may have powerful mechanical simulation computers. These would be microchips capable of modeling the mechanical activities of, say, 1000 or more rigid objects in real time, each with its own coordinates, momenta and other physical properties. Some thermal and electrical features may be included as well. Combinations of such computers would make a powerful onboard tool. The simulator will also need other powerful computers to deal with the dynamics of inertial systems.

Human operators should be able to invoke the Station simulator at any time. Also, several versions should be running continuously in the background, seeking to anticipate problems. Whenever a potential malfunction is uncovered, a CAD-type problem-solving system will propose rearrangement of equipment or repairs. In many cases, these will be within the abilities of available robotic-control programs and the simulator may ask permission to make the repair using mobile robots. In some cases, no human supervision will be needed, provided that the robotic manipulations are feasible and verified. Otherwise, the system can arrange for the availability of materials, schedule the removal of other activities from the scene, and mediate the repairs as dictated by local astronauts or distant controllers. This can be done either by remote control or by supervisory control of assembly robots.

2.3.2 The Robot Team

To carry out its many jobs, the overall computer system will use a vast complement of automated mechanical equipment. Robots of many kinds will be perhaps the most sophisticated devices. One can imagine a robot pool with perhaps a few dozen members of varied sizes. Some will stay mostly in specific local areas, doing routine tasks, e.g., maintenance. Others may operate from a "garage," responding to a dispatcher's call, and taking with them the set of end-effector hands, tools, and parts needed for a particular job.

Robots in 2010, some human-like in appearance, and others structured very differently, will be capable of human-like dexterity and grace. They will be able to move their tool-arms quickly, smoothly, and precisely, performing the required tasks deftly and unerringly.

Such speed and precision will emerge from major fundamental advances in three prime areas of robot technology: intelligent task management, sensing and vision, and manipulator control. In particular, it will happen when we have solved the problem of controlling flexible manipulators using end-point feedback. The result will be a robot that can see what it is doing, as a human does, and will no longer need to be stiff (and massive) to be precise. This payoff is especially great in the weightless and variable force environments of space. Even though the robot's vision processing may fall far short of a human's, special markings and beacons throughout the Space Station work areas will make human-like precision possible. Section 2.5 and Chapter 3 discuss many of these issues.

At the onset of the program, of course, humans will control robots almost joint-by-joint as they do now. But this will soon give way to end-point-command steering when we have mastered the stability and control problems. Gradually, it will be possible to give commands at higher and higher task levels, releasing humans to devote full attention to strategic roles that only they can play.

Later members of the versatile 2010 robot team will be competent aides to humans, carrying out work assignments with only high-level crew supervision. Robots will perform many routine payload deployment, inspection, maintenance, and even repair tasks. Humans will communicate with them through efficient, user-friendly, interface equipment (sometimes at a high level, sometimes in more detail).

2.3.3 Data Management

The Station's data management system must be redundant, resilient, and flexible. The ideal model is a two-tiered system, with a *core network* and a parallel *operational network*. Both networks are multi-node, distributed systems, reconfigurable in software and fault-tolerant. Both use fiber-optic bus technology.

The *core network* handles basic station survival and housekeeping functions, e.g., emergency and minimum power, environmental control and life support systems, attitude and structural control, thermal control, hazard avoidance, proximity navigation support, core communications and telemetry, navigation, and propulsion. The core network is *fail-operational*. Although it is expandable, technological updates are infrequent.

The *operational network* handles user needs, over and above core needs, including scheduling, resource allocation, general communications and telemetry, computational support, experiment monitoring and control, high-precision navigation and pointing, communications with free-flying platforms and teleoperators, and monitoring and control of teleoperator support equipment. The operational network can take over for a failed core network but the chance of this happening will be very low. The operational network often has nodes added and removed as payloads are changed on the station. These reconfigurations are easy, relying on large data busses to plug into, and on standardized organization and communications protocols.

The operational network may make requests of the core network, e.g., for suppression of environmental control functions during experiments, but the core network may refuse the requests. The operational network is *fail-safe* (at least).

2.3.4 System Monitoring

There will be distributed sensors of many types, including pattern-recognition video, with the monitored data evaluated by expert systems that interact conversationally with the crew. The data from the distributed sensors are evaluated by rule-based inference systems which look for anomalous data or unusual trends.

System status and anomalous situations will be reported to the crew through a conversational natural language interface, i.e., voice communication and graphic displays.

The expert system includes an "explainer" that elucidates the computer decisions for the human crew member, including detailed explanations of failure diagnoses. The person can ask for more details or for reevaluations with hypothetical data or rule modifications.

The expert system also has learning ability, in that it can convert the data and decisions provided by people into new data and inference rules for its relational database. The updated rules are integrated into its inference structure, and internal checking routines are applied to verify the continued integrity of its inference logic.

2.3.5 Communications

Later ground communications will use second-generation Tracking and Data Relay Satellites with easy, simultaneous accessibility by a wide array of Earth-based users. High bandwidth laser communications will include many channels (both directions) with voice channels and video links easily available between station and ground. A variety of communications connections also are available for nearby operations and links to free-flying platforms. If there are remote tethered facilities, data flow may be by cable or optical fibers of substantial length.

Infrared sender/receiver headsets will allow any crew member to communicate with any other member, or by voice with distributed computer systems, from nearly any location. Simple spoken routing commands will allow individuals to select any combination of conversants.

2.4 DESIGN TENETS FOR GROWTH IN AUTOMATION

Automation will be a rapidly advancing technology during the lifetime of the Space Station program. It will greatly affect both the ground and the space elements of Space Station operations. Thus a dominating challenge is to design infrastructure that will accommodate this rapid evolution. With such provision, automation will continually improve the Space Station's utility and cost-effectiveness. Machines will do more routine tasks previously performed by humans. Large quantities of information will be available to the crew and support staff. Ongoing developments will make qualitative, not just quantitative, changes in what can be accomplished.

Classical retrofit of the basic station, some years after initial establishment, would in most cases be prohibitively expensive. And yet, a central tenet of Space Station design must be to facilitate the rapid assimilation of new technology, particularly in the fast moving areas of information processing, artificial intelligence, and robotics. This conflict can be resolved by introducing non-traditional design features up front.

A few examples of such design tenets illustrate the underlying philosophy the design should provide

- Standard umbilical utility connections, pervasive both inside and outside the Station, to accommodate the needs of both astronauts and robots. The utilities provided at each point must include access to the Station's computer network, as well as to power, water, oxygen, high pressure gas, thruster propellant, etc.

- Standard attachment fittings at each umbilical location and throughout the Station's interior and exterior to allow automated devices to restrain themselves temporarily.
- Data buses that allow components to be upgraded or replaced as "black boxes" without forcing changes in the overall system as well.
- Bar-code labels for every part of the Space Station, every beam, every fastener and every component, and provide inventory and configuration data for future computer-managed configuration control.
- Highly-visible navigation markings and an upgradable beacon system (both internally for IVA and externally for EVA). These will allow astronauts and automated devices to easily determine their location and orientation and will minimize the cost of automated vision systems. These markings shall be dual human/machine readable, such as standard optical character recognition fonts or normal text plus standard bar codes.

There are many other specific recommendations given elsewhere in this study. But beyond these lists of features, the design process needs an *underlying philosophy*, that is, tenets that cover system specification and can be used to grade contractor performance.

To establish this philosophy firmly from the beginning, *contractor selection and performance criteria must provide for future innovative utilization of automation.*

The definition phase contractors must be directed to apply their efforts to Space Station automation, present (IOC) and future. The quality and quantity of proposed automation should be a major criterion for selecting execution phase contractors. In their proposals, contractors should describe the expected evolution of advanced automation over the life of the program, how they provide for evolution in their design, and how they plan to assimilate automation technology developments from programs such as the DoD strategic computing initiative (DARPA 1983). Contractors should define their underlying philosophies of automation and should indicate how these philosophies will undergo phased implementation over time. The plan should explore synergy, allowing different automated functions to share information.

To meet the requirements for technology transparency, major contractors should design Space Station elements to accommodate operations based on the best technology expected at the time of implementation. Then the contractor should design a cost effective IOC station *specifically intended to be upgraded* in an orderly, time-phased manner to the technological capability-baselined each year. The view of the "year station" will be wrong in detail, of course, but without a growth concept in mind when the IOC system is designed, cost-effective upgrading to new technologies will be impossible.

2.4.1 Utility Support Structure and User-Payload

The Space Station should be divided physically into a utility support structure and replaceable or reconfigurable modules (RRMs). RRMs are the units which contain payloads and accommodate users.

The utility support structure is the Space Station spine the RRMs plug into. This structure will be physically large. It must be constructed or deployed in space. Additions or deletions may be made occasionally to the utility support structure, but it will not be optimized for the interchange of major segments.

The utility support structure will provide only routine functions that are not conveniently supplied by RRMs, and that are not expected to change over time. It will provide power, orbit maintenance, attitude maintenance, heating and cooling, communications with Earth, and intermodule communications. Other services, such as supplying liquid oxygen, may be useful.

The utility support structure will probably not supply a central computational utility for the support of RRMs. The state of the art in computing is too volatile for this to be a reasonable option. However, provision of wide communications channels (e.g., via fiber optics) for data transfer among modules may be a function of the utility support structure.

In contrast, the replaceable or reconfigurable modules must be very adaptive. Replaceable modules will be transportable from Earth to orbit and sometimes from orbit to Earth by the shuttle. A reconfigurable module can be developed in space using payloads specifically carried from Earth, supplemented by creative use of material already on hand, e.g., leftover hardware, external tanks, or experiment modules no longer needed. RRMs may supply their own power communications, etc. and be self-monitoring to avoid interfering with other station operations.

The Space Station will evolve primarily by on-site adaptation, exchange, or addition of RRMs.

2.4.2 Replaceable or Reconfigurable Modules

Reconfigurable modules provide an alternative to the substantial launch expense of sending up entire *replaceable* modules. The argument for this approach follows.

The usual interpretation of *module* is a large, preassembled system--often occupying the entire shuttle cargo bay. It might be a power station, living quarters with life support, or an automated factory. These are *modules* in the sense that they are interchangeable, and independent of each other. Let us call this approach *macro-modularity.*

THESIS: Macro-modularity approach does not consider the advantages of space. Macro-modules allow one to "exploit" space in various ways for particular processes. But, generally, they do not exploit space for their own use. They are so bound by previous thinking that, for them, the vacuum, selectable acceleration, and availability of radiation are only nuisances to cope with in expensive and cumbersome ways. Worst of all, they make poor use of orbiting mass, the most expensive resource of all.

Instead, we should aim toward *micro-modularity.* This is the idea that, whenever possible, large objects and structures should be assembled from smaller ones. These smaller parts should be standardized so that they can be used interchangeably for many purposes, and reused whenever those purposes change.

THESIS: The micro-modular approach makes the best use of orbiting mass, over the long run, as we find new applications and projects to do in space. It permits great flexibility in repairing and modifying structures. By reusing materials already in place, it reduces costs and delivery times. It lends itself extraordinarily well to automation, first by remote control and teleoperation, and later by artificial intelligence methods as they evolve--and it can start to be useful without automation. It permits much wider ranges of experiments in the field, possibly eliminating multiyear pauses now forced by macro-modularity.

The trouble with the old approach is that each system, with its own single-purpose use, involves such a high transportation expense that it must be perfect from the very start. This detracts from many of the goals of a permanent, experimental, scientific Space Station.

If macro-modules must be reconfigured on Earth, transportation cost will be a major consideration. If history is any guide, the following effects will occur:

- Some endeavors will simply be foregone because of lift costs.
- Extra time and funds will be required on Earth to minimize the mass of each experiment. This may also affect the robustness of the equipment.
- Launch costs are also highly length and volume dependent. *Form* and *fit* will tend to dominate the *function* of the experiments in determining costs.
- Scheduling bottlenecks will cause highly inconvenient launch delays.

All of these problems will be reduced considerably if the macro-modules are not perpetually shuttled back and forth between Earth and low-Earth orbit. Instead, reservoirs of mass, volume, volatiles, tools, interchangeable micro-structures, and components should be allowed to gradually accumulate in orbit.

This approach will be particularly useful if the *standards* of micro-modularity are planned from the start, with emphasis on suitability for automation and robotics.

The Micro-modular Standard

All components, wherever possible, should be manufactured in modular form, with conveniently located connection points, and marked for optical and tactile identification with precision fiducial points and identifying bit patterns.

The connection points make it possible to assemble larger units. Advanced fastener technology will be helpful for this, but standard screws and bolts, etc. will do at first. A prototype standard might require regular, unique markers, surrounding threaded *1/4*-20 holes. This is already an international standard for optical equipment.

Fiducial location marks allow important new possibilities. Every part can have a unique identification so that a computer system can keep track of all materials. Universal product (bar) codes already are a proven technology. We do not have to wait for a more advanced computer-vision system to mature.

As we have stated earlier, a computer database could keep track of every part and every connection point. In many cases, locations can be specified to within a micrometer. When a new device is needed, a computer-aided design system could automatically investigate the availability of components and materials. It could even propose to borrow them from other systems, and estimate the cost of the resulting downtime.

2.4.3 General Automation Replaceable Module

Advanced automation (Artificial Intelligence--AI--and robotics) is a multipurpose technology that applies to every operational aspect of the Space Station. There is, therefore, a logical argument for treating AI and robotics as a utility and making them part of the utility support structure. This must be avoided because of the rapid rate of change in this field. Space Station design should instead provide for a general automation replaceable module (hereafter referred to as the module). Every few years a new module will replace the old one.

At some point, the module will include a "robot pool" (like a motor pool), facilities for servicing and repairing robots, computers and programs for controlling robots, symbolic computers and AI programs for general use, and perhaps a numerical supercomputer utility.

Objects that are logically a part of the module may, of course, be physically attached elsewhere, but controlled from the module. An example would be a fixed robot manipulator attached to the utility support structure on a location remote from the module or mobile robots that travel about the Space Station.

2.4.4 Stages of Automated Assembly

STAGE 0. *Manual uses.* Assemble parts by hand, if necessary. Furthermore, the astronaut could hold a mobility device designed to locate and grasp anywhere from 1 to 4 connection points (using the computer database to select them, and to supply their approximate locations and load capacities). This would lead to new, fast, reliable construction methods which would otherwise have to wait another generation to work with ordinary, unprepared materials.

STAGE 1. *Teleoperation.* Use a semi-automatic mechanical hand to link the connection points and manipulate structures.

STAGE 2. *Direct Supervision.* Provide automatic assembly and operation methods using direct human supervisory control.

STAGE 3. *Task Supervision.* Perform automatic assembly of more complex structures, with only task-level human supervision.

STAGE 4. *Adaptive Design.* Use CAD and planning programs in space to design new structures from a database. Components can be borrowed from inactive equipment and experiments and restored later.

STAGE 5. *Autonomous Development.* Employ artificial intelligence, as it becomes available and adaptable, in the non-micromodular components of the Space Station. Possibly adapt CAD to actual fabrication of components on site.

2.4.5 Hierarchical System Architecture

There is always a temptation to design and build a system with a central computer(s) that is optimal by fixed criteria. The result is usually a flat, *monolithic system design.* It tends to be hard to understand and hard to maintain or modify. This sort of optimization and minimization is taught in engineering schools, and it is appropriate for mass-produced, expendable products. Because it minimizes the cost of hardware and the high cost of transportation to space, there is a great temptation to use this style of design in space systems. The Space Station, however, is to be a long-term system that can *evolve.* Designers need not be as tyrannized by mass and volume (form and fit) if a piece of hardware is to be launched once, not repeatedly. Short-term inefficiencies (such as extra weight) should be accepted to achieve long-term flexibility.

The *hierarchical system* is well suited to managing large, complex domains. Any level of the hierarchy should be capable of performing its function without the intervention of any higher level. However, any level should also be capable of being partially, or almost completely, controlled by the next higher level. Biological organisms use this kind of hierarchical organization. For example, breathing is autonomically controlled by the brainstem, but it can be overridden (within limits) by emotion (a midlayer phenomenon), or even controlled consciously by the cortex (the top layer). In the event of unconsciousness, lower level functions remain reliable. With the Space Station, the aim is to produce a system that is understandable, maintainable, reliable, and modifiable.

2.4.6 The IOC Space Station Design

The IOC Space Station design should make things easy for robots, rather than relying on the development of arbitrarily skillful robots. *Robot mobility must be a central design consideration* in both the utility support structure and in all replaceable modules. The following are some examples:

1. Think through assemblies, disassemblies, and repairs that might be done in space and have someone try to design a robot to do each of them. The exercises alone will bring out design aspects that might otherwise have been ignored. It will also make convenience for robots a criterion for good design.
2. Design the main structure so that simple robots can move about on it and gain access to every outside part. Perhaps with clever design, the frame itself can be the scaffold. Wheels, invented to carry gravity-imposed loads, may in low or zero-gravity be inferior to a legged system that moves from one standardized grasp point to the next. If the structure has the proper geometry, the legs could be very simple. Better to design the structure and the mobility system together than trying to design complicated, heavy, crawling robots versatile enough to move over an arbitrary structure.
3. Minimize distribution networks, i.e., pipes and wires, to simplify construction, repair, and modification. Where there is a choice between a central plant with a distribution network and distributed small plants, prefer the latter. Examples include power, cooling, fuel, and communications. Note that solar power and access to black sky for heat dissipation are already distributed by their very nature. Communications by lightbeam eliminates some of the need for a wire network. Usually the only reason for a distribution network is economy of scale at the central plant. In space this is often outweighed by the complexity, conduit weight, loss of redundancy, and unreliability of joints, entailed by a network.

2.4.7 Competition

This report explores and emphasizes the application of automation and robotics to many aspects of Space Station design, operation, and growth. The recent and continuing explosive growth of capabilities in microelectronics encourages us strongly. However, we should remember that applying an expert system or a robot to a given task or function may not necessarily be the best solution. In many cases, good mechanical design or simple hardwired circuits will meet a wide range of needs. A healthy competition must be maintained between A&R proponents and more classical designers. Of course, access by both groups (often of overlapping membership) to advanced CAD systems both speeds and sharpens the competition.

The Panel wants to emphasize that optimizing the Station design should not preclude evolution and growth.

2.5 REQUIRED TECHNOLOGY ADVANCEMENTS

Reaching the cost-saving levels of total automation described above will take time. For implementation in the Space Station by, say, 2010, NASA must invest special congressional funds *now* in several key areas of *fundamental technology*--in computer automation, expert systems, robots, and man-machine interfaces--that will produce the specific crucial leverage needed. NASA must develop better ways to quickly space-qualify off-the-shelf industrial technologies. Even broader opportunities will be afforded by designing the Station to accommodate terrestrial technologies.

The reader can recognize these key technology advances by comparing today's systems of computer automation and robots with the corresponding future capabilities predicted in section 2.3. Special aspects of the Space Station project indicate where NASA's base-technology investment should focus to achieve the most effective leverage on the broader national automation effort.

2.5.1 Robotics

Chapter 3 covers robotics in detail. Here we will cover only some of the most important general points.

Clearly, robots could undergo truly revolutionary changes. In 1992, they will still be crude, clumsy, unthinking machines, little better than today's robots, and they will see limited use. By 2010, they *could* have developed into automatons that perform at near-human levels in a broad range of areas.

Generally, today's "robots" are just single arms with a simple, pliers-like gripper or some other elementary tool. Only a limited repertoire of sensors are available. Visual systems (standard video cameras or range-finding systems) exist, but only a tiny portion of the information in the images can actually be understood and used. Today's robots only perceive the world as a source of events, and cannot understand their interrelationships. Robots *do not maintain internal models of their environment.* The programming languages used to control today's robots are not sophisticated enough for a truly flexible response to external situations that change or are not anticipated, since they incorporate only a few primitive motion control commands. Sophisticated tools for analyzing sensory input are generally unavailable.

By 2010, in contrast, robots ought to be near-human in their manipulative, task-management, and sensory capabilities. Indeed, in several ways, robots can be significantly better than humans at a wide range of tasks.

This will not happen by itself. *Fundamental advances are needed* to move from the crude state of robot technology that will be available in 1992 to the level that *could be available. These advances would make the 2010 Space Station much more effective and much less costly to operate.*

Manipulation: Today's robots are crude and uncoordinated. They must use manipulators that are massive and, hence, move ponderously. Momentum and inertia are severe problems. By contrast, a person's arms and fingers are light and *limber.* This is an enormous advantage, especially in the zero-gravity space environment. Movements can be much quicker, more deft, and more precise. Humans control their arm and finger movements by using feedback gracefully from many sensors, at their end effectors and distributed throughout their structure. Only recently in the laboratory have we begun to learn how to achieve fast, stable control with distributed systems of sensors. Technology advances in manipulators are *crucial.*

Sensing: Humans possess kinesthetic sensors that indicate the configuration of the arms, fingers, etc.; sensors of forces and touch and fine texture, stereo sound, and temperature; and a prodigious vision capability. To give all these (and several more) to tomorrow's space robots, technology advancement is needed in

- Sensors of *manipulator configuration* that go far beyond today's rigid joint angle encoders.
- Sensors of the *distribution* of forces and torques.
- *Finger-tip sensors* that can recognize the texture of a surface.
- Discriminant systems to *sense radiant energy* of many wave lengths, from radar to light.
- Systems of visual *perception* and real-time visual image *recognition.*

An important part of any A&R technology advancement program will be efforts to improve both sensors and their modeling power. Manipulators for space applications are another key area.

2.5.2 Information Management

Chapter 4 emphasizes the importance of well-targeted technological advances in information management. In particular, it singles out the development of expert systems as the key to an efficient, expandable, increasingly intelligent information management system for the evolving Space Station. This recommendation is made in spite of the fact that current expert systems generally require several years to develop, debug, and optimize, yet still run slowly and require extensive human interaction.

Nevertheless, expert systems are workable artificial intelligence techniques that offer significant economies in their present form. The hardware and software advances that could move them nearer to providing real-time results, self-questioning and answering capabilities, and common-sense (as well as logical) decision making are visible on the technological horizon. Since both industry and academia are becoming increasingly involved in the development of such systems, NASA's A&R program could provide a significant focal point. This would both assure success for the IOC information system and lay a solid foundation for the autonomous system of the 2010 Space Station.

Establishment of a NASA knowledge engineering laboratory is recommended to define the systems, collect and codify knowledge, develop automated methods, and accelerate the intensive development of the hardware and algorithmic and knowledge representation software. Not only should this facility provide the latest and best equipment and libraries for symbolic computation, it should also serve the needs of special teams formed from NASA personnel familiar with mission operations, and from experienced astronauts, and knowledge engineers charged with developing systems. It should be part of a high data-rate network of industries, universities, and other NASA centers to help focus the overall program.

Modularity and standardization are the essential ingredients for an information management system that can grow with the Space Station. Insofar as possible, principal software and hardware subsystems should be designed for self-contained operation. They should also allow control by higher levels, and present standard interfaces to other systems. A structure of this type will both facilitate add-ons and make upgrading of computing hardware and software possible, while the system continues to operate in a restricted mode above core level. In addition to standardized interfaces, excess capacity is needed, especially in the initial network configuration, and all units should be designed to accommodate increasing parallelism of function. Without these features, it is unlikely that the desired degree of autonomy can be achieved by 2010.

It is also important to space-qualify commercially available computing and peripheral equipment through early demonstration projects, and to delay final IOC selections as long as possible. The technology is advancing at such a rate that a few years of additional development could make a major difference in the size, power requirements, and operational capabilities of the units selected. An open-ended, modularized system with hierarchical control should make this possible.

As to language standardization, performance tests should be carried out as soon as possible to choose a single language for general operations (perhaps Ada or C), and a single language for artificial intelligence applications (possibly LISP or PROLOG). Special dialects for robot control, human interfaces, and other special purposes could then be translated into one of these, automatically, for execution. Adoption by NASA of one language in each category, and the establishment of criteria for their use, will do much to promote further standardization and development.

Finally, a permanent testbed and development facility for the Space Station information management system should be established at a NASA center in the near future. All subsystems of the Station should be tested in this facility before installation, and should be duplicated in it to build up a redundant Earth backup system linked to the Station through broadband microwave channels. Workstations with advanced simulation functions should be provided, and arrangements should be made at the outset to store the data accumulated during the design and operational phases. Portions of this permanent and comprehensive database can then be duplicated onboard the Station.

2.5.3 Earth-Based Design and Production

Chapters 5 and 6 deal with the ways in which automated techniques will help leverage the design and manufacturing of space facilities, especially the Space Station. Ways must be found to make the production of space hardware quicker and less expensive. Automation in the design center and on the shop floor will entail several new technologies. Here we cover only the most critical of these.

Standardized CAD/CAM: Many companies are vitally interested in establishing standard methods of representing data in CAD and CAM systems. However, most companies are too small to effect standards alone. NASA has the economic power in the Space Station program to establish and enforce standards if they are developed in concert with industry. This could have a major influence on the rate of CAD/CAM development and also on the ability of contractors to deliver new parts rapidly and at low cost.

Mass and volume: Previous restrictions on lift capability have forced NASA into extensive design programs to severely restrict weights and sizes of components. Thus nearly every item was "special" and correspondingly expensive. The higher lift capacity of the STS will allow NASA to use more standard industrial components. In the case of *lift once* systems, such as the Space Station, mass and volume design constraints need not be as restrictive as with sortie vehicles, such as the orbiter.

Space-qualifications: As discussed elsewhere, use of standard industrial parts can also result in a much more rapid development cycle in Space Station equipment and modules, provided *space qualification* can be speeded up.

2.5.4 Reliability and Interchangeability

Robots and computers must be made increasingly rugged and reliable. Any major piece of equipment that must be "swapped out" (replaced by a new part sent from Earth) will compete with other items in the inevitable launch bottleneck. Subcontractors charged with building station parts should be encouraged, wherever possible, to include interchangeability as a design criteria.

2.5.5 Simulation

Continued progress must be made toward the advanced simulation technology described earlier in this chapter. Space Station crew members should be able to model the effects of current trends or proposed changes in station parameters. Processors should be dedicated to a perpetual search for failure mode scenarios and ways to prevent them.

2.6 PRE-IOC TECHNOLOGY DEMONSTRATION PROJECTS

Advancement of automation and robotics throughout the Space Station requires early demonstrations of semi-autonomous robots, and expert systems in the pre-IOC time frame. This section presents several such demonstrations (summarized in Exhibit C in the Executive Summary). Many of the terms are defined in the Glossary.

2.6.1 Pre-IOC Robotic Demonstrations

A number of demonstrations could be conducted on Earth in the near term, and some later transferred to space. Candidates for such demonstrations include the following:

Near Term (Present to 1988)

Earth-based demonstrations:

1. Automated assembly of Space Station-like parts under human supervision.
2. Automated inspection of space structures.
3. A robot helper to assist astronauts with routine maintenance tasks.
4. Means to identify critical human factors of man/machine interfaces for the Space Station.

Mid Term (1988-1992)

1. Specific advances in teleoperation of robots demonstrated in space, working perhaps from the Oak Ridge Advanced Teleoperator System or other new-generation teleoperators. Such demonstrations on real cargoes would increase confidence in IOC systems.
2. Semi-Autonomous Robots: A small computer-controlled, sensor-equipped robot to carry out onboard demonstrations in the shuttle bay under astronaut or other high-level supervision. (Boxing the experiment in a container could minimize space qualification effort.) This could demonstrate important new capabilities, such as fast, precise end-point control of lightweight flexible manipulators and mobile-robot control in micro-gravity.
3. Introduction of limited voice control to assist human operators.
4. Testing of a milli-gravity manipulation device.
5. Real-time simulation of shuttle or Station systems.
6. Early demonstration of techniques for in-space parts adaptation and fabrication.

Far Term (1992-2000+)

Post-IOC deployment demonstrations:

1. Multiple cooperative robot systems in the space environment.
2. Advanced sensor fusion for perception.
3. Integration with expert systems for self repair and self diagnosis.
4. Autonomous robots (starting at IOC).

Chapter 3 discusses some of these demonstration projects further.

2.6.2 Pre-IOC Demonstrations of Expert Systems

It is important that both the IOC and its successors take advantage of automated systems that "learn." Self-programming software and databases offer ways to improve and update automated systems smoothly to meet new demands, while requiring less human intervention.

Expert systems are a key element in this area. Chapter 4 discusses them in some detail. Here we will list only a few *possible demonstration projects* that might be performed, pre-IOC, to maximize confidence in, and use of, these promising technologies.

Some of the suggested demonstrations, listed in Exhibit C of the Executive Summary, are discussed below:

Pre 1989 demonstrations:

In spite of the short time scale, some versions of space relevant expert systems may be demonstrated before 1989. For instance, simple expert systems might help in crew activity planning or in health status monitoring.

Ground-based test beds for station power, life support, and thermal control should, from the start, include expert systems for utilities monitoring. This will ensure a smart management capability when the IOC system is installed.

New fault isolation techniques should be tested, possibly in space hardware.

Post 1989 demonstrations:

As IOC approaches, it should be possible to test and verify more advanced expert services. Examples might include voice control systems, onboard inventory control and station simulation, a flexible experiment manager, and internal and external communications monitoring.

2.7 CONCLUSION

Subsequent chapters will explore many of these ideas further. The important issue is that the Space Station is a means, not an end in itself, and it must not be frozen into an optimized design based on early 1980s technology.

If we are to achieve advances possible by the year 2010, we must begin a program now of fundamental technology advancement. This program should be sheltered from the day-to-day demands of Space Station implementation and operations, but still interact vigorously and creatively with those responsible for the basic IOC Space Station.

Especially, we must be sure that the *circa* 1992 Space Station is capable of readily accepting higher levels of automation that emerge from the technology advancement program.

2.8 REFERENCES

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Chapter 3

ROBOTICS

3.0 SUMMARY

Robots can increase the Space Station's capabilities and cost-effectiveness by

- Handling routine tasks and minimizing the use of crew time.
- Performing dangerous work that involves hazardous materials or extravehicular activity.
- Carrying out servicing activities such as resupply and maintenance.
- Allowing for the development of space-based repair and manufacturing facilities.
- Performing housekeeping functions such as inspection of the spacecraft itself.
- Handling materials and performing other functions that are difficult for humans in the micro-gravity environment.

Current robots have limited ability and intelligence. They can perform only simple, predefined tasks by themselves. The Space Station will need more capable systems that can operate more independently. It will also require simpler, more natural human interfaces than are now available. The robots must be able to use computer aided design/computer aided manufacturing (CAD/CAM) databases, respond to generalized commands, and perform self-calibration, self-diagnosis, and self-repair.

The areas in which NASA should concentrate its technology advancement efforts, in order to achieve these capabilities, are

- Producing space-worthy robots with autonomous capabilities.
- Combining the function of autonomous robots with remotely controlled manipulators (*teleoperators*) to create hybrid systems.
- Improving user interfaces to include color and stereo displays, force feedback, and voice activation to make the remote operator feel almost present in the workplace (*telepresence*), and to allow easy human control at the highest possible task level.
- Manipulating objects in micro-gravity.
- Developing systems for making manipulators work together.
- Improving robots' abilities to sense and control their environments, through better sensors, perception, actuators, manipulators, and end effectors or "hands."
- Developing self-contained, self-powered mobile systems that maintain information on their current status.
- Creating systems that have sufficient dexterity and understanding to assemble extended parts.

Achieving these advances will require vigorous and continuing technological effort. In some fields NASA must create excellence that *leads* the world. In others it may acquire needed technologies by *leveraging* or *exploiting* outside developments with internal expertise. Exhibit G contains specific categories divided in this way, along with recommended baseline and minimal funding levels. The Delta column is the difference between the two effort levels, and the Fallback Order is the order in which categories should be reduced or dropped (lowest numbers first) in case of funding disruptions. Within divisions, categories are listed in order of importance. Each category appears only in the highest applicable division. We assume that NASA should also leverage or exploit developments in areas in which it must lead.

Exhibit G

A&R Technology Program: Man/Machine-Robotics

	Category	Baseline Program ($M/year)		Minimal Program ($M/year)		Delta $M/year	Fallback Order
		Research	Demos	Research	Demos		
NASA	Space Manipulators	10	2	6	2	4	5
must	Materials Handling Technologies	8	2	4	2	4	5
lead	Robot Mobility in Space	8	2	4	•	6	5
	Man/Machine Interfaces	25	4	11	2	16	4
NASA	Robot Sensors/Integration	16	4	10	2	8	3
applies	Reconfig./Repair Robots	3	•	•	•	3	2
leverage	Hi-Level Robot Progrm. Lang.	6	•	•	•	6	1
NASA can	Factory Robots	< 1	< 1	•	•	•	•
*exploit**	Lightweight Motors	< 1	< 1	•	•	•	•

* Examples of potential off-the-shelf purchases.

3.1 INTRODUCTION

This chapter concentrates on technology advancements in robotics that are necessary for the Space Station to achieve its optimal level of automation. NASA can build on the large amount of work done in robotics in recent years. Still, this is an immature field requiring extensive further development. NASA must play a key role in seeing that both general and space-specific capabilities are available to fit its needs.

Generally, today's robot is just a single arm. End effectors, e.g., elementary tools such as a simple pliers-like gripper attach to the end of the arm. The robot can be made mobile by placing it on a simple, wheeled vehicle programmed to run along a set path. Available sensors include ultrasonic proximity sensors like those used commercially to open doors, touch-pads that can form a crude tactile image of an object in contact, and instrumented wrists that perceive the forces applied to the robot's hand. The robot can obtain visual information from either a standard video camera or a range finding system. However, its ability to process this information is usually quite limited because of restricted image processing capabilities.

The programming languages used to control today's robots are not advanced enough to allow flexible responses to changing or unanticipated conditions. Normally, these languages have only a few simple motion control commands, such as "move from point A to point B along a straight line." Although actions may depend on information received from sensors, e.g., "halt as soon as an object is touched," they seldom provide sophisticated tools for analyzing sensory input. For example, making a robot grasp a door handle and open a door, to say nothing of coordinating two hands to remove the plastic wrapping from a box of film, is still a challenge for the laboratory.

Today's robots do not have an internal picture of the world around them. All they do is respond in an isolated manner to individual events as they occur. Robots do not yet have any sense of context, continuity, or history. In other words, they do not see themselves as part of an overall environment.

In a possible scenario for 2010, by contrast, robots are near-human in their manipulative, task management, and sensory capabilities. The primary exception is visual information processing, where human abilities are likely to be out of reach for a much longer time. Indeed, in some ways, robots are already far more adept than people. They can use finely-structured range-to-object information, and they can swap special-purpose end effectors of different sizes and configurations. These and other advantages may increase greatly.

Advancement is necessary to move from the crude state of robot technology that will be available in 1992 to the level that would make the 2010 Space Station much more effective and much less costly to operate.

Let us begin examining the needed development by first considering manipulation. Manipulators used in today's robots are typically massive (in order to be stiff) and hence ponderous in their movements. Research should be directed toward light and limber manipulator systems with high strength-to-mass ratios that can use feedback from many sensors. Fast, stable control with non-colocated systems of sensors will be necessary.

Humans have a marvelous array of sensors: kinesthetic ones that indicate the position of the arms, fingers, etc.; separate sensors of force, touch, and texture; stereo sound; smell; temperature; and of course, above all, vision. To give all these (and several more) to tomorrow's space robots, research is needed in the following areas:

- Sensors of manipulator configuration that go far beyond today's rigid joint angle encoders. These should be able to indicate in detail the bending and torsional configuration of highly flexible manipulators, like the reader's own joints, and the configuration of the "tendons" controlling them.
- Sensors of the distribution of forces and torques throughout a machine's arms and fingers, with local computing to interpret the combined data.
- Fingertip sensors that can detect and reconstruct in three-dimensional detail the texture of a surface with which they come in contact, just as human fingers can.
- Discriminant systems to sense radiant energy at many wavelengths, from heat to light. These would allow not only proximity-ranging to nearby objects, but also a determination of their shapes.
- Visual recognition of objects, which is relatively easy now, and real-time visual perception, which has many generations to go and warrants major effort.

We can expect to have available, in the next two decades, highly-developed factory robots that can perform repetitive manipulative tasks with speed, accuracy, and reliability in *structured* environments. They will have high quality visual, acoustic, tactile, force, torque, and other sensors. These machines will be programmable in two modes: (1) by a person leading them through the desired sequence of motions either directly or through an exact model, and (2) off-line, by using a CAD/CAM database containing models of the robots, workpieces, and parts of the environment. Multiple processors will control dynamic behavior of joints, and later the end effectors, to orchestrate and coordinate motions, and to communicate with other computers and devices.

In later decades, with development of more nearly autonomous robots with greater capabilities, the role of astronauts will change. They will operate at increasingly higher levels of control. This gives extreme importance to the development of improved man/machine interfaces, a topic to be discussed in detail later.

The following sections examine technology areas in robotics critical to the advancement of automation on the Space Station. We start with a discussion of terminology, concise descriptions of the current state, and projections of emerging technologies.

3.1.1 Teleoperator Systems

The term *teleoperator* commonly refers to a multi-jointed manipulator system, whose actions can be controlled continuously and in detail by a human operator, either remotely or close by. The first such machines were used for handling nuclear materials. Now, astronauts use the remote manipulator system (RMS) of the space shuttle to help launch and recover satellites. Other current applications include remotely-controlled submersibles, aircraft drones, and materials-handling systems for remote or hazardous environments.

As previously discussed, robots currently have limited capabilities in unstructured environments. Under such conditions, teleoperation, i.e., *continuous human supervision at some level*, is necessary. This is seldom worthwhile in Earth-based activities unless the task is too dangerous or impossible to do except by remote control, or where manpower is severely limited. All of these conditions, however, apply in space.

Early space systems might combine technology from factory robots with advanced teleoperators for use in less structured environments. The astronaut could guide the resulting hybrid machine to the vicinity of a task, and then invoke standard programs. These will allow the machine to work semi-autonomously using its own adaptive sensors to solve minor problems such as misalignments. Position and angle references can be updated by scanning easily interpreted markings distributed all over the Space Station.

Embedded computers smooth the motions of modern teleoperators in response to human control. Electronic sensors help the remote operator guide the devices and sense the forces exerted on workpieces or other objects. Still, state-of-the-art teleoperators require total, detailed human supervision; being excruciatingly slow and ponderous, they often produce deep operator fatigue after just a short period.

The principal long-term goal in teleoperation is to make human operators feel as if they are actually present at the workplace. We call this *telepresence*; Section 3.3.3 discusses it in detail. Improvement and integration of multiple sensors, interfaces, and manipulative controls may eventually make operators almost as productive through remote control as on the scene.

3.1.2 Hybrid Teleoperated Robots

A promising approach for space, particularly while robots are still primitive, is to use a *hybrid system* that combines teleoperation with some autonomy. Such a system is sometimes called a *telerobot.*

Advanced visual telepresence could allow investigators on Earth to conduct experiments as if they were actually onboard the Space Station. *In this situation,* robots will perform repetitive experimental tasks automatically, while researchers concentrate on more important issues. The hybrid approach will allow the investigator to get a feel for conducting an experiment in the space environment. Gradually, with the inclusion of more intelligence, robots can begin to perform such tasks as inspection, repair, maintenance, and construction. This, of course, will depend on advances in several key technology areas that will be discussed later.

The Space Station will have associated facilities (co-orbiting or remotely tethered research observatories, etc.) requiring periodic repair, cleaning, and maintenance. Given the life-support and safety problems of human EVA and the hazards of handling materials such as cryogens, the servicing of these systems (and of satellites) will be a prime candidate for early automation. Telerobots are well suited to tasks such as cleaning lens elements and replacing hazardous consumable materials. They can also service transport vehicles and refurbish and repair satellites. Another potential application of automation is the establishment of manufacturing facilities in space for crystal growth, integrated circuit chip fabrication, and pharmaceutical production.

A facility for assembling large structures is another area where telerobots can enhance human productivity and safety. Section 3.2.1 addresses the development of such a facility.

Three classes of telerobots can be considered for near-term applications. First, limited capacity, transportable hybrids for use within the Space Station could perform materials-handling and monitoring tasks, such as loading and unloading test samples in biological and pharmaceutical experiments. They could also move materials and products in experimental manufacturing systems, and help with cleaning, waste handling, and process monitoring. Repair operations such as removal of panels and replacement of modules are other possible applications.

Larger, externally attached telerobots, such as the Space Transportation System's advanced RMS equipped with force and optical end feedback, could load and unload shuttle payloads, perform automatic refueling, do external repairs, and help assemble structures. The robots should be movable to attachment points distributed around the Station.

Finally, teleoperators incorporated in free flyers could perform simple satellite servicing operations. They could also help in monitoring and inspection by bringing special sensors into position at astronaut command.

In conclusion, hybrid systems afford a natural transition from total operator control to autonomous operation. They can benefit Space Station operation by freeing crew members from effort-consuming, repetitive, or hazardous tasks. With telerobots, staff members can accustom themselves to working in the space environment and thus gain the experience required to tailor future experiments and tasks more efficiently. Finally, the dual nature of telerobots offers additional safety. In the event of mechanical, electrical, communications or software malfunction, autonomous actions by the robot or human telepresence can offer multiple ways to control the telerobot.

3.1.3 Autonomous Robots

Finally, in the long term, the evolving network of space facilities will feature more and more systems that do not require supervision. Initial automated systems will be stationary units, such as for utilities and life support. Advances in robotics and information management will lead to extremely versatile autonomous machines that move about, perform experiments, or reconfigure, repair, or assemble the Station itself. Planning for them must start now. For that reason, we recommend that an autonomous mobile robot be present on the IOC station. The initial autonomous robot will be limited in capabilities, but can be useful (see Appendix 2-A).

The following sections will describe these ideas in more detail, first in illustrative scenarios and then in a discussion of needed research and development.

3.2 SCENARIOS

This section presents four scenarios (assembly, inspection, satellite servicing, and manufacturing) illustrating potential uses of automation and robotics on the Space Station. Each considers different stages of Space Station evolution to demonstrate how technological advances will affect and benefit our ability to do things in space. The scenarios deal with different functions and physical locations, i.e., within the Space Station, external to, but attached to the Space Station, and incorporated in a free flyer. The reader should also refer to the reports by design and technology contractors of the Automation Study for similar projections.

3.2.1 Assembly Scenarios

Construction of large structures requires the assembly of many modular elements arrayed upon trusses. Trusses can be assembled at the Space Station or obtained from the shuttle in deployable form. As one possible approach, two telerobotic arms, working together, combined with an assembly pallet or holding fixture, will allow rapid construction and minimize labor requirements. Assembly telerobots can initially be part of the construction base. Later, they can be part of an OMV (orbital maneuvering vehicle) for transport to and from remote work sites. As they evolve, telerobots will do increasingly diverse tasks.

Assembly of the Space Station is the first major construction task. Then, at IOC, platform construction and enhancements begin. Assembly of space structures for advanced missions such as exploration, observation, processing, and experimentation will be done during the ensuing years. The general goal of automated assembly and construction is to increase the effectiveness of astronaut labor, reduce EVA time, and provide more flexibility to handle the unforeseen problems typical of large, complex construction projects.

IOC Assembly Scenario

Astronauts will assemble the Space Station in EVA with the assistance of large, coordinated teleoperators similar to the current RMS but equipped with new, "smarter" end-effectors. Astronauts will generally control the teleoperators completely. They will have only limited learning capacity for unattended performance.

Astronauts will have primitive voice control over the teleoperators and the OMV that ferries subassemblies into position. A CAD/CAM terminal at the worksite will provide detailed assembly instructions. Parts will be labeled to aid in identification. Telepresence capabilities embedded in the smart end effectors will allow testing of the integrity of joined pieces during construction, and will aid in recognizing assembly interferences and other anomalies.

New technologies needed to perform assembly and construction in this highly structured environment include

- Development of telerobot learning techniques.
- Advanced end effectors incorporating telepresence.
- Primitive voice control of teleoperators and OMV.
- CAD/CAM database for assembly.
- Accurate, reliable manipulation of objects in micro-gravity.

Year 2000 Assembly Scenario

Construction of enhancements, modifications, and special mission hardware will require the ability to work with less structured designs and diverse assembly concepts. Less EVA will be required since both large and small telerobots can be directed from inside the Station. An OMV-like vehicle, the construction and assembly maneuvering unit, will have a limited life support system, twin teleoperator arms, a CAD/CAM/CAE (computer aided design, manufacturing, and engineering) terminal, and spare parts and tools storage. This OMV will ferry remotely controllable tools and parts from subassembly sites to assembly points. Onboard tools will check dimensions and alignments of structures during construction.

End effectors will have micro-motion and micro-manipulation capabilities along with tooling modules. These will provide a limited on-site machining and forming capability. All teleoperators will be able to work with smart tooling and clamping pallets both in subassembly operations and during on-site construction. Astronauts will spend most of their time at a computer workstation using the extensive database, expert systems, and automated planning and simulation tools.

New technologies needed for achievement of this scenario are

- Expert systems embedded in CAD/CAM/CAE databases.
- Improved robot perception and control.
- A new maneuvering vehicle with considerable utility.
- A localized capability to measure precision distances.

- Advanced machine vision and optical image processing.
- Tools for small scale machining and forming.

Year 2010 Assembly Scenario

Building large, complex structures for mission use will require adaptive assembly, working with many designs, and dealing more autonomously with unstructured construction plans. To prevent bottlenecks and lift surcharges, necessary small parts must be altered or fabricated on-site, using a CAM-driven machining center. Telerobots will perform joining tasks such as resistance spot welding, electron-beam welding, and continuous joint and seal forming. They will also have advanced end-of-arm systems enabling localized forming and machining, telepresence, and improved perception.

Astronauts will mainly supervise assembly from inside the Station or from the construction and assembly maneuvering unit. Access to advanced CAD/CAM/CAE systems with extended expert systems, dynamic interactive simulation, and automated task planning will minimize EVA time and astronaut labor.

The technologies required to make this scenario feasible include

- Extended expert systems.
- Advanced CAD/CAM/CAE technologies.
- End effector modules to include welding, cutting, machining, and forming.
- Space Station fabrication and machining facility driven by a CAM system.

3.2.2 Space Station Inspection and Repair Scenarios

Inspection of the Space Station's hull and associated structures is critical, and yet thorough flaw inspection is a time-consuming and labor-intensive process. Its automation requires precision manipulation of sensitive and delicate probes and sensors over large surfaces. Many of these must be in contact with or near to the area under scrutiny to allow detection of subsurface flaws. Automated inspection also requires automatic data acquisition and analysis to quickly define flaw presence and severity. Repair after detection will involve a variety of procedures to patch micro-meteorite damage or fatigue cracks and repair other effects of aging, as for example, in composite materials.

IOC Repair Scenario

In the 1992 time frame, the use of telerobots to inspect the hull and structure appears to be feasible. The Space Station computer will periodically direct the astronaut to inspect a particular area following a set schedule. The astronaut will manually position a telerobot similar to the RMS on an exterior surface. The telerobot's end effector will contain interchangeable modules consisting of sensors such as high resolution machine vision or surface contact probes, depending on the type of material being inspected. Automatic inspection, once begun, should no longer require the astronaut's attention. A typical procedure might involve sweeping over an exterior surface (e.g., a solar array or thermal radiator) at low velocity using high-resolution machine vision. The inspection system would use CAD/CAM data for the current hull sector to direct the RMS and avoid obstacles.

A laser beam could sweep the inspection path, highlighting cracks, holes, and surface blemishes. A second camera in the end effector could use high magnification lenses and a laser-specific filter to see flaws in great detail. Upon finding a flaw, the inspection-path routine would halt, and a more detailed subroutine would be activated, perhaps employing eddy-current, electric-current, scanning electron microscope, X-ray, or other inspection techniques.

If a detected flaw exceeds predetermined size limits, the astronaut would be summoned to investigate and make repairs. All flaws, regardless of size, would be characterized, and the resulting data stored in a computer database for ground-based structural engineering groups and for daily review and repair planning by the astronaut team.

In repair mode, the astronaut would reconfigure the RMS end effector by removing inspection modules and replacing them with repair units such as sealant and adhesive dispensers and simple patch applicators. Telepresence features in the end effectors would allow the critical positioning and application of pressure-sensitive patches.

The scenario requires the following technologies well in advance of 1992:

- End effectors allowing rapid module interchange.
- Improvements in high-resolution machine vision and high-speed data processing.
- Development of a knowledge base for hull failure mechanisms and degradation phenomena of key surfaces (e.g., hulls, solar cells, windows, mirrors, thermal radiators).
- Probes for efficient inspection of composite materials.
- CAD/CAM database for hull and structural details.

Year 2000 Repair Scenario

The year 2000 would see telerobots, with more autonomy and with the ability to inspect and repair larger, more complex structural areas. This will be accomplished through the use of well developed CAD/CAM databases and an in-depth knowledge of areas of the Space Station with high incidence of flaws. The robotic inspection system's end effectors would have extensive capability for automatic repair of most surface flaws and some structural flaws through simple patching routines. Complex or large hull repair would require astronauts to use the RMS as a teleoperator. The technology required to achieve this by 2000 includes

- Improved adaptive control for micro-motions within end effectors.
- Development of detailed Space Station CAD/CAM databases.
- Continued improvements in high-speed, high-resolution machine-vision systems.

Year 2010 Repair Scenario

The year 2010 scenario would see the inspection apparatus become an adaptive, autonomous robot able to inspect entire structural and hull features without human attendance and with very little direction. The inspection robot would still be usable as an astronaut-guided teleoperator. In addition, it would have extensive independent repair capabilities ranging from the application of surface patches to the large-scale removal and replacement of panels. The robot's role may also include periodic inspection of such equipment as pipe, cable, connectors, solar array panel elements, and antennas.

Another crucial role of mobile robots will be to help maintain the central *Space Station Simulation* model described in Chapter 2. Built in stages from the early CAD/CAM database, the simulator will by 2010 be an accurate, real-time representation of the entire infrastructure, down to the smallest piece. It will allow pre-test simulations of proposed changes, and will spend part of the time searching for failure modes through "what if" scenarios.

Mobile robots will be dispatched to verify each failure mode uncovered by the simulation. In this way, inspection will not only be routine and automatic, but thorough and imaginative as well.

Among the technology requirements for the 2010 scenario are

- Advanced inspection sensors and sensor data fusion.
- Adaptive control systems for coordination of multiple telerobots.
- End effectors with micro-motion and micro-manipulation capability, and automatic reconfiguration by module interchange.
- Expert systems for decision support and analysis, simulation, failure mode search, and repair sequencing and planning.

3.2.3 Satellite Servicing and Repair Scenarios

Vehicles such as the OMV and orbit transfer vehicle (OTV) will come to be among the most valued tools in the Space Station. Perhaps 80% of projected Space Station activities involve vehicle servicing, including satellite maintenance and repair, retirement and exchange of devices in orbit, refurbishment, resupply, and refueling.

Much of the OMV workload will be scheduled tasks such as the weekly resupply of a co-orbiting materials processing platform, or the bimonthly refueling of a large satellite. Some tasks will be of a more spontaneous nature. The following scenario describes a typical example.

IOC Satellite Servicing Scenario

A low-altitude reconnaissance satellite has a malfunctioning magnetic stabilizer and is running low on fuel. Calculations reveal that the early model OMV could handle the problem. The basic idea is for an operator in the Space Station to use the OMV manipulator system to capture the satellite and return it to the Space Station for servicing.

The OMV had just returned from another experiment platform and was refueling itself when it received the word to attach the arms and end effectors required for a satellite capture. A number of remote controlled thruster packs are also stored on the OMV for later use in stabilizing the satellite's tumble. (Some EVA astronaut assistance may be necessary this soon after IOC.) After replenishing itself, the OMV requests a clear departure corridor and detaches itself from the Space Station. Once clear, it begins a series of rocket burns to alter its orbit.

As the OMV approaches the satellite, the remote operator orders a station-keeping minimum separation of 50 meters. The astronaut then commands OMV sensors such as radar and laser scanners to define the satellite tumble mathematically. Simulation by the Space Station computer indicates that as many as three passes might be possible (based on reserve fuel). This gives the operator twelve-second grip windows. It is determined that any other approach at capturing the satellite would damage the OMV's manipulators.

The Space Station computer programs the OMV thruster system for the first approach. The operator activates the master manipulators, switches on the necessary lights and vision systems, and removes a thruster pack from its storage location. Through vision, force feedback, and tactile sensing, the remote operator is able to quickly attach the thruster pack to one of the satellite's hard points. Subsequent passes of the OMV allow for the attachment of more thruster packs. Once this is accomplished, computer controlled commands are sent to the packs to stabilize the satellite's tumble. Next, the OMV manipulators, under control of the remote operator remove and restore the packs. The satellite is then grappled and returned to the Space Station. On return, Space Station beacons and passive systems guide the OMV to a satellite-repair work station where it can dock.

A small, mobile manipulator on the Station moves into position automatically, and an operator is summoned to attach the satellite to a fixture. The OMV is released to return automatically to its storage and refueling bay. Once there, it will automatically attach connectors for power, communications, and refueling. It puts special tooling or end effectors in their proper storage bins and waits for its next mission.

Meanwhile, the small telerobots and fixtures in the satellite repair work station begin the initial visual inspection. Assessment of exterior damage detects no leaking fuel. The remote operator specifies and supervises removal of fasteners and, finally, the access panels themselves. The operator then compares the view from the camera to the satellite's CAD/CAM data sent to the Station computer only a few hours before. There seems to be no physical damage to the system. Unable to determine the problem via telemetry, the ground station asks for an opportunity to attach the satellite computer to the Space Station computer. Following diagnosis, the operator will prepare the satellite for tethered storage. There it will wait for the necessary parts to arrive from Earth.

This scenario requires development of the following technologies:

- Automated rendezvous and docking.
- Telepresence interfaces for the OMV telerobot with visual display, force feedback, and tactile sensing.
- Dexterous manipulators and end effectors.
- Limited voice control of the telerobot.
- Automated refueling.
- Simulation software for the planning of robot actions with time delay.

- CAD/CAM database for object modeling.
- Quick-change capability for tools and end effectors.
- Limited expert systems for diagnosis and repair.

Year 2000 Satellite Servicing Scenario

Interfaces between remote operators and either OMVs or the mobile advanced RMS are on a much higher level. The heightened onboard intelligence in place by 2000 would allow sophisticated natural language commands, automated planning, and spatial reasoning. Machine vision plays a much larger role in controlling the vehicles and manipulators. The OMV and mobile RMS will need less supervision for common tasks such as attaching themselves to objects. The increased autonomy will be the result of improved ability to coordinate multiple arms, navigate, track, and plan.

New technologies needed include the following:

- Advanced natural language processing.
- Enhanced voice control for multiple speakers through increased vocabulary recognition.
- Improved robot perception.
- Coordination of multiple robot arms.

Year 2010 Satellite Servicing Scenario

Many more robots will be available for space work. Evolution of machine vision, expert systems, and multi-system coordination and planning will allow vehicles such as the OTV to operate in nearly complete autonomy. Robots will automatically perform diagnosis and prognosis for systems under repair as well as for themselves. This may mean that simple satellite or platform repairs could be performed on site, allowing the process to be completed in a single OMV trip. New classes of repair problems will be resolved through coordinated use of multiple robots.

Among the new technologies needed are

- Robot self-repair capability.
- Multi-robot system coordination and planning.
- Extended expert systems for self-diagnosis and repair.

3.2.4 Manufacturing Scenarios

In the near term, space manufacturing will take two forms: simple reprocessing of Earth-provided materials using micro-gravity, e.g., pharmaceuticals and crystals, and repair and fabrication of parts needed on site. In the long term, the special attributes of space will attract more advanced industrial activities.

The near vacuum of space facilitates the use of electron-beam lithography, electron-beam welding, and ion-beam implantation. Lack of contaminants may enhance the direct production of circuits. Free-fall conditions help in bio-organic separation processes, deposition of uniform thin films, and elimination of contamination from container walls through the use of acoustic positioning. A fully automated and isolated space manufacturing unit would avoid contamination from humans and surroundings, eliminate mechanical vibrations, and protect against accidental emissions of toxic chemicals and bio-organisms. Tethered or co-orbiting platforms may be required.

The above-mentioned products use expensive materials and have a high market value for their size and mass. Their high value will likely justify the expense of space manufacturing and testing. With time, however, decreases in lift cost may make it profitable to produce items with lower value-to-mass ratios, and larger mass throughputs. The early station should not be so constrained as to forbid ambitious later endeavors.

The following technologies and components require development:

- A space-worthy, small load capacity telerobot, fitted with visual, tactile, and other sensors, and with interchangeable end effectors, having an extra degree of freedom for positioning along a rail.
- A telepresence interface for the telerobot, including voice control and visual and force feedback.
- A machine vision inspection system with integrated lighting, optics, microscopes, and micropositioning hardware.
- Special purpose hard-automated process modules.
- Limited expert systems for diagnosis and repair of modules.
- Standardized interfaces, languages, and processors.
- Special tools for repair, refurbishment, and production of other tools.

Year 2000 Manufacturing Scenario

The earlier system would be expanded and improved. The following new technologies would be necessary:

- Advanced telerobots for assembly operations, requiring the combining of information from visual, tactile, force, and torque sensors.
- More dexterous end effectors and interchangeable tools.
- Improved and extended vision systems to make telerobots more autonomous.
- Hard-automated process modules for additional stages of manufacturing such as packaging.

By this time, the ability to repair and fabricate some replacement parts will be crucial to Space Station operations.

Year 2010 Manufacturing Scenario

It should be possible to develop a fully automated manufacturing system capable of making sophisticated products. A candidate product might be a *super-computer on a chip*, i.e., a powerful large-scale computer fabricated on a single slice of gallium arsenide, using electron-beam lithography. The ultra-pure crystals would also be grown in space. Such an ambitious goal would require development of

- Specialized process modules for the numerous stages.
- Cooperative manipulation of two robot arms.

- Extended expert systems to help plan, control, and monitor all operations.
- Significant increase in robot autonomy. It should be possible to program robots off-line using CAD/CAM databases and natural language to perform high-level manipulative tasks with minimum supervision.

This is, of course, a modest space industrialization scenario by some standards. Eventually, some of the possibilities discussed in Chapter 6 may lead to large-scale use of extraterrestrial resources. Such advanced automated forms as self-replicating units are not beyond our hypothetical reach in the 21st century. Again, such ventures should not be precluded, by unnecessary constraints built into the early Space Station.

3.3 TECHNOLOGY DEVELOPMENT AREAS

This section introduces important technology development areas for Space Station robotics. Accompanying reports prepared by ARP members (see appendix for this chapter) and contractors contain more detail than is presented here. Readers interested in a more thorough treatment should refer to those materials.

3.3.1 End Effectors and Mechanization

In present-day manipulators, the end effector is usually a parallel-jawed tong that allows crude grip movements. Three rotary motions of the terminal wrist combined with rectilinear movements of the supporting arm allow the hand to be aligned with an arbitrarily-oriented workpiece. Common hand tools such as wrenches, pliers, and hammers can be fitted with channeled pads that the tongs can grasp securely. In addition, the end-effector may be able to hold power-driven tools such as electric drills, rotary impact drivers, brushes, sanders, grinders, and needle scalers. The remote operator can guide and use them with direct "feeling" of contact, alignment, and reaction forces of tool and workpiece. The emphasis in these devices is clearly on versatility, simplicity, and adaptability to poorly-defined tasks in an unstructured environment.

Today's factory robots emphasize fast, precise, and reliable execution of a few repetitive tasks. Typically, they move well-defined parts, tools, or specialized devices through programmed motions in a highly structured environment. The end effectors, wrists, and arms are somewhat like those of the servo-driven portion of a manipulator or teleoperator. However, because of the emphasis on precise position control of the end effector, the structural and drive elements (for comparable load capacities) are generally massive and rigid to minimize deflections. Special spring-loaded or compliant end effectors or parts holders can often maintain contact forces within acceptable limits. Force measurements by sensors in end effectors, wrists, workpiece holders, or support tables are necessary to provide compensatory end effector displacement.

End Effectors

Parallel-jawed, spring operable end effectors with one-way closing drive allow the control of position and force in one direction only. One can increase the versatility of these simple devices in several ways: by making jaw faces remotely interchangeable to allow replacement of damaged devices or the insertion of ones suited to heavy work, and by changing tong tips or entire assemblies remotely to select types suited to different surfaces or having different opening or closing ranges.

A special purpose two-way drive end effector, power-driven in both the opening and closing directions, is mechanically more complex, but has significant advantages over the spring-opening type. In the latter case, (1) slight damage to the bearings may prevent the spring from opening the tong and, (2) significant effort is required to close the tong to contact a workpiece, even before any holding force is applied. The bidirectionally-powered drive can also be used (with contact faces on the *outer* sides of the jaws) to grasp hollow parts from the inside.

Telerobots used in the Space Station will require special end effectors with capabilities beyond the simple grasp function. For applications not requiring twist (or roll) motion, a special two degree-of-freedom end effector may be used to actuate a latch or produce other movements in the grasped workpiece. Sensor arrays on the tong jaw faces could detect area-distribution of contact forces (hence, part shape or form). Examples include slip sensors, tong tip contact sensors, and proximity sensors. End effectors may provide auxiliary power and communications capability to an auxiliary device.

Finally, end effectors with special, possibly computer-enhanced, sensory capability may be used for inspection or testing. Examples might be visual examination sensors with close-up television, microscope, or endoscope; radiation detector probes; scanning electron microscope probes; excited fluorescence probes; and surface mechanical impedance testers with variable-frequency vibratory excitation and response measurement.

Mechanization

The end effector, workpiece, or tool-holding platform may have fitted special-purpose devices such as jigs and fixtures, tools or parts holders, or adapters to simplify repetitive or complex fabrication or assembly operations. These devices may be passive, or power-driven by built-in actuators or by manipulator forces. They may even incorporate status or condition sensors, e.g., "out-of-parts," "ready," "out-of-limits," etc., and transducers, e.g., temperature, multi-axial force, multi-axial displacement, etc. A few examples are briefly presented below.

1. Storage racks or caddies for holding tools or fixtures in well defined locations and orientations to facilitate quick or programmable exchange.
2. Passive, compliant, end effector mounted workpiece holders to control assembly forces. Examples are commercially available remote-center-compliance devices for holding parts such as precision bearings or bushings. These accommodate significant angular and positional misalignment and allow insertion into close fitting holes with clearances of a few ten-thousandths of an inch, a task difficult for even skilled mechanics to accomplish without jamming or binding.
3. Similar instrumented remote center compliance devices with multi-axial transducers measuring angular and positional deflections (and, indirectly, forces), providing control information for automatic alignment correction.

4. Compliant work holder platforms performing functions similar to 2. They may also be fitted with breakaway devices that allow them to float when a pre-established force level is exceeded, preventing tool or part damage.
5. Instrumented compliant platforms similar in action to 3.
6. Multi-axial force and moment sensors interposed between wrist-joint and end effectors functioning similar to 3.

Spring-powered impact tools can deliver a controlled impulse (hammer blow) to the work. An adapter can convert this linear impulse to a rotary impulse that can tighten or loosen threaded fasteners. A modification of the linear tool with a terminal hook or shackle can provide a reverse-impulse to break loose and extract pin-type fasteners such as hairpins or cotter keys.

Repetitive or difficult operations such as crimping, forming, bending, and riveting may justify special purpose assembly and fabrication devices. Either built-in actuators can perform the operation or the robot's end effector can work directly. For operations such as rivet-heading, a mechanical impulse-generator might be more appropriate. This could be held by the end effector or built into the special device. In the latter case, the end effector would only have to provide the driving force, while the tool position is pre-established in the fixture.

3.3.2 Control Systems

Control systems govern telerobot activities and behavior, including maintenance and housekeeping. They must cope with operating environments that often involve a great deal of uncertainty. Other types of control systems will be needed for use in chemical processing, experimentation, and structural and attitude control. However, since control techniques for these applications are well-known, they will not be described further here, except as they relate to telerobots.

Control System Architecture

It appears natural to organize the control system as a hierarchical structure because lower-level functions are often repetitive, and because the tasks can usually be described hierarchically, as well. A particular telerobot, for example, could be described at a high level as installing modules, while at a lower level it is fetching a fastener, and at a still lower level it is controlling actuator voltages. In a hierarchical control scheme, high-level commands are decomposed until they become specific, time-phased instructions for actuators and sensors. Sensory information, on the other hand, is combined further up the hierarchy into symbolic descriptions. There is extensive interaction between control levels.

A hierarchical decomposition might involve the following levels:

- Central Control Station.
- Agent.
- Task.

- Process.
- Coordination.
- Axis and Detection.

These control levels do not necessarily have well-defined boundaries. Each involves both control and perceptual functions.

The *central control station* supervises several telerobots. It handles communications and operator interfaces (including speech control, displays, and force-reflecting master controls). It also provides interactive task planning aids and models of vehicle capabilities and configurations. Furthermore, it can access databases describing the entire Space Station and environment. From the station, operators can control telerobots directly or supervise nearly autonomous activity. As system capabilities evolve, the control station computers will do more of the overall task coordination and verification.

The *agent level* is an extension of the telerobot's on board control station. It handles communications and oversees dedicated activities such as startup and shutdown. It has access to information from all onboard control levels.

The *task level* is subordinate to the control station. It performs task activity planning and monitoring, and high-level perception such as situation assessment and recognition. It also allocates resources in response to the task, robot status and external situations and then initiates execution. Multiple subtasks may be active simultaneously. If the task level encounters situations it cannot handle, it notifies the control station. This level requires extensive symbolic processing. At IOC the task level will not be sophisticated, but its intelligence will increase with time.

The *process level* is lower still. It executes and monitors well-defined processes in known situations (such as installing snap-action girder fittings, and normal, obstacle-free docking) that can rely on simple geometrical perception and do not require a great deal of reasoning. Multiple processes can be active simultaneously. The process level can handle benign anomalies as reflex actions, but more severe problems require intervention from the task level. Process-level commands are decomposed into coordination-level commands and sent downward. Process-level capabilities will be fairly well-developed by IOC although space applications will require some testing.

The *coordination level* is subordinate to the process level. It coordinates and monitors vehicle actuators and sensors in several modes, such as position-force, stiffness, and velocity control, using information derived from perceptual processes. It takes account of kinematic and dynamic interactions. Sensor information fusion begins at this level, and is used to construct and maintain a stabilized low-level world model.

The *axis and detection level* is the bottom-most decision realm. It includes axis control in the servomechanism, sensing, signal processing, and feature extraction. Multiple sensing modes, including multispectral stereo vision, tactile, radio frequency, proximity and force, structural stress, axis position, velocity, and torque, might be included. An inertial reference unit is important as well. After closing the necessary low-level loops, the sensor data is processed and passed to the coordination level which uses it in world model construction and maintenance as described above.

Control System Evolution

In the near term, humans will handle most of the difficult cognitive processing, such as allocating resources, finding an object of interest in a cluttered scene, or responding to significant failures. The control system will coordinate axes autonomously and deal with well-defined and repetitive situations once humans have specified procedures and objects of interest.

By the year 2000, improvements in computing, machine perception, planning, and reasoning should allow telerobots to operate more autonomously and require less operator intervention. One would expect, for example, the systems to be able to recognize objects close to defined positions, plan paths automatically, and avoid obstacles.

Capabilities past the year 2010 are extremely difficult to predict. Still, it does not seem unreasonable to project that telerobots of that era will be able to perform many autonomous activities, such as cooperating with one another, assessing situations, and allocating resources optimally. They might be able to deal autonomously with significant error conditions that require recognizing distorted components and generating plans based upon functional needs (such as removing a blockage to clear an exit path) in real time. In this time frame, telerobots will require only minimal human intervention to perform their normal tasks.

3.3.3 Telepresence and Human Factors in Telerobotics

The term *telepresence* describes advanced telerobots with a high degree of integration between man and machine. For remote work this may require providing a quantity and quality of sensory feedback sufficient to approximate actual presence at the work-site. This will be a critical transition technology until robot autonomy is achieved.

In the IOC version of the Space Station, optimal telepresence will be essential to the effectiveness of remote manipulators. In addition to realism, the telerobot control station must provide interactive facilities that are efficient, comfortable, and do not lead to undue fatigue.

By IOC, it is possible to develop a telepresence system with the following major characteristics:

- Stereoptic color vision system, slaved to operator head motion.
- Head-mounted vision display.
- Paired 7-degree-of-freedom manipulator arms with force control.
- Force-indicating hand controllers or exoskeleton arms for control.
- Two grapple arms or one docking device.
- Interchangeable end effectors.

Sensory Technologies for Telepresence

Sensory technologies for the man-machine interface are essential to IOC telepresence capabilities. The following paragraphs discuss critical technology issues that must be addressed to meet initial needs and those beyond IOC.

Stereoptic vision provides the operator with depth perception, often critical to successful task performance. One approach to providing it may be mounting the principal stereo cameras on a platform with at least two degrees of freedom (tilt and pan). Because the operator's hands will be busy, the camera platform should be controlled by head motions, voice, or both. Computer control of the cameras to track the end effectors is also a desirable option. Other remote cameras should provide oblique and closeup views of the worksite. Color offers additional cues that aid in scene recognition and understanding, particularly in the unusual lighting conditions of space.

If the work-site cameras are controlled by the operator's head motions, then a head-mounted display is also desirable. A binocular display, for instance, works by providing a separate view for each eye. The display system should allow superposition of computer-graphic information, e.g., a heads-up display.

New display techniques will play a major role in allowing efficient telerobotics under conditions of noticeable time delays, such as when an Earth-based operator controls an experiment in geosynchronous orbit. Predictive displays will let the human operator see the effects of manipulator commands without delay. By IOC, the predictive and preview display could be a model-derived line drawing superimposed on the actual video image. In later systems, the predictive display could be an accurate computer generated image of a three-dimensional model of the manipulator's environment including high-resolution, real-time, shaded, and stereoscopic images. An automatic vision system could compare delayed returning images with the predictive displays and alert the operator to differences.

When the work is performed in a visually confusing or disorienting environment, (e.g., if the manipulator and work object are rotating, moving shadows could be distracting), a model-based display could represent the situation in a stable coordinate system and eliminate extraneous motion.

Visual fatigue may reduce productivity even in highly motivated station operators. All the worries about posture and lighting ergonomics apply here; in addition, the harsh visual environment of space prevents the beneficial effect of visual relaxation by viewing a distant natural scene. This is an area deserving of human factors study.

Information from tactile and other force sensors on the manipulator should be conveyed to the operator. Many current teleoperator systems accept force as an operator command, and lower-level servo loops direct the manipulator to exert that force. In the absence of time delay, this loop should be extended to provide force-feedback to the human operator.

Where there *are* time delays, predictive force feedback based on a dynamic model of the manipulator's environment will be useful to improve on the low productivity of move-and-wait tactics.

Computers in the manipulator supervisory control loops can assist with accurate sensing of the manipulator positions. Slip sensors are also useful to indicate when manipulators are losing their grip on objects. In general, force, torque, and position-sensing abilities appear necessary in a near-term telepresence system.

For telepresence systems beyond IOC, advanced contact sensors can give the operator detailed information on shape, compliance, slip, and contact forces at the worksite. Transformations of some sensory information may convert measurable inputs into other forms, e.g., texture into sound. Different operators would tune the telepresence system to suit their preferences.

Voice Recognition Control

Voice recognition is a current technology that is beginning to be applied in telerobotics. It will help increase the flow of information from human to machine without interfering with hand-controlled operations. Current applications of voice control include camera pointing and programming of set points to which the manipulator(s) and camera can be directed with a voice command. These applications are ideal for IOC because current technology can easily support their limited vocabulary requirements and the Space Station's small user population.

As supervisory control and then autonomous operation are realized, voice recognition and improved natural language understanding will allow the operator to communicate with higher parts of the hierarchical pyramid, opening the utmost flexibility in controlling remote operations. The supervisory control computers will be able to respond conversationally to the operator during teleoperated activities.

3.3.4 Perception

Perception is defined here as the translation of characteristic or relational object properties into the information required to perform a robot function. The properties can be geometric, mechanical, optical, thermal, acoustic, magnetic, radioactive, or chemical in nature. They are used to form a hierarchy of symbolic representations constituting knowledge about the state of the world associated with a given task at a particular time. Perception is critical to manipulation, in that the manipulator system must perceive the relationship between itself and its physical environment.

Perception is usually divided into two categories: noncontact sensing and contact sensing. Noncontact sensing refers to information-bearing signals generated by transducers that are not in physical contact with the object being sensed. There have been some notable advances in noncontact sensing, especially in the area of computer vision. A typical system involves a television camera interfaced to a computer that analyzes the scene being viewed. These systems may be used to inspect, count, orient, or locate parts and to guide the actions of manipulators. Currently available computer vision systems are inadequate for many planned robotic applications in space, due to the harsh lighting conditions and the unstructured nature of the workplaces. Other noncontact sensing techniques use other types of processes such as radar, sonar, or thermal emission.

Future Space Station robotic applications would be aided by a vigorous program of technology advancement in sensors. A critical area is the improvement of visual, tactile, and range transducers.

As the name suggests, contact sensing involves transducers that are in physical contact with the object whose properties are being measured. Contact sensing systems usually involve touch, force, slip, and pressure signals. Systems that perceive these types of signals are crucial to dexterous manipulation. The use of touch and force feedback can result in extremely high precision movements, even with an imprecise manipulator.

Touch or tactile sensing involves the measurement of very small forces at several points on the robot hand. Switches, piezoelectric devices, pressure sensitive plastics, and strain gauges may be used. At present, there are no adequate tactile sensor arrays, and the interpretation of tactile images is in its infancy. Tactile analysis will provide valuable information about the exact location, shape, and identity of parts in robotic applications. Force sensing provides information about the net force and torque acting on a manipulator hand. Forces can be measured by equipping a manipulator with a special wrist that has strain gauges or piezoelectric sensors. Force sensing is critical to precision position measurement since it allows small deviations to be translated into large forces that are easy to measure. A major area of research involves the development of methods for the fusion of data from a variety of sensors, especially visual and tactile.

3.3.5 Manipulation in Space

Virtually every manipulation task performed on Earth involves gravity. Screws can be rested in a hole in preparation for driving, objects will remain at rest because of gravity-generated friction, objects can be pushed and slid tangentially to horizontal surfaces, and mating surfaces can be brought together with little guidance using gravity-generated forces. Workers can apply torques by bracing themselves against the earth.

None of these familiar conditions need hold in space. The body forces can even vary continuously. This has two major consequences. One is that we will have to find substitutes for the steady force field normally provided by gravity. The other is that we will have to develop a branch of the *science of manipulation* that allows for variable acceleration vectors.

A related consideration is that Earth-based manipulation is limited to objects that can be lifted by a manipulator, or supported by air-pads, flotation, rafters, or balancing devices. In free fall, objects of great inertial mass can be manipulated because they are weightless. However, their acceleration is limited by the available manipulator force. More important, the relative velocities of interacting bodies must be limited to control contact forces during manipulation, assembly, or docking. Deceleration with maximum available force requires a finite distance to reduce relative velocity to zero to avoid uncontrolled (and possibly catastrophic) momentum on contact. As a result, there is a pressing need to develop predictive controls and displays. Control techniques that involve modeling of payload masses and prediction of their responses will be extremely important.

Researchers need to consider gravity *explicitly* for both terrestrial and space applications. This will result in a more fundamental understanding of manipulation in general.

Research efforts must be initiated in the following areas pertaining to manipulation in the variable-gravity environment:

- Development of a science of manipulation, independent of specific manipulator design or control.
- Specialized tactics for the variable acceleration environment.
- Actuator improvements (many implications for the entire field of robotics).
- Manipulator design.

3.3.6 Operation Planning and Databases

A hybrid system with both robot and teleoperator features can be a major tool with a long lifetime in the Space Station. As such systems become more autonomous, they will be able to perform more tasks, thus saving time for the human operator, one of the most valuable and costly resources on the Space Station. Key to the development of even low levels of autonomy will be CAD/CAM databases containing detailed descriptions of all components of the Space Station itself, everything within it, and every external object that the telerobot might encounter. Planning algorithms will be necessary to use the databases to generate programs for telerobot operation. A few simple examples will illustrate the areas requiring technology advancement.

The telerobot will perform materials handling chores that are hazardous, unpleasant, or inconvenient for people to do. Initially, this will be done via directly human-controlled teleoperation. Later, astronauts will be able to issue simple high-level commands to the robot. "Robot, push button A on panel X (perhaps located on a normally uninhabited module)." "Robot, turn dial B on panel X 10 degrees counterclockwise." "Robot, pick up container C and put it in storage bin Y." The human operator may have previously guided the telerobot to the vicinity of container C or panel X so that it does not have to search a wide area. A telerobot that can follow such simple commands can perform many useful housekeeping and experiment-management chores. With a suitable supervisory control system, any malfunction or uncertainty can interrupt the robotic activity, raise an alarm, and allow a human operator to take over.

Responding to such commands requires several levels of CAD/CAM-driven planning algorithms. At the top, a task-planning system will divide the task into simpler subtasks for which telerobot program segments can be generated automatically, based on information derived from the CAD/CAM database and on sensor inputs. For example, the command to push button A, would result in the generation of a program segment to make the telerobot scan the surrounding area with its vision system until it recognizes panel X. Next, a program segment would be generated to determine the relative position of the panel. From the database description of panel X, the precise location of button A can be determined. It is then a simple matter to generate the program segment to make the robot move to the button and push it.

Putting container C in storage bin Y involves computing from its database description a position for gripping the container. The next program segment would direct the robot to grasp the container. If the database contains descriptions of the storage bin and its location, a path to its vicinity can be computed. Program segments can be generated to make the telerobot move to the bin and place the container in it.

Generating robot program segments from database information is not simple, but is feasible during early Space Station operation with a modest research effort. The generation of program segments to make the telerobot move to the vicinity of the storage bin requires the development of path planning and obstacle avoidance algorithms. Also important is the development of a world model containing a description of every object in the domain of robot activity. This model must be updated frequently with information extracted from the robot's sensors. Potentially the most complicated part of the operation is the generation of the program segment to place the container in the storage bin. In a weightless environment, bins will probably be closed. The telerobot therefore must recognize that the bin is closed, realize that it must open the bin, plan how to open it, and then close it again after depositing the container.

A more complicated task would be simple repair by module replacement. "Robot, replace module D in device Z." Either via teleoperation or the inverse of the storage operation described above, the telerobot would arrive at device Z with the replacement module. Next, the telerobot must figure out how to remove the old module and replace it with the new one. In general, this is a very difficult problem. However, if the device were designed with automatic repair in mind, only relatively simple operations would be required, e.g., removing an access barrier of some kind, pulling the old module out, and pushing in a new one. Given the ability to remove and insert the modules, the planning issues reduce to determining where the objects are with respect to the robot. This problem can be solved by using information from sensors and the CAD/CAM database similar to that described above. Of course, there are also complex joint motion and contact force control problems to be solved.

While many of the individual capabilities required in the above scenarios exist, research is needed on several planning issues before the operations become feasible. A major challenge is to develop general ways for dividing programs into segments that can handle a broad range of situations. This requires investigation of the following problems:

- Task planning.
- World modeling.
- Motion planning.
- Knowledge representation.

Task planning research is needed to address the general problem of generating an adequate sequence of subtasks. It will involve expert systems and other artificial intelligence work. *World modeling* will address questions of how to acquire and represent information on the physical status of all points in the robot's work area. The world model will be used during robot operation to modify its planned behavior. Knowledge of how the robot is constructed will also be used.

Motion planning occurs at two levels, gross and fine. The distinction is generally more one of technique than principle. Gross motion planning typically involves determination of interference-free paths for a robot from one point to another. In fine motion, it is necessary to determine motion constraints and, perhaps, force or torque constraints among the objects to be manipulated. These constraints will influence program strategies for achieving the desired motions. The planned motions also require run-time strategies for obstacle avoidance and joint motion and contact force control; significant technology advancement is needed in these areas.

The principal issues in *knowledge representation* concern what information needs to be kept and how it should be represented and related to information typically kept in CAD/CAM databases.

The hybrid operation provides an ideal experimental domain for this advancement. Operations can be performed via teleoperation, initially. As autonomous capabilities are developed, they can be integrated into the system naturally, with the human operator providing high level intelligence and intervention in case of uncertainty or malfunction.

3.3.7 Maintenance of A&R Hardware

Self-calibration, or built-in auto-calibration, will be an essential feature of many automatic devices, control systems, robots, and teleoperators aboard the Space Station in the 1992 time frame. As an example, telerobots performing manufacturing or experimentation should have a reference home or base coordinate fixture in their work envelope. They would be programmed to go to the home position periodically. During this operational sequence, their joint encoders would be measured and recorded. The design of the home position fixture and the end effector would enable absolute accuracy of initial calibration. They would also, through use of instrumented-compliance features, enable the robot to return to the exact home position. This second set of encoder values would also be measured and recorded.

A comparison would next be made between the observed encoder values and the base assigned limits. Diagnostics could then discriminate between a possible mechanical or kinematic defect, or a dynamic control defect, should the inaccuracy be beyond pre-established limits. An astronaut would be informed of the problem and would question the computer to isolate it further. The astronaut would then decide whether to perform repairs.

In the year 2000 time frame, sufficient diagnostic data would be gathered and analyzed to allow long-term failure-mode prognosis based on well understood degradation of measured diagnostic parameters. The computer would detect these trends well in advance of failure and would inform the astronaut of mean time to failure and machine status. This feature would be of great value in critically designed machines such as large telerobots that may be occasionally subjected to overloads, excessive speeds, or unusual conditions. Such maintenance could greatly extend machine life.

By the year 2010, robots would be capable of diagnosis, prognosis, and a degree of automated self-maintenance. The astronauts' interface to the automation would be at a high, mission-oriented level and could include many extraordinary machine performance requirements. Any harmful operations would be performed within the limits of recuperation afforded by automated servicing, maintenance, or replacement of basic components. This intelligent extension of machine performance beyond continuous-duty, full-endurance parameters will be made possible by an expert system embedded in the machine controls. It would contain a knowledge domain of wear, fatigue, and yield strength values for all critical machine components.

Robots would maintain and repair themselves, other robots, and other automated equipment. This would require modular construction extending from the arm structure itself to the motors, resolvers, electronic drivers, and onboard computer systems. Besides permitting easier servicing, the diagnostic functions would then become much more specific in defining the device's fault and cause relationships.

To achieve the desired level of self-calibration, diagnosis, prognosis, and repair, research will be necessary in the following technological areas:

- Expert systems.
- Harmful effects of the space environment.
- Fatigue and wear rate information in the space environment.
- Automated servicing, maintenance, and repair of automation elements.
- Diagnostic sensor technology.

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- Fatigue and wear rate information in the space environment.
- Automated servicing, maintenance, and repair of automation elements.
- Diagnostic sensor technology.

3.4 IN CLOSING

This chapter has addressed the major robotics technology areas deemed by the Panel as critical to the Space Station. Progress in many of these areas will hinge on advances in *computer science* and *knowledge engineering*. The following chapter covers those technologies.

Chapter 4

COMPUTER SCIENCE AND KNOWLEDGE ENGINEERING

4.0 SUMMARY

New developments in computers, networks, databases, and artificial intelligence can make the Space Station more capable and less expensive to operate by

- Automating basic operations, thus reducing crew involvement and providing more consistent operation over long periods of time.
- Simplifying and automating the development and maintenance of onboard computer-based systems.
- Allowing large onboard databases with intelligent user interfaces. (These can result in greater Space Station autonomy, more automatic operation, and more extensive onboard manufacturing, training, and staging facilities.)
- Making the Station easier to modify, expand, maintain, and repair.
- Providing onboard expert systems to handle many routine tasks and reduce the Station's dependence on ground support and communications.

Current technology in *computer systems* has the following major limitations:

- Insufficient fault tolerance and inability to allow expansion and modification.
- Lack of standardization of computer languages and networking methods.
- User interfaces that cannot take advantage of or adapt to varied skill levels, and which do not explain their actions.
- Lack of adequate languages and development tools for real-time systems.
- Long lead-time for space qualification of hardware.

Current technology in *knowledge based and expert systems* has the following major limitations:

- Difficulty of defining and collecting knowledge.
- Slow execution.
- Lack of development tools and standards to codify and represent knowledge.
- Lack of tools for checking, verifying, and validating systems.
- Inability to effectively represent uncertainty and missing knowledge.
- Inadequate links between symbolic computational facilities and real-time or numerical systems.

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NASA should emphasize technology advancement in the following areas:

- Expandable, fault-tolerant, and secure hierarchical computer networks.
- Effects of radiation, vacuum, and low gravity on computing elements.
- Man-machine and man-computer interfaces for use in space.
- Small, specialized computers as hosts for limited-purpose expert systems.
- Modifiable and extensible expert systems capable of handling uncertainty.
- Verification of expert systems.
- Integration of expert systems and symbolic computing with real-time control and data acquisition and with numerical computation.

Vigorous and sustained activity will be necessary in order to bring about these advances. Exhibit H shows suggested categories (divided into areas in which NASA should *lead, leverage,* or *exploit*). The Delta column is the difference between the recommended *baseline* and *minimal* funding levels. The Fallback Order is the sequence in which categories might be reduced or dropped (lowest numbers first), in case of cutbacks, and result in the least harm to a high-quality program. Each category appears only in the most important applicable division; for example, we assume that NASA should also apply *leverage* or *exploit* developments in areas in which it must *lead.*

Exhibit H

A&R Technology Program: Information Management

	Category	Baseline Program ($M/year)		Minimal Program $M/year)		Delta $M/year	Fallback Order
		Research	Demos	Research	Demos		
NASA must *lead*	Exp. Sys. Mission & Payload Control, Planning, & Directing	5	1	2	•	4	8
	"Smart" Simulations	8	2	5	1	4	8
	Fault-Tol., Reliable S/W Tools	6	1	4	•	3	7
	CAE Standards	2	•	1	•	1	5
	S/W Language Standards	2	•	1	•	1	5
	Auto. Design-For/Integr. Techn	3	•	2	•	1	3
NASA applies *leverage*	Space-Related Custom H/W	1	•	•	•	1	8
	Communications Networks	7	1	5	1	2	8
	Large-Scale Databases	5	1	4	•	2	8
	Knowledge-Based System Dev.	8	2	5	1	4	8
	Sensing Algorithms*						
	CAD-Directed Programming	3	1	2	•	2	6
	Real-Time Exp. Systems	2	•	1	•	1	4
	Facility "Seed" Funding	5	•	2	•	3	2
NASA can *exploit*†	Computer Architecture & Chip Technologies	3	•	2	•	1	1
	Speech Technologies	1	•	1	•	•	•

* Money applied in Man/Machine Sensors/Integration.
† Examples only.

The Space Station's control and information management system incorporates most of the requirements that motivated the Japanese Fifth Generation Computing Project. It has a similar time schedule and promises similar spinoffs for the general economy. A major advantage of the Space Station project, however, is that it has a specific aim and is therefore less likely to suffer from a lack of practicality, overall direction, or visible progress.

4.1 CRITERIA AND RECOMMENDATIONS

This chapter focuses on Space Station developments needed in the areas of computers, networking, database management, and expert (knowledge-based) systems. The fundamental aim here is to create and sustain a state-of-the-art control and information management system in the Space Station.

4.1.1 Criteria

We may divide our underlying criteria in this chapter into design principles and operating methods. The *design principles* we intend to promote are

- Allowance for continued growth and reserve capacity in computing power, network capacity, database storage, and high-speed communications.
- Allowance for ever-increasing automation, leading toward eventual reduction of human involvement in routine functions.
- Standardization and restriction of the number of computer languages, interfaces, networking methods, and database formats.
- Requirement of fault tolerance and spaceworthiness.
- Use of state-of-the-art hardware, software, and methodologies to the limits allowed by more efficient space qualification standards.

The *operating methods* we intend to promote are

- Ever-increasing autonomy of the Space Station from ground control.
- Simplification and automation of mission and payload planning and control.
- Allowance for periods of crewless operation of the Space Station.
- Allowance for monitoring, direction, and control of the Space Station from ground operations, if necessary.

4.1.2 Principal Short-Term Recommendations

The following are important short-term goals in the area of information systems:

- *Develop a secure information system architecture* with centralized control, distributed processing power, fault tolerance, reserve capacity, and extensive expandability. The system should link all computers in the Space Station.
- *Develop a standardized network interface and protocol* that allows for expansion, high data rates, and media independence.

- *Select a restricted set of high-level languages* on the basis of functionality, portability, standardization, and conformity with modern software engineering principles. There should be only one language used for general operations and one for knowledge engineering. Special languages required for database management, simulation, robotics, etc., as well as simplified user interface dialects and program design languages, should incorporate routines for translation into these basic languages.
- *Attempt to develop knowledge databases and advisory expert systems* in the areas of planning and scheduling, mission and operational control functions, environmental monitoring, power distribution monitoring, equipment diagnosis and repair, communications, health maintenance, and inventory.
- *Develop an onboard interactive workstation* with symbolic programming capabilities and a graphical user interface for: running expert systems, training and briefing, scheduling and planning, and information retrieval and management.
- *Start developing an integrated Space Station database* to include computer aided design and computer aided manufacturing (CAD/CAM) parts and system models, operating methods, and programs for robots.
- *Establish a central NASA laboratory for knowledge engineering.* This should provide large-scale symbolic computational power and simulation facilities, software tools, program and knowledge libraries, and standard interfaces for connections to real and simulated equipment. It should allow for the definition, collection, and representation of knowledge for use in expert systems and other applications. The laboratory should also serve as the focus for training and for demonstrations aimed at showing project managers practical applications of knowledge-based systems.
- *Form knowledge-based application teams* to verify, validate, update, and extend knowledge-based applications for Space Station sub-systems. Each team should consist of a knowledge engineer, a subsystem expert, and an astronaut.
- *Investigate data storage and transfer methods* for representing, storing and accessing the large amounts of data required for information management, both onboard and on the ground, as well as methods for secure data transfer.

4.1.3 Principal Long-Term Recommendations

The following are more ambitious, long-term goals:

- Move from advisory expert systems to actual control of selected major functions.
- Move from heuristic, rule-based expert systems toward model and reasoning-based systems that include: common sense reasoning, extensibility, self-learning, and methodologies for making constrained decisions when available knowledge is incomplete or uncertain.
- Develop expert systems for more general applications such as navigation, surveillance, construction, manufacturing, satellite repair, and crisis management.
- Upgrade onboard workstations to allow extension, modification, reprogramming, verification, and validation of expert systems.
- Extend onboard simulation capabilities.

- Extend the NASA knowledge engineering facility to include simulation, verification and validation, and checkout.
- Integrate expert systems for unified information and control.
- Develop standards for the specification of knowledge as part of the documentation of all subsystems.
- Develop methods and standards for automatic logging of events such as repairs, maintenance, and manufacturing operations for use in CAD/CAM and knowledge databases.
- Move databases to onboard storage with ground backup.
- Develop standards for security and privacy of databases and communications.

4.2 THE OVERALL COMPUTER SYSTEM

The overall Space Station computer system must allow for incremental growth, provide reserve capacity, offer fault tolerance, and permit hardware and software changes without extensive redesign or reconfiguration. It should use a limited set of standard languages and network interfaces, and provide easily maintainable hardware and software.

4.2.1 Overall Architecture

The overall architecture must provide for modular growth, fault tolerance, maintenance of critical central functions, high-speed signal and symbolic processing, real-time operation of subsystems, and access to large amounts of on-line and ground-based storage. The requirement for modular growth means that the system must be largely distributed, allowing the addition of new computing units without taxing the capacity of a central system. The way in which the Space Station is to be assembled from modules dictates that the system must grow unit by unit. On the other hand, there must be a main control unit, with built-in redundancy, to provide overall direction and keep subsystems from conflicting with each other or interfering with vital functions.

The overall system may well have a hierarchical structure similar to the human nervous system. Elements would range from simple sensors and actuators at the periphery, to the main control unit. Technological advances will surely allow ever more powerful machines in space. While the Initial Operational Capability (IOC) computing elements may be largely dedicated microprocessors and minicomputers, later units may be the equivalent of today's supercomputers or experimental parallel processors.

Certain issues here require further study; there are two questions of special importance:

- Should the IOC system include a central machine with much greater capabilities than any of the others? This could be a miniaturized version of a modern mainframe. The alternative would be to use only specialized minicomputers with optimized firmware.

- How will the onboard system provide the large amounts of on-line storage required? Hard disk units are bulky and delicate, current videodisks are not writable, and solid state bulk storage is still in the experimental stage.

Developments in computer architecture, hardware, operating systems, and mass storage devices are proceeding rapidly. New very large scale integration (VLSI) chips may incorporate many complex control, simulation, and CAD/CAM operations, thereby greatly increasing the speed and reliability of specialized small computers. Flexible operating systems for supercomputers may soon enable them to operate like high-speed versions of today's multi-purpose minicomputers. Moreover, new non-von Neumann architectures featuring massive parallelism and different processing concepts, (such as data flow) are under intensive development. Finally, several new mass storage architectures (user-shared, distributed function, etc.) have appeared with up to terabyte capacities and gigabit per second transfer rates. The best approach may be to allow as much time as possible for these developments to mature before making final hardware decisions.

We should note that the automation and robotics programs outlined by the contractors all assume an expanding network of relatively small, specialized machines. This could create several problems, including unreliable elements, conflict resolution between elements, safeguarding vital functions, and achieving a final integration of unprecedented complexity. The architecture should be able to incorporate new machines, while retaining the system's security and fault tolerance. Thus, the main control module should monitor all system elements and take action when it discovers aberrant behavior.

There should also be an Earth-based computer development system capable of functioning as a backup for the onboard system through a high capacity communications link. The system should also allow backup control and status reporting through the ground link. This would permit ground-based personnel to monitor and control operations directly if no crew were present, or under emergency conditions.

The Los Alamos experience, discussed in Appendix 4-A, favors distributed processing along with centralized and redundant control. A hierarchical design will allow an initially centralized system to change over into a highly distributed one as the Space Station evolves. This will avoid both obsolescence in the IOC and expensive retrofitting. Designing the system to decentralize further in time will allow more functionality, higher performance, and greater reliability.

Special care must be exercised in system development to provide a high degree of fault tolerance for the main control and other critical functions. Failure anywhere in the hierarchical system, even at the top, must not affect essential operations.

Evolution of the Space Station will require both an expansion of the overall computer system and the development of more powerful subsystems. Improved communications, more capable specialized peripheral processors, and intelligent robots and sensors will all be necessary as the Space Station grows in size and functions. It is of primary importance to emphasize this networking aspect of the design from the outset.

4.2.2 Designing for Growth

The key to designing for growth is to make the computing and communications software as hardware-independent as possible. The ideal approach would be to specify the system tasks and software first, delaying the selection of hardware as long as possible. In practice, however, the hardware's physical and electrical characteristics must be determined early in the design process to allow allocation of space, cabling, and power. This still allows upgrading later if the software uses portable, standardized high-level languages, and if the system features standard, expandable interfaces. During the past decade, technological advances typically have resulted in more powerful computers with no increase in space or power requirements.

Other factors that allow for growth include

- Reserve network bandwidth, computing power, and database storage capacity.
- Self-configuring systems software, in which the operating system automatically determines the current system resources and reconfigures itself appropriately.
- Modules that are self-identifying by name and function.
- Onboard development, test, and simulation facilities.
- Secure fault-tolerant systems that protect existing computing elements from interference when new elements are added.

4.2.3 Computing Elements

Initially, most onboard computers will probably be traditional single-processor von Neumann machines. Later, however, the network may include parallel machines, specialized units, and peripheral processors of various types. While such machines are now in use, practical experience with them is limited and little systems software exists. Not much is known about making them fault-tolerant, and adequate tools for development and evaluation are not yet available.

One way to achieve greater computing power eventually is through the use of specialized hardware units aimed at specific classes of problems. For example, array processors outperform comparably priced general purpose computers by factors of 10 to 100 on such tasks as Fourier transforms and finite element analysis. A typical application on the Space Station might be the control of autonomous vehicles, where specialized machines could handle cognitive functions, control, and communications. Appendix 4-B describes a comparable application involving a submersible robot vehicle.

A specialized machine requires a definition of the nodes and processing elements, an architecture to interconnect the elements, and software. Many different interconnection methods (e.g., Boolean n-cubes, trees, perfect shuffles) and meshes and nodes (e.g., ones capable of performing floating point, search, and logic operations) have been proposed, as have a number of languages and operating system concepts for exploiting parallelism. The importance of software development cannot be overemphasized. Existing languages, software tools, and performance measurement tools are generally not applicable to specialized architectures.

DARPA has a program in progress to develop and evaluate specialized computers for signal processing, symbolic processing, and multiple functions. The program involves building several prototypes to compare different approaches. Each of the basic areas is discussed briefly below. Candidate architectures include parallel processors, uniprocessor LISP machines, and multi-function hybrids with at least 1000 processors. The project also involves the development of software support, programming languages, and programming environments. NASA should arrange to participate actively in this program through personnel exchanges, joint committees, and review procedures.

Signal Processing

Signal processing involves taking real-time data from a sensor and performing a series of operations on it. These may include transformations (e.g., Fast Fourier Transforms, correlations, and filtering) and are dominated by multiplications and additions. Computational rates in excess of 1 billion operations per second are often needed. Applications include radar, sonar, image, and speech processing.

Modern signal processors use grouped computing elements such as systolic arrays. These involve many simple elements arranged in a highly regular structure which "pump" data from cell to cell in a wave-like motion to perform successive operations. The aim of the DARPA project is to use this architecture to build a system capable of executing 1 billion or more operations per second by 1986 and to proceed toward one capable of 1 trillion operations per second by 1990.

Truly advanced vision systems seem to require about three orders of magnitude more processing capability than is now available. One way to provide this could be through special components interconnected to exploit their inherent parallelism via general-purpose host computers or by high-speed networks.

Symbolic Processing

Symbolic processing deals with relationships between non-numeric objects, and with the inference or deduction of new information through reasoning. Examples of symbolic computation include searching and comparing complex strings and images (e.g., partial pattern matching). Applications requiring large amounts of symbolic processing include vision systems, natural language systems, speech understanding, and planning.

Most processing of this type is now done in LISP; special LISP machines are available commercially, offering computing rates in excess of one million instructions per second. DARPA expects to develop machines with about 50 times this performance level using advanced technology. The Japanese are pursuing a similar program based on the PROLOG language which, though far less widely used at present, is receiving considerable attention.

Multi-Function Machines

A multi-function machine can execute a wider range of tasks than specialized processors but at lower speed in any particular problem area. Its processing elements are usually general-purpose processors communicating either through shared storage or a high-speed network.

A key problem in utilizing multi-function machines is the development of models and algorithms for concurrent programming. Typical models include control-driven, data-driven, and demand-driven representations. In the control-driven case, as exemplified by concurrent PROLOG and parallel LISP, the arrival of the requisite operand set drives actions. This model has the advantage that concurrency can often be specified implicitly. The data-driven model requires the arrival of data at a computing element, whereas in the demand-driven model, a demand for results is necessary to invoke further actions. Of course, composites of these models such as concurrent object-oriented programming have also been proposed.

4.2.4 Networks

Almost every computer in the Space Station will require interprocessor communications. Thus the Station must have a sophisticated networking capability built in during the earliest stages of its development. This network must also

- Possess considerable excess capacity.
- Use standard protocols.
- Have high bandwidth and the ability to accommodate a wide range of data rates.
- Be media-independent.
- Allow widely varying data rates.
- Permit easy expansion.
- Allow the attachment of a large number of devices.
- Provide for fault tolerance and graceful degradation.

Many intrasystem communications methods have appeared in recent years. While they are mostly serial, high bit-rate systems based on coaxial cables or fiber optics, they are generally incompatible because of differences in cabling, protocols, and physical connectors. Standards such as the Institute of Electrical and Electronic Engineers Token Bus Standard (a token-passing algorithm for media access by peer network interfaces) are therefore essential. NASA must stay abreast of new developments in this area and assist in efforts to create additional standards in related areas.

4.2.5 Network Interfaces

The wide variety of boundaries between subsystems demands special attention. For example, the power distribution system should allow mobile devices to acquire power for themselves and for tools and equipment at a wide variety of locations. A robot should be able to proceed under its own power to a failed part, attach a data cable to the network, take measurements from the failed part, and report these to the central diagnostic and control system.

One way to reduce the large amount of cabling required is through the use of intelligent interfaces. These microprocessor-based systems can be installed close to equipment and can perform low-level control, data collection, conversion, error-checking, and communications functions. Such interfaces also reduce the need for centralized computing power.

4.2.6 Computer Languages

Careful standardization of high-level languages is of prime importance to the Space Station's information and control system. The languages should be standard portable ones available on many computers, and the number should be restricted as much as possible. Those selected should also have well-developed sets of software tools and complete programming environments.

Typical candidate languages include Ada and C. Ada has facilities for program and data abstraction, mechanisms for handling timing and concurrency, provisions for control over number representations, and the ability to handle entire software systems as packages. Moreover, DoD's efforts to standardize Ada and enforce its use should ensure the availability of compatible compilers for new generations of computers, and should result in acceptable portability. The C language is a highly efficient, block-structured language widely used in systems programming; it is also the native language of the popular UNIX operating system. NASA should compare languages for a variety of required Station functions before adopting one as its general-purpose programming language.

A specialized language for artificial intelligence will also be necessary to handle symbols, lists, and logical relationships. It should be capable of extensive program recursion. As suggested earlier, the leading candidates in this case are LISP and PROLOG. NASA should also conduct a comparative study of these two languages to determine which is best suited to Space Station applications. Both DoD's efforts to promote the improvement and standardization of LISP, and the Japanese attempt to do the same for PROLOG in their Fifth Generation Computing Project should be monitored carefully.

Robot programming, database querying, simulation, and other applications will require specialized languages, but all statements in these should be translatable into the general-purpose language ultimately selected. Chapter 3 contains more details on the development of programs for robots.

The need to reduce the cost of developing and maintaining software is a primary reason for choosing no more than two modern high-level languages. Ada, in particular, has been designed specifically to promote the development and maintenance of large-scale embedded software systems. Several studies have shown that over half of the total software cost can go into maintenance for large projects. The key to effective software maintenance is to plan for it during the design and development phases. Special emphasis on documentation and the use of software structures that facilitate understanding and modification is required. The Space Station software development environment, as described in Attachment C-9 to the Space Station Phase B request for proposals, deals with these issues extensively.

4.2.7 Real-Time Systems

The Space Station's overall control and information management system will include many real-time systems. Initially these may involve telerobots and CAD/CAM systems as well as traditional control systems. Among the required capabilities are

- Data acquisition at many different rates.
- Coordinated real-time control of distributed devices.
- Millisecond process cycle times.

As more of the Station's operations are automated, real-time computing requirements will increase. For example, robot arm control will require cycle times on the order of 1 millisecond, and joint force or motion control using force or tactile sensors may have to be even faster. This highlights the need for a general purpose language capable of handling real-time and concurrent operations. In fact, the language should be able to accommodate a variety of distributed devices within a single program.

Clearly, development and performance evaluation tools for real-time systems will be required. Real-time software for multiple parallel processes and distributed execution is particularly difficult to develop, and no highly efficient implementation has yet appeared. Since the Space Station software will be one of the first large, complex applications using such features, NASA will have a strong stake in its quality and efficiency. This calls for active efforts to perfect it from the start.

4.2.8 Man-Machine Interfaces

The design of man-machine interfaces will be of utmost importance, as discussed in Appendix 4-C. They should feature touch-menu input, graphics, and voice techniques, and should provide physical cues for robot operations, such as feedback when teleoperating a robot arm. High resolution graphics and novel display techniques will be important, as will methods for interacting with expert systems and other decision support systems.

In particular, interfaces based on voice commands and natural language are desirable to increase productivity. Appendix 4-D describes some of the considerations involved. Such interfaces improve man-machine interaction under a variety of working conditions, including work in a pressure suit. However, they will require the development of a standard natural language shell, restricted continuous speech recognition, and perhaps a limited language translator for foreign astronauts.

Since many Space Station applications will involve critical functions, speech verification will be required to prevent harm arising from inaccurately spoken or interpreted commands. Voice verification will also be needed to prevent interference by unauthorized personnel.

4.2.9 Fault Tolerance

The Space Station's information management system must have the following fault-tolerant features:

- Ability to withstand computer, communications link, network, and peripheral failures, and to re-route channels around a point of failure.

- The highest possible level of survivability for life support systems.
- Fail-operational features for all critical systems.
- Ability to detect erroneous commands and data inputs.
- Recovery to a consistent state after failures.
- Automatic detection of and recovery from failures.
- Allowance for system growth and reconfiguration.

The remoteness, cost, and criticality of Space Station systems require ultra-high reliability of critical core functions as distinct from less stringent payload/experiment requirements. The distributed system as a whole must be able to recover from a failure of any part. This has far-reaching implications for the software that must execute on the system, and is an area requiring considerable additional research and development.

4.2.10 Space Rating of Computer Hardware

One major impediment to NASA's keeping up with the state of the art in computer equipment is the need for space-qualification. Often, by the time equipment has been space-rated, it is already obsolete in the commercial world. This is especially irksome where ultra-reliability is not an issue, as in non-core, experiment-related hardware.

Among the methods NASA should explore to avoid or alleviate this problem are

- Use of non-space-qualified hardware for non-critical functions. Astronauts have already been allowed to take personal computers aboard the space shuttle. This practice should be continued and other standardized computing elements, such as Winchester disk drives, should be tested as missions permit.
- Capsules for isolating standard equipment from the space environment.
- New general standards for space qualification on a series of levels.
- Designs based on military-qualified devices and standards. (A typical example would be the use of microprocessors conforming to Military Standard 1705A. These are highly capable, rugged, and radiation-hardened. The Jet Propulsion Laboratory is currently using them in its MAX multiprocessor system which can be configured to meet a wide range of fault tolerance and speed requirements.)

4.2.11 Technology Advancement Areas

In summary, key technology advancement areas in computer and software systems requiring special NASA efforts include

- Comparative analysis of current general-purpose and artificial intelligence languages.
- Development tools for real-time, parallel, and distributed systems.
- Development of reliable, fault-tolerant, distributed computer systems.
- Methods for protecting non-space-rated computing hardware.
- Metrics and evaluation methods for software reliability.
- Development of specialized VLSI chips for robotics, CAD/CAM, image processing, speech processing, networking, and interfacing functions.

4.3 DATABASE ENGINEERING

Equal in importance to the Space Station's computing and networking capabilities is the definition of the structures and representational characteristics of the databases involved. The Space Station will have a variety of database requirements. It will need, for example, technical information on all aspects of its own design and operation, the satellites to be serviced, and the experiments to be conducted. This data will be necessary both for the automated repair and assembly capabilities that will be developed and to assist human maintenance activities. In general, the Space Station databases must provide

- Incremental growth and reserve capacity.
- High-speed access to large amounts of data.
- Various types of information, including textual, video and experimental data, CAD/CAM representations, programs, and procedures.
- Earth replication backup.
- A standardized structure.
- An intelligent interface and simplified query language that provide easy access for human users, computers, and robots.

4.3.1 Database Contents

The overall database should include

- CAD/CAM data. All contractors should be required to provide this in machine-readable form and in a standard format.
- Activity logs and schedules. These should replace the traditional briefing binders and flight datafile notebooks.
- Repair and servicing data.
- Knowledge collected for use in expert systems.
- Inventory and location data.
- Images of parts for use in computer aided manufacturing.
- Text and pictures for use in simulation, training, and briefing.
- Manufacturing control information and rules for simple fabrication on site.
- Programs for use with robots and other automated equipment.
- Technical information on satellites and experiments.
- Experimental data.

Note, in particular, that information on geometries of components, their locations and interconnections, their assembly or disassembly, tolerances, materials, and surface properties will all be necessary. A significant fraction of the databases will come from industrial systems; hence, compatibility with these systems will be important, and the designers of the database systems must try to achieve this with a minimum amount of translation software.

4.3.2 Data Management Technology

NASA has already initiated a program in data management technology. Its goal is to define an adaptable high-performance system architecture that can serve any conceivable mix of sensors, data processors, mass storage, and communications systems. And, as has been emphasized previously, the Space Station's data management system must be able to survive operationally if any part fails or is damaged. It should also be able to adapt easily to changing applications, preferably without intervention by crew members. Furthermore, it must feature a common data interchange medium between subsystems with widely differing internal technologies.

A truly adaptable data management system requires massive reserve capacity. It should also possess many nodes for accommodating an extensive onboard network. Three technology areas will contribute toward this end: 1) electro-optical components, 2) advanced networks and protocols, and 3) modeling and analysis tools. It is important for NASA to extend its data management technology program to include distributed databases that are fully compatible with distributed processing techniques.

4.3.3 CAD Database Requirements

Computer aided design is one of the most widely discussed automation technologies of our time. It promises to alter dramatically the way products are conceived, designed, pretested, critiqued, and turned into hardware. NASA has shown its awareness of this area's importance by insisting that Space Station contractors present designs in a uniform CAD format. The graphical kernel system is part of a nationwide effort to develop universal representations for three-dimensional moving part arrays that contain physical parameters as well as geometric descriptions.

Uniform CAD standards will allow NASA to evaluate and compare alternative designs with identical test procedures, and to experiment with high-speed processors much more intensively before building initial prototypes. Form and fit, which drive hardware costs up as physical models are revised, can be optimized and tested on a computer screen.

Today, shuttle operators rely heavily on paper backup for every mission. This mass of documents must be condensed, coordinated, and unified into a usable database if the Space Station is to reach its planned level of capability. The database must include all design representations from overall function schematics to CAD images of individual parts, and provision should be made to incorporate new data as it becomes available. Such a database will be required to control robots, operate manufacturing facilities, and assemble structures. As has been stressed previously, allowance must be made for object recognition; that is, the database must include representations of parts and assemblies for use in pattern and visual recognition systems.

For possible future use in automated on-site fabrication and assembly, the database should also include such manufacturing information as process parameters and sequencing details. This kind of stored information will be essential to meet the long-term objectives of creating autonomous intelligent robots and fully operational expert systems. For the IOC, existing orthographic part representations common to most CAD systems should be adequate. However, a mechanism such as bar code identification will be necessary for inventory management and to help teleoperated robots recognize parts.

Chapter 2 notes that these CAD images should be accessible through a Space Station simulator, available to both the crew and ground support personnel. Initially, the system should perform only two functions: 1) storing the support material now kept on paper, and 2) allowing total inventory control. Later, however, it should enable an astronaut to sit at a display and "walk" through the station, seeing depictions of all parts in their current locations, with symbols representing their status. Eventually, this should lead to an intelligent system that continuously works through a variety of scenarios to predict failure modes.

In the mid-term 2000 time frame, the CAD system should be coupled with geometric modeling software to generate three-dimensional graphical representations of parts. These could then be used in heads-up displays, information management systems, and simulations.

4.3.4 Large-Scale Databases

As information needs grow and as expert systems, CAD systems, and intelligent robots come into widespread use in the Space Station, very large amounts of data will accumulate. This will surely be in the terabyte range and may possibly involve many terabytes. NASA must plan now for the secure storage, maintenance, enhancement, and retrieval of this data.

If, as is likely, much of it is stored on the ground, high-speed communications channels will be necessary to move portions to and from space. These links will require high-reliability error-correcting coding. They will also need encryption to provide security for military applications, confidentiality for private company data, and privacy for data such as medical records and personnel information.

As the amount of data increases, onboard databases will require new mass storage architectures with larger capacities, dedicated processors, and special high-speed interfaces. Proper attention to the storage and manipulation of data on an unprecedented scale may be crucial to the entire Space Station effort.

4.3.5 Technology Advancement Areas

In summary, key technology advancement areas for NASA to track or influence in database engineering are

- Distributed databases.
- Methods for managing and accessing very large databases, such as dynamic buffering, associative masking, and self-structuring.
- Intelligent database interfaces accessible by humans, computers, and robots.
- Standards and methods for database security, confidentiality, and privacy.
- Space-rated mass storage systems with terabyte capacities.

4.4 EXPERT SYSTEMS

An *expert system* is a computer program that uses knowledge and reasoning techniques to generate advice and make limited decisions normally requiring the abilities of a highly trained person. Recent advances in computer languages, computer technology, and artificial intelligence have led to widespread interest in and experimental development of such systems. Typical example application areas include electronic circuit design, computer systems configuration, computer aided instruction, medical diagnosis, geological evaluation of sites, oil well dipmeter analysis, locomotive maintenance, and aircraft carrier flight operations.

Such systems have obvious applications in Space Station activities planning, maintenance and repair, system monitoring, environmental monitoring, communications, medical information and diagnosis, and mission and payload control. Factors that particularly favor their use include heavy crew workload, variations in crew training, and the need for Station autonomy.

4.4.1 Development of Expert Systems

The design, debugging, optimization, and validation of an expert system is a major undertaking. One may take years to develop fully, even if design tools are available. Initial versions usually run slowly, yield inaccurate or inconsistent results, and provide misleading explanations of their methodology.

The following steps are necessary to produce a useful system:

1. Collection of knowledge through extensive interaction with human experts. This stage often takes man-years of strenuous effort.
2. Development of a representation for the collected knowledge.
3. Programming of the application system, either in a symbolic programming language such as LISP or PROLOG, or in a higher-level applications language.
4. Validation of the system through consistency checking, testing, evaluation by experts, and operation by potential users.

These tasks are currently done largely *ad hoc*, and are very time consuming. Standard methods must be developed.

A further problem in developing expert systems for the Space Station is the obvious lack of relevant experience. There are no experts with years of Space Station work behind them. Initial experience must be derived from previous missions and simulations, and the systems will have to be refined through feedback from actual operating experience. This places major importance on the development of systems that are flexible and extensible, and on the establishment of procedures and standard methods for deriving knowledge from mission experience.

4.4.2 NASA Knowledge Engineering Laboratory

Because of the difficulty of developing the needed expert systems, it is recommended that NASA establish a knowledge engineering laboratory. This facility could provide a focus for system design, development, coding, debugging, testing, validation, documentation, maintenance, and extension. Its core should consist of packages aimed at solving a few key types of problems such as equipment maintenance, information retrieval, task planning, and monitoring. These packages could include software tools and symbolic simulations. Each simulation could contain a subsystem model and allow fault injection, as well as viewing and analysis of outputs. There should also be tools for consistency checking, verification, and performance evaluation.

The laboratory could serve as a resource for system teams consisting of knowledge engineers, experts on particular subsystems, and astronauts. Team members should be able to access its facilities over a nationwide network such as SPAN or the ARPANET.

The laboratory staff could also assist NASA in the following areas:

- Personnel training.
- Demonstration projects.
- Specification and collection of knowledge.
- Automation of development methods.
- Standards for knowledge databases provided by contractors and equipment suppliers.
- Monitoring of contracts involving the development of expert systems.
- Standards for testing, verifying, validating, and documenting expert systems.
- Development of new tools for automating knowledge acquisition, validating knowledge databases, and comparing alternative techniques.
- Integration of different views of the Space Station (e.g., electrical, mechanical, and life support) in a database system.

4.4.3 Demonstration Projects in Expert Systems

It will be important to test demonstration expert systems in space as early as possible. One approach would be to develop carry-on projects for the shuttle. Another is to develop initial advisory systems for use in both the IOC and ground operations. Early systems may provide no more than: 1) informational responses about operating procedures, security management, fault isolation, maintenance, and repair of basic control systems; 2) simple interactive systems for crew training through computer aided instruction and simulation, crew activity planning, and management of construction projects, experiments, and manufacturing processes; and 3) first-stage robot control.

Early goals should include

- Specification and initial development of a structured database that will eventually contain information about the Station's components, control systems, experiments, and operating principles.
- The codification of mission and payload control procedures and of knowledge gained from previous projects (Skylab, Spacelab, and shuttle missions).
- The development of an interactive onboard workstation capable of running expert systems. It should have a user interface featuring touch menus, voice input, graphical information displays, and functional simulations.
- The demonstration of ground-based expert systems for planning, fault diagnosis and repair, and health maintenance.

The Space Transportation System (STS) offers an environment for aggressive development of expert systems initially as consultants and later as control elements.

Consultant demonstrations are under way for shuttle navigation (high-speed re-entry, ascent). Expert systems for control and monitoring of computer resources, structuring of simulations and control of the STS power systems are under development. The structured nature of STS operations lend themselves well to the process of embedding the experience of human flight controllers in expert systems. This will result in the accumulation of extensive human experience rather than its loss through retirements, reassignments, or forgetfulness.

4.4.4 Expert Systems in the 2010 Time Frame

In the 2010 time frame, onboard expert systems should function as part of an integrated information and control network, capable of long-term automatic operation including self-repair. The network should feature massively parallel processing, qualitative decision making on the basis of incomplete or even partially inaccurate information, and accumulation of expertise on how to solve a wide variety of operating problems.

Real-time response should be possible for information and simulation systems, especially in crisis situations. All network and machine operations should be transparent to the user. Interfaces should be voice or touch-menu driven. Each early subsystem should allow the introduction of more competent and powerful hardware and software as it becomes available. Note that all of this assumes both reserve capacity and modularity in the network and in its computing elements.

Later systems should also feature

- Self-learning and modifiability.
- Onboard updating of the knowledge database, extension and reprogramming of the system, and revalidation of its consistency, accuracy, and fault tolerance.
- Effective handling of uncertainty and missing information.
- Automatic collection of knowledge for inclusion in later versions.

4.4.5 Key Technology Advancement Areas

The areas in expert systems requiring development emphasis are

- Software tools and standards for consistency checking, verification, validation, and performance evaluation.
- Space-rated workstations.
- Implementations on special-purpose and advanced architecture computers.
- Real-time operation.
- Integration of systems under central control.
- Reliability and fault tolerance.
- Implementation of common-sense reasoning.
- Combinations including quantitative models and real-time constraints.

4.5 MATHEMATICAL METHODS

Whereas this report has emphasized applications-oriented research in information management, it should be remembered that the useful techniques of today had their origins in what were once obscure mathematical disciplines.

Progress in technical areas such as computer networks, fault tolerance, real-time systems, software reliability, CAD/CAM, distributed databases, and expert systems, depends strongly on the development of adequate mathematical foundations. Subjects such as sensitivity analysis, optimization, graph theory, nonlinear analysis, computational complexity, finite mathematics, linear and dynamic programming, and information theory require further exploration. Appendix 4-E describes several relevant mathematical topics in more detail.

It is recommended, therefore, that NASA pursue a development program in mathematics with an emphasis on crucial areas related to computer systems, computer algorithms, artificial intelligence, and special methods such as function-level programming.

Chapter 5

INTERACTIONS WITH PRIVATE AND GOVERNMENT SECTORS

5.0 SUMMARY

Interactions with other public and private institutions will be a key element in developing the Space Station and using it effectively. NASA should implement new incentives to encourage significant contributions from industry, national laboratories, and academia, and it should also take full advantage of major external advances in technical areas such as automatic control, computer aided design and computer aided manufacturing (CAD/CAM), and robotics.

The Space Station can be of significant use to other institutions as an experimental laboratory, for demonstrations of space manufacturing and assembly, and as a base for satellite servicing and other space operations. Space Station technology in automation and robotics can also result in general advances in factory automation, in the development of hybrid teleoperator/robots (telerobots), and in the standardization of computer languages, networks, and databases. Telerobots, in particular, should have widespread applications in handling toxic materials, construction, machine repair and maintenance, commercial and service work, military operations, agriculture, and services for the aged and disabled. Space Station applications can also demonstrate automated inspection systems, materials handling by remote control, and advanced manufacturing systems.

5.1 OVERALL STATEMENT

The Space Station program, including its automation aspects, will be justified by its benefits to society. Conversely, many public and private institutions will help make a highly automated Space Station technically and economically feasible. *Economic incentives should be designed to elicit contributions from these institutions.*

Besides NASA, the institutions involved will certainly include other U.S. government agencies, universities, industrial firms, and foreign governments. We shall discuss interactions with each of these. However, we will categorize key interactions as follows:

First, NASA will, in addition to its own internal expenditures, pay others to develop automated systems and techniques for the Space Station.

Second, industry, government, and universities will use the Space Station's unique facilities in two ways: those subsidized at least in part by NASA (e.g., for training or basic science) and those paid for by users. Fees for the latter will partly offset the costs of the Space Station.

Third, and perhaps most important, are the external effects. That is, the construction and evolution of automated systems for the Space Station will produce new technologies and procedures that will benefit society in many ways. These benefits could include the standardization of computer languages, development of robots and expert systems with terrestrial applications, and medical research in space undertaken jointly by the U.S. and foreign governments.

5.2 INSTITUTIONAL CONTRIBUTIONS TO THE DEVELOPMENT OF SPACE STATION A&R

We shall first discuss incentives for institutions to contribute R&D efforts to Space Station automation. Here we confine ourselves mostly to principles rather than contractual details. Second, we discuss specific kinds of technology transfer from the private sector to the Space Station.

5.2.1 Incentives

To design incentive mechanisms, we need to discuss the objectives of both NASA and its contractors when they contract for development work in robotics, automation, and artificial intelligence (AI).

What does NASA want?

NASA's primary objective is progress in automation and robotics for use in the Space Station. Specifically, NASA could use two approaches:

- It could sponsor more fundamental, less goal-oriented work. Such work is open-ended, and its course and destination cannot be pre-specified. The scientist follows where the problem leads with the aim of increasing understanding. Such work can sometimes result in a giant step forward. The difficulty is to couple it to mission objectives. In an industrial laboratory, this coupling can sometimes be accomplished by the sensitive intermediation of skilled R&D managers. It is not clear to what extent such coupling can be accomplished in *contract* research, even in the presence of a technically outstanding overview committee.
- NASA could lead the R&D by setting out a sequence of short-term, small-scale technological problems, a little beyond the state of the art. NASA would define this sequence using its own internal technical expertise. Providing incentives for such work is a standard problem; presumably the solution would involve periodic assessment and renewal of contracts contingent on accomplishment. This kind of project would appeal more to engineers than to those involved in pure research.

What do the contractors want?

The objectives of contractors are far from uniform. We will consider separately industry, government and national laboratories, and academia.

Private Industry

Private industry wants to maximize long-term profits from production, cost-reduction, product innovation, and expanded markets. Most industrial laboratories are not interested in working, or will not do high-quality work, for cost plus a percentage.

From the point-of-view of a profit-maximizing firm, R&D is a high-risk activity whose output is difficult to appreciate; hence, some additional incentive is required.

These considerations lead us to suggest that

1. *Incentive contracts* might provide for payment dependent on the success of the project, and exclusive rights to the new technology including, for example, sale of the resulting product to NASA, probably at a discount.
2. NASA might offer to private industry those projects that give promise, if successful, of *future production contracts.* NASA would have to be prepared to explain to the public that such contracts are not a subsidy to the industrial firm, but rather a normal reward for a risky undertaking.

National Laboratories

The objectives of government, national, and other non-profit laboratories include assurance of continued existence, growth, and maintenance of long-term scientific interests and styles. Here cost-plus contracts are a familiar and acceptable mechanism.

Academia

The objectives of academic organizations are similar to those of national laboratories, but with some differences. Contracts may be made with institutes and laboratories within the university, but here the individual researchers (professors) have much more influence on policy and research. Their objectives include recognition by their academic peer groups. It follows, for example, that open publication of research results is essential. Their research interests and criteria for success do not necessarily bear a relationship to NASA's objectives. Therefore, it is an important problem for NASA's management to identify individuals and groups at universities who are both creative and will try to help meet NASA's objectives. One means to this end is to maintain a strong R&D capability within NASA.

Note that even for national laboratories and academia, cost-plus contracts, while acceptable to the contractors, may not be desirable from NASA's point of view, since they lack incentives for efficiency.

We mention finally two additional incentives for an industrial firm participating in Space Station development. First, by being intimately involved in the project from the start, it may secure a long-term pipeline to important technical developments. Second, perhaps not trivially, the project will have a bonus of prestige both inside the industry and in society as a whole

It may be necessary to mount special efforts to encourage groups that would not normally be NASA contractors to participate in the Space Station effort. The use of contests, award programs, and other related techniques may be particularly applicable here.

5.2.2 Private-Sector Developments Applicable to the Space Station

There are areas of technology where the private sector has a clear lead, and where NASA could well benefit by *leveraging* development or by directly *exploiting* commercial products and techniques. As discussed in Chapters 2, 3, and 4, this may require some effort to develop new methods for space-qualifying terrestrial hardware. As will be noted in Chapter 6, the Space Station can be designed with the objective of increasing the use of systems developed for Earth markets. Fields chosen as examples are

- Automatic control systems.
- Environmental control and agriculture.
- Industrial and undersea robotics.
- Fluid handling.
- CAD/CAM technology.
- Materials transport in space.
- AI systems.
- Navigation systems.

Automatic Control Systems

Private industries, universities, government laboratories, and private institutions are vigorously developing fault-tolerant control procedures for defense, manufacturing, and process applications. Most researchers agree that a hierarchical (deterministic) approach is the most appropriate for the wide range of practical needs. Major program efforts are currently concentrated in the following areas:

- Use of state-of-the-art microprocessors such as the 68000 and 8086/8087.
- Standardized programming languages.
- Fault tolerant architecture.
- Local area network protocols.

The scale of these efforts makes it appear wise for NASA to adopt a standardized chip set, language, communications protocol, and architecture from the private sector.

Environmental Control and Agriculture

Recent significant developments in aircraft, dwelling, and factory environmental control may be applicable to the Space Station. In the long term, progress in hydroponics, aeroculture (nutrient-rich mists), and large-scale microculture may result in technologies useful for food production and environmental control in space.

Industrial and Undersea Robotic Arms

Robotic or teleoperational arms are in widespread use today in factories, in oil rig activities, and undersea. These technologies might be adapted to space by taking into consideration issues such as lubrication and low-mass structure. Since the cost of space boost can decline sharply, NASA may need to re-examine the cost tradeoffs of developing a completely separate manipulator technology.

Fluid Handling

High-speed, two-way, fluid flow transfer systems have been developed for terrestrial applications such as refueling race cars, combat vehicles, and aircraft. Fluid handling requirements in space are complicated by low gravity and the use of cryogens or hypergolics, but there may still be ways to use Earth-developed components. Particular attention should be paid to two-way flow, quick connect/disconnect couplers, and self sealing lines, because of the high value of fluid in space. Operations in milli-gravity environments, such as at the ends of tethers, may allow use of more conventional fluid handling methods.

CAD/CAM Technology

Manufacturing requirements have led industry to develop excellent three-dimensional representations of parts via CAD. As discussed in detail in Chapter 2, this technology could aid astronauts in operational planning activities and in simulating functions such as docking or extra-vehicular activity (EVA). Databases used initially to hold onboard parts inventories could evolve into full-scale station representations. Using CAD databases for robotics planning and expert systems is discussed in Chapters 3 and 4.

Compatible CAD representations, provided by all contractors, can allow the Space Station to be managed without the large amount of paper currently required for the Space Transportation System. This will save both overhead and information access time. Scenarios can be tested quickly with sophisticated software.

NASA has many reasons to be interested in CAD and CAM. Space hardware is expensive partly because of the modeling, tests, and inspections each part must go through before a design is optimized. CAD/CAM should enable contractors and NASA to actually go through more iterations in less time, using less manpower.

The fact that space hardware has very small production runs usually means high cost. Because there are few economies of scale, it does not pay to automate production. But CAD/CAM methods may make it possible to produce specialty parts in small lots with sophisticated turnkey systems, taking a part from computerized representation to physical form in a short time. This is of special interest to NASA.

Materials Transport in Space

Recently, software and, to a more limited degree, hardware for materials handling, has evolved significantly. These new developments should be considered for use in the Space Station for handling and moving of solid objects and materials. It may be better to use the best industrial robotic practice rather than inventing new designs for space.

Artificial Intelligence Systems

NASA can use AI developments to create larger, deeper knowledge bases. Knowledge-based system design tools will speed the programming of expert systems, reduce development time, and cut costs while improving code quality.

Navigation Systems

Automated navigation systems for teleoperated spacecraft, platforms, and satellites can be developed from technology now existing in the private sector. Using radio signals from the Department of Defense (DoD) NAVSTAR/Global Positioning System

(GPS) satellites, such systems could provide accurate positioning, velocity, attitude, and docking information in a straightforward, compact fashion. Complete GPS receiver and antenna assemblies that do not require knowledge of the classified code are now available in packages the size of a book. Centimeter positioning and milliradian attitude accuracies are achievable on Earth.

These examples all have the common feature that enormous industrial and university efforts have already gone into technology development. NASA should evaluate the economic and scheduling benefits of adopting or adapting this work versus a new development. It should also examine how the Space Station can be designed to make economic use of these terrestrial systems.

5.3 USE OF THE SPACE STATION BY OTHER INSTITUTIONS

We now discuss, in turn, use of the operational Space Station by industry, other government agencies, universities, and foreign governments. Such use could involve a variety of economic arrangements. For example, an industrial firm might rent a "room" in the Space Station, or a unique piece of equipment, for special experimental or manufacturing purposes. At another extreme, NASA might sponsor experimental work in space by a university researcher.

5.3.1 Use of the Space Station by Industry

The Space Station will offer a variety of unique industrial opportunities for research, development, manufacturing, and services. These include

- Access to sustained accelerations between zero and high accelerations.
- High vacuum.
- Isolation from disturbance and contamination.
- An abundance of cosmic-ray primaries.
- Observability of the earth.
- Assembly, maintenance, and repair of satellites.
- Assembly of large-scale, low-gravity structures such as factories and energy plants.
- A staging base for lunar exploitation.

Drawbacks of space, from the potential user's point of view, include

- Lift costs.
- Insurance costs.
- Space qualification and "man-rating" of hardware.
- Need to fit into constrained volumes.
- Power and heat rejection limitations.
- Lack of reservoirs of raw materials.

Many of these constraints will fade as lift costs fall and as material accumulates in orbit.

From an economic point of view, designing for growth means designing for low incremental cost of new uses of the Space Station. Many proposals discussed elsewhere in this report can help achieve this end, e.g.,

- Modularity and micro-modularity.
- Accumulation of resources in orbit.
- An optimal level of automation (this level rises as automation and robots become less costly compared to human labor).
- A Space Station designed for reasonable maximum (increasing) use of terrestrial technologies.

Space Station costs can be partially recovered through rental of its facilities to industry. The problem is to establish rental fees that would attract usage and eventually cover costs. Space Station costs range in a complex hierarchy from fixed to variable. Highest in the hierarchy are facilities costs required to bring the evolving Space Station to a general configuration at a given time and to operate it. These costs will likely increase with time. Depending on policy, federal tax revenues might cover general facility costs. Lower in the hierarchy are specific facility costs permitting particular classes of industrial use. These might be borne in part by the particular industrial users. Lowest in the hierarchy are variable costs which depend on the quantity of a particular use (work hours, number of occurrences, power usage, etc.). Direct fees should cover these variable costs.

5.3.2 Use of the Space Station by Other Government Agencies

Use of the Space Station by government agencies other than NASA should be encouraged. Personnel exchanges between NASA and these organizations should occur during all stages of the Space Station program.

During the design stage, NASA should endeavor to create a station that will be of maximum use to other government agencies, as well as to commercial and international interests. In many cases, NASA may have to make educated guesses about what services other organizations may require. Agencies that do not typically use space assets will not know what to ask for in Space Station design. On the other hand, any that do admit to needing a special design feature stand in jeopardy of being charged part of the development costs *now*, in return for transient benefit *later*.

Other technologically advanced government organizations could help NASA in the design of the Space Station. The Defense Advanced Research Projects Agency (DARPA) of the DoD has competence in AI and robotics, as do various military laboratories. The Bureau of Standards of the Department of Commerce has AI and robotics capability oriented toward flexible manufacturing. NASA should draw on the expertise in these agencies to help evaluate proposals in AI and robotics.

NASA personnel should be sent to work in the other agencies' laboratories for on-the-job training and to cement working relationships. One- to two-year tours would allow a NASA person to obtain enough expertise to effectively direct the contractors' AI and robotics efforts. In exchange for the personnel on loan from NASA, the host agency should supply its experts on a part-time basis during the definition phase of the Space Station to guide and monitor contractors' efforts.

Several agencies could use an operational Space Station (taken to consist of both manned and unmanned elements). The National Oceanic and Atmospheric Administration (NOAA) has responsibility for weather monitoring from space. Even if the gathering of weather data is transferred to commercial interests, someone will have to do R&D on advanced payloads. And even if NASA does the actual R&D, NOAA must define requirements. Similarly, the Departments of Interior and Agriculture and the Environmental Protection Agency could gather valuable data from space to aid in their work. The Department of Commerce should have an interest in unique manufacturing processes or services practical only in the space environment.

NASA traditionally cooperates with the Department of State on international programs. There may well be considerable international involvement in the design and operation of the Space Station.

Military uses of Space Station capabilities (either for R&D on future military systems or for actual operations) are being debated. Policies should be developed to maximize the efficacy of the major United States investments in Space Station capabilities.

5.3.3 Use of the Space Station by Universities and Research Institutions

Many of the conditions and facilities that make the Space Station attractive to industry will also make it attractive to academic research. In addition, it will provide unique opportunities in astronomy and other non-industrial fields. The Station's utility was noted by Professor Peter M. Banks in his statement* before the House Subcommittee on Space Science and Applications as follows:

> *Preparation and advocacy for scientific use of the Space Station has been underway in the science and applications communities since the early 1970s. Workshops and other meetings have been held among scientific disciplines to examine the utility of coordinated facilities having a scale and complexity not accommodated on automated spacecraft. Studies conducted in many disciplines, including the life sciences, materials research, solar-terrestrial research, and earth observations have considered the opportunities offered by a large resource Space Station and have concluded that important tasks could be effectively accomplished with this facility or facilities coordinated with it.*

Scientific payloads may have special requirements such as ultraclean environments. In addition to basic research topics in the sciences, particular topics of fundamental engineering research might include space telecommunications, large space structures, advanced materials research, advanced electronic design for the space environment, and applications of automation and expert systems. In fact, such science and engineering research, while undertaken by universities, could be expected to have long-term benefits for NASA's mission and for the Space Station in particular.†

* P.M. Banks, Statement before the Subcommittee on Space Science and Applications, Discussion on NASA's Task Force on Scientific Uses of the Space Station, Thursday, February 9, 1984.

† A more detailed discussion of these issues will be available in a forthcoming report of the Task Force on Scientific Uses of the Space Station, Space and Earth Science Advisory Committee (SESAC), NASA.

5.3.4 Use of the Space Station by Foreign Governments

Opportunities should be sought for foreign participation in Space Station activities, where there is both technical complementarity and an opportunity to increase international amity and reduce tensions.

Working arrangements with the space programs of United States allies such as Western Europe's European Space Agency and Japan should be explored in terms of both finance and technology. NASA cooperates extensively with foreign countries (e.g., Apollo-Soyuz, Spacelab, and scientific programs). From a political point of view, much can be gained in international prestige and visibility by encouraging foreign support for the Space Station. From a technical point of view, NASA should examine the research capabilities of prospective partners. Once this is done, NASA should then attempt to integrate these partners into the Space Station program to make the best use of their technical expertise. NASA should develop a mechanism for shared funding with foreign governments in research and development areas of mutual concern. Perhaps a consortium whose participants share costs and results would be appropriate.

We should also watch for areas of collaboration with Soviet scientists, both because of potential technical advantages, and in the hope of achieving some modest reduction in international tensions.

5.3.5 Cost Sharing of Terrestrial-Based Facilities

Extensive use of Earth-based facilities is anticipated during the Space Station's lifetime. This section discusses the sharing of launch support, communications, and experimental facilities.

Launch Support Facilities

The unique needs of the space shuttle will dictate concentration of launch and support facilities. Some sharing of additional facilities should be considered with DoD, other friendly governments, the USSR, and China, as part of a development plan for international cooperation.

Communications

The Tracking and Data Relay Satellite channel capacity required by a large, active Space Station may well grow geometrically as new uses evolve. There is an opportunity to share communications facilities, channels, and Earth stations in commercial use.

Experimental Facilities

Scientific research in the Space Station will require extensive Earth-based support. Here again, the use of existing facilities, shared databases, instruments, procedures, and the like will increase effectiveness and lower overall costs.

5.4 EXTERNAL USES OF SPACE STATION TECHNOLOGY

Below, we mention several varied areas of automation and robotics for which the Space Station can serve as a focus of significant progress, and describe potential applications of such progress and their benefits, both public and private. These areas include telerobots applicable to terrestrial use, and the standardization of computer languages, networks, and databases. These examples are meant to illustrate, but not exhaust, the possibilities.

5.4.1 Telerobots

Telerobots developed for the Space Station show promise of terrestrial application in many areas.

If a completely automated manufacturing system is developed for space, such as for the production of gallium arsenide single crystals and the subsequent processing into semiconductor devices, the following benefits could result:

- Advanced robots with integrated visual, tactile, and other sensors.
- Improved performance of robots due to careful design and better materials.
- More dexterous end effectors.
- Expert systems for diagnosis, repair, control, and planning of many functions.
- Advanced programming methods for robots using CAD/CAM databases.

Automation technology developed for space will have a significant impact not only on manufacturing industries but also on the service industries that employ 80 percent of the U.S. workforce. For agriculture, construction, work in the deep seas and deep mines, human services (particularly those directed to the disabled and the aged), the military, safety and security, and health, a major contribution of new space technology will be in the development of telerobots.

Such devices, in the Panel's opinion, may become the most common robots, far exceeding factory robots in number. They could be our future electromechanical servants, machines combining advanced high technology engineering with interactive human control. Human intelligence with its enormous versatility will analyze new tasks, select the sequence of operations (often through stored programs), and solve problems, thus providing the higher levels of intelligence that current machines woefully lack. Descriptions of a few potential application areas for these systems will illustrate their generality.

Toxic and Radioactive Materials and Hostile Environments

Robots can perform manipulation and inspection at sites that are dangerously radioactive (near or inside nuclear reactors) or that contain toxic gases, biochemicals, or other pollutants. Specialized tools can be developed for repair or maintenance of "hot" equipment, and for transporting or removing toxic materials. The latter tasks should be made repetitive so that a telerobot can perform them unattended.

There are many hostile environments on Earth where telerobots could be used. The nuclear industry could use them to enter radioactive areas for examination, inspect welds, and manipulate stuck valves. Such devices would be programmed to know their own "reactor environment" and could even grasp and remove injured people from the scene.

Applications in the Construction Industries

Applications in construction include loading, unloading, and moving heavy materials, laying bricks and cement blocks, automatic trenching and other earth-moving operations, and arc welding. These systems may be particularly useful in large construction projects such as dams and bridges, as well as for maintenance such as sand-blasting and outdoor spray-painting.

Repair and Maintenance of Machines

Another use is for repair and maintenance of machines, especially in hazardous conditions. After the teleoperator guides the robot into position and chooses the appropriate stored program, the robot could remove and replace defective parts, lubricate, test, clean, and perform other routine operations. As an automobile mechanic's helper, it could remove and replace wheels, steam-clean the engine, and unbolt and bolt accessories. Ultimately, as research leads to the development of expert systems for diagnosis and repair, robots could assist the mechanic by invoking stored programs, each specialized for the particular model of automobile under repair and for the job at hand.

In space, the deep seas, deep mines, the polar regions, and other inhospitable or dangerous regions, economic repair and maintenance by robots will be a driving force in expanding extraction, production, and even manufacturing of useful products. It will permit automated processes to be conducted with supervisory personnel not physically located at the dangerous sites.

Applications in Private and Public Services

There are many mundane commercial and service tasks that machines can do. Potential applications include washing windows of tall buildings, cleaning and painting exteriors, repairing street pavement, separating waste, disposing of toxic waste, cleaning institutions, firefighting, acting as mobile aids for police in handling dangerous materials and people, or doing automotive lubrication, refueling, and tire changes. These applications will have to await the development of specialized machines with large enough markets to warrant affordable mass production.

Military Applications

Programs to introduce robots into military operations are now of some interest. Many military personnel are engaged in ordinary service tasks such as loading and unloading munitions, construction, maintenance, and refueling tanks and vehicles. Telerobots could also perform dangerous tasks under battle conditions, such as mine detection and disposal, reconnaissance, perimeter surveillance, and other operations. Although these machines may be expensive because of the rigid requirements for fieldworthiness, their market is potentially large because their use reduces casualties and increases efficiency in performing hazardous operations. A substantial increase in the efficiency of service and "on-line" military personnel is possible (NRC 1983). A decrease in the number of personnel can be projected.

Agricultural Applications

Many areas of agriculture could benefit from the use of more intelligent autonomous robots. A mobile robot with specialized end effectors (hands and tools) would be valuable for stoop-labor applications, such as pruning, picking, and cultivation. The range of materials handling tasks in horticulture, aquaculture, and hydroponics can be extended. Interesting research is being conducted in Australia in automated sheep shearing. In the long term, agriculture and ecological management will profit from techniques developed for large-scale life support in space. Advances in modeling methods, biological recycling techniques, and robotics could have major effects on Earth.

Applications for the Aged, Infirm, and Disabled

The development of mass produced low-cost robots would be particularly important for the millions who are physically disabled (i.e., those who are blind, bedridden, or confined to wheelchairs). These machines would free them from the need for continual human care and allow them to become more involved in ordinary activities.

Servicing and Manufacturing

Space Station subsystems will have to be inspected, repaired, or replaced in a semi-autonomous manner. For example, an experiment might need to have its film canister exchanged bi-weekly, or a mechanical joint might have to be lubricated. The systems integration and machine perception developed for such applications will have many uses on Earth. Semi-autonomous robotic servicing systems would be most appropriate in large, complex but well structured systems such as ships or factories, but could also be economically justifiable in high-volume applications such as aircraft or automobile fleet maintenance.

Another requirement in space will be the location and repair of structural damage caused by micrometeorites and other debris. Automated flaw detection in composites, coatings, and other advanced materials will be a natural fallout of such space station capabilities. Technology in this area is badly needed, for example, in the aircraft industry, for products such as wing sections and structural skin elements. Considerable progress will result from NASA and corporate cooperation in developing the next generation of production aids.

As discussed in Chapter 3, the Space Station's advanced telerobots will demand improved sensors and sensory processing. Better tactile sensors, faster vision processing, short- and long-range scanning, laser ranging, and a variety of non-destructive evaluation probes will all be necessary. Such developments will also be welcomed for terrestrial applications ranging from telepresence to third-generation robotic systems. Manufacturing systems will require much less structure as a result of new sensors and high-speed, integrated sensory processing.

Space Station automation developments will also advance the state of the art in manufacturing design. Advanced CAD/CAM system modeling and planning are progressing quickly in industry but, as discussed earlier, NASA requirements will help raise these areas to new levels.

The Space Station's use and continued development of a CAD/CAM system to model, coordinate, plan, and design operations will be of great benefit to Earthbound systems. One complex problem is modeling and coordinating the actions of several arms. New generalized methods for solving problems of this type would have direct applications to similar terrestrial manufacturing.

Construction

Space construction represents an excellent way to prove the worth of a telerobot in reducing EVA time. Once a truss system is decided on, a device to build it can be designed. If some uniformity can be established, the space mobile constructor could lead to similar terrestrial devices. Mobile construction telerobots of this type could be used to build modular homes, geodesic domes, and buildings or bridges. If carefully designed, these structures might also later accommodate robots for inspection, cleaning, or repair.

5.4.2 Standardization of Computer Languages, Networks, and Databases

NASA's adoption of standard computer languages, networks, and databases will promote their subsequent adoption by the private sector.

Earlier sections discussed the importance of designing the Space Station for growth and cost-effectiveness in the year 2010. This task is particularly difficult concerning computers because of rapid technological advances. Few fields change with such frequency and magnitude. By the year 2010 we can expect at least two to four entirely new generations of computers with vastly enhanced capabilities. Indeed, their use will increase the capacity for new and more extensive experiments and automation in the Space Station. The Initial Operational Capability Space Station must be able to incorporate the capabilities of these new computers as they become available.

This problem will be ameliorated somewhat by the fact that not all aspects of computer technology change as fast as the hardware. Interconnection mechanisms, computer languages, and database systems evolve much more slowly. Some languages have been with us now for 25 years or more, and important new languages will probably have similar lifetimes. Communications systems, languages, and databases have thus become the basis for portability between generations of computer hardware. Similarly, they can be the basis for accommodating change and growth of computer technology for the Space Station. New generations of computer hardware are usually designed to accommodate existing standard communications systems. With a modest software effort, a database system used on one generation of computer hardware can be used on the next. Thus, programs written in a high level language that run on a computer of one generation can be expected to run on one of the next generation as well. It is important, therefore, to use standard communications systems, databases, and languages. As new generations of hardware arrive, the vendors will produce the compilers, communications software, and database systems to function with common standards.

The standardization of languages, communications, and databases has many benefits besides accommodating generational changes in computers. First and foremost is the ability to easily incorporate software and data developed elsewhere if the standards are ones commonly used in industry and government. This opens the doors to a vast market of useful products. While some of the Space Station's needs will be unique, others will be shared by industry or other segments of the government. Second, standardizing on widely used languages and databases will allow NASA to obtain staff from a sizable pool of trained people. Third, the cost of developing and maintaining software and databases will be lower. We should note that standardization need not result in technological backwardness if careful choices are made.

5.5 REFERENCE

NRC (1983) *Applications of Robotics and Artificial Intelligence to reduce risk and improve effectiveness: A study for the United States Army*, 91 pp, Committee on Army Robotics and Artificial Intelligence, Manufacturing Studies Board, Commission on Engineering and Technical Systems, National Research Council, National Academy Press, Washington, D.C.

Chapter 6

BROADER OPPORTUNITIES

The Space Station is a means to broader opportunities in time, space, and society.

6.0 SUMMARY

Prior to the Space Transportation System (STS), space programs focused on achieving well-defined goals in specific time frames. The STS was designed to support multiple projects over many years. This trend will go on. No single project will ever fully define the Space Station. It will change over time, spread over space, and it will mean different things to different people. Despite our best predictions, the Space Station in the year 2010 will probably not resemble what anyone today would expect. And yet, current design decisions must prepare for and accommodate both short- and long-term goals.

We should not consider the Space Station as a frozen image, but rather, as part of a three-dimensional *continuum* that includes

- *Time*: The Space Station represents a continuing human presence in space. It will support new and changing missions, stimulating growth as years pass. Section 6.1 discusses this.
- *Space*: The Initial Operational Capability (IOC) Space Station will contain the seed elements of a growing space presence, expanding in and beyond near-Earth space. Some components will create opportunities well beyond Earth orbit. Section 6.2 covers this aspect.
- *Society*: Benefits of the Space Station need not be restricted to space or to the period of initial development and implementation. The program can extend society's reach by expanding its access to space. It will support machines that use solar energy, and nonterrestrial materials that seed growing industries. New wealth can be created for Earth. Advanced space systems will support increasing populations beyond Earth's confines.

America is planning a project that will last more than a human generation. Its future space systems must remain flexible to absorb *expected* technological improvements, thereby accommodating growth. Section 6.4 explores some *breakthroughs* to prepare for, and section 6.5 lists recommendations that can create and help us prepare for broader opportunities.

6.1 A CONTINUUM IN *TIME*

Previous chapters have discussed the evolution in time of a planned Space Station. Chapter 2 describes the Space Station from the point of view of the year 2010, listing design tenets, and warning of pitfalls. Chapters 3 and 4 examine how the expanding technologies of robotics and information management will affect Space Station design and operation. Chapter 5 touches on how developing practices in manufacturing will affect the construction and maintenance of the Space Station.

While these are far reaching discussions, a few points must still be made about an *evolving*, growing space capability.

Prior space ventures were limited in time, design, and the community of people involved. To some extent, this reflected the constraints of a less mature technology base. For example, Skylab demonstrated that humans could live in Earth orbit for extended periods, given resupply from Earth and intensive support by teams of mission controllers. Like the Gemini and Apollo systems, the spacecraft was optimized around a fixed architecture and not designed to grow or change. Much the same is true of the Soviet Soyuz/Salyut space station system. The United States' STS is more flexible. It has demonstrated a wide range of short-duration manned capabilities. However, in its present form, it still requires expensive support by mission controllers and Earth-based centers. Unfortunately, it is still considered to be a design frozen in time.

The new challenge is to make systems that actively support expanding human endeavors in space, but require minimal human attention. Advanced A&R should handle routine tasks, freeing people in space to do higher-level work. The Space Station is only part of this development. All people involved in design should view the IOC Station as one part of a continuum of activities involving rapid growth of terrestrial technologies into space. It is a means to growth, not an end in itself.

Designers face a common quandary: how to give a system a long lifetime while allowing for growth and change. For example, B-52 bombers have evolved over 30 years. Because of their large size they could accept many additions and modifications. This was important in the 1960s and 1970s, when the design cycles of large aerospace craft often lasted over a decade. But these cycles are shortening as computerized methods of design, testing and construction improve. Commodious space systems could accept many new automation techniques allowing both short upgrade schedules and long overall lifetimes.

Because a well planned Space Station can evolve and grow larger, the Space Station program can build gateways to broader opportunities. As the program matures it will create and be led by new industries, building a progressively more efficient and supportive infrastructure on Earth and beyond.

The "Space Station Era" may well resemble a stage in the expansion of the U.S. transportation system. In 19th century America, for example, both railroads and the factory systems that made locomotives and rails expanded interdependently. Space systems offer opportunities for similar developments, both off and on Earth.

Space systems can be segmented in function and location. The infrastructure need not be *physically* integrated, as in most aircraft or the space shuttle; individual modules are much easier to upgrade. Evolving space systems industries can respond to future needs, just as railroads were able to meet the transportation requirements of a growing country better than could canal-based networks.

The STS and its advanced versions can influence Space Station growth. Applying A&R to the STS can improve its efficiency and decrease operational costs. A&R can, for example, reduce the number of support personnel, improve crew effectiveness, and provide greater access to payload operations.

Many nations and groups will construct and operate orbital facilities in the 21st century. Some world leaders and ordinary citizens celebrating the inauguration of the Space Station will be able to remember flights of the first commercial airplanes. At the rate technology is evolving, we can expect changes of far greater magnitude to follow the original Space Station. New terrestrial industries must anticipate and design for these changes.

6.2 A CONTINUUM IN *SPACE*

As the Space Station evolves, it will be associated with a growing number of systems dispersed widely through space. Initially, the systems will be launched from Earth to be used as is or assembled into larger units. The early Space Station could begin to repair itself and build facilities from such items as the many external tanks, each of which is now thrown back to Earth following STS launch. In-space assembly and manufacturing can lead directly to facilities on the moon which can grow, primarily using lunar materials. The stage will then be set for expansion beyond cis-lunar space.

Modern industry is linked over wide regions by transport, power and communications. These interconnections allow regional groups to accomplish much more than can a single factory or individual. Widely dispersed space systems will also be connected. Eventually, great resources of power, materials, and control of physical processes will be available to them over large regions of space. The Space Station is the starting point.

6.2.1 Dispersal in Orbit

Already, an independent, polar-orbiting, unmanned platform is considered an important part of the IOC Space Station. This trend toward distributed infrastructure will grow as transfer vehicles move to and from higher orbits. Separated hardware will feature standardized systems, shared operating procedures, and coordinated goals.

Dispersal in orbit will allow experiments or industrial processes that would be incompatible in the same structure. For instance, sensitive optics should be kept away from the inevitable outgassing of habitation modules and emergency releases of reactive compounds used in materials processing. Habitats, in turn, should be separated from space industrial units dealing with high-energy conversion of metals, impact experiments, or transfer of liquid propellants. These diverse elements could be co-orbiting or connected by long tethers.

Multiple elements dispersed in various orbits could support experiments requiring high gas-pumping rates, protection against thermal changes, shielding from electromagnetic signals, low-level but long-term acceleration (using tethers, spin, or electromotive forces), or isolation.

Many programs may be performed reliably only in space. Possible examples are studies of the growth of large numbers of plants or animals in a completely sealed environment to study trace-element metabolism or very low-level toxicology. It is virtually impossible to seal a large volume on Earth (say one the size of the ET, which is approximately 9 meters in diameter and 50 meters long) against trace-level leakage of gases or dust from outside. In space, however, ETs might be used as large "test tubes" at reasonable unit expense. Simple telerobots could help conduct experiments or demonstrate advanced support systems over long periods.

A key function of the IOC Space Station might be to rework used satellites or bulk materials from Earth into new components. For example, external tanks (ETs) might be outfitted as experimental chambers, or the twenty-five ton lots of ET aluminum might be formed into new shapes. Excess propellants, dense bulk materials in volume-limited flights, or even waste from life-support modules, may be accumulated in spare tanks for later use or recycling, thereby leveraging expensive orbital mass. Thus, one decade's garbage may be the next decade's valued resource.

6.2.2 Space Shop--Seed for Manufacturing

Earth-orbital and lunar industries must be capable of materials processing, manufacturing, and repair. These will be vital, in seed form, to Space Station operations. For example, if a furnace used to make solid state components loses power, and molten materials solidify in it, the unit may have to be torn apart, cleaned, and reassembled*. This will require a small but capable shop such as might be found onboard a naval vessel. A *space shop* should use the latest techniques in automation and robotics. It should allow materials and manufacturing specialists on Earth to use telerobots to accomplish large, complex tasks in space. The IOC space shop should support the start-up and growth of primary industry off the earth. It should lead directly to systems usable on the moon (NASA 1982).

The initial Space Station should incorporate prototypes of materials-handling units. The space shop could even make many of its own components from bulk or semifinished materials supplied from Earth, derived from salvage, or from the moon. A well targeted program might lead rapidly to the in-space demonstration of bulk material processing. Target processes should leverage lift capacity of the Space Transportation System, and extend industrial skills to space. A space shop could use a CAD/CAM database developed for the Space Station program.

Advanced automation is affecting manufacturing (OTA 1984a) and our living and work places (NRC 1983). How we obtain basic engineering materials is changing profoundly. For example, automation has introduced large improvements in the specificity and speed of analytical chemical instrumentation used for industry and research

* See design team study by General Electric.

(McLafferty 1984). Unit chemical and physical processes are increasingly controlled by advanced automated techniques. Many terrestrial procedures will be applicable to processing in space. Techniques developed originally for processing and manufacturing in space will find applications on Earth.

Development of small industrial facilities in space can quickly lay the groundwork for aggressive growth in low-Earth orbit (LEO), on the moon, and beyond. Earth-approaching asteroids, Mars, and its moons will become more accessible, given a growing industrial system of production in LEO and in cis-lunar space. Even the IOC Space Station could start and force this critical growth in basic industrial capabilities off Earth.

6.2.3 The Role of the Moon

The moon offers many useful resources for a growing space system. Many people consider the moon important to our national space program (OTA, 1984b). The United States has operational experience derived from Apollo, and detailed knowledge of lunar materials and geochemistry. Since the moon is airless and much smaller than the Earth, the machinery needed to launch useful quantities of materials from its surface can be relatively small and simple. It can be a source of materials to use in orbit about Earth, for lunar facilities, and in deep space. Soils for shielding, glass and metals for structures, and oxygen for propellants are only a few of the many possible products. It may be advantageous to construct large solar power stations on the moon's surface, using local materials, to supply power via microwaves to users on the moon, in space (facilities and transports), in LEO, or perhaps even on Earth.

Small manufacturing units (materials gathering, beneficiating, thermal and physical processors, chemical processors, flexible production systems, and warehousing and transfer systems) will extend the automation and robotics features of the Space Station to encompass most significant functions of industry on Earth (NASA, 1982). There are many common factors among the equipment and procedures needed to support human life and industry in Earth orbit, in lunar orbit, or on the moon itself. At the very least, the Space Station must not be designed to preclude the use of lunar materials or delay access to them. Lunar industries will eventually enable major explorations, for example, of the asteroids, Mars and its moons.

The Space Station should be designed from the first to enable incremental growth from LEO to the lunar surface. *Critical systems* (habitation units, materials processing units, transfer vehicles, etc.) *must be designed to allow operations around and on the moon with minimal reworking.* Modules should be compatible with operation in one-sixth gravity and with lunar landings. From the first, the Space Station design should allow for the use of lunar-derived materials in logistics support and expansion. For example, a manned Space Station element in geosynchronous orbit should accept radiation shields derived from lunar materials. Lunar materials can be returned to LEO using aerobraking. There they could be incorporated into elements of the Space Station and also leverage the uplift effectiveness of Earth-to-orbit transport systems. Orbital transfer vehicles must be designed to support missions to low orbit about the moon.

6.3 A CONTINUUM IN *SOCIETY*

The Space Station represents more than a continued and expanding presence in space. It will catalyze a wide range of Earth-based activities over a long period, activities that affect technology, management, and society as a whole.

6.3.1 R&D Relationships

Until now, space research and development has been considered separately from terrestrial R&D. But the concept of a continuum will have to be applied in this area also. The Space Station should be designed from the start to absorb, as much as possible, advanced off-the-shelf Earth-developed hardware and procedures. It will be decades before the Space Station primarily uses technology developed in space for use in space. When this happens, humankind will truly have outgrown Earth's confines. Paradoxically, these events will be hastened by designing the IOC to incorporate advancing terrestrial developments with minimal adaptation. This was noted in the Executive Summary.

NASA in the 1980s exists in much different national and world contexts than in the 1960s. In 1964 the NASA budget of 6.5 billion dollars controlled over one-half of the government and private R&D of the United States. NASA and DoD certainly dominated national and world activities in these areas. NASA personnel were experts in most of the nation's technical capabilities. They were experienced in virtually all segments of the engineering and scientific world. NASA could afford to rework and create advanced technologies and systems to meet national space goals.

Twenty years later, in part due to NASA's successes and to the dispersal of many NASA and DoD workers to other segments of the national economy, NASA R&D is small compared to the U.S. expenditure in 1983 of over 93 billion dollars by government and private organizations. On the average, approximately half the profits of major U.S. industrial corporations are spent on R&D. Worldwide R&D spending is probably two to three times greater still and growing.

The computer industry creates new technologies so rapidly that NASA has not been able to allocate enough resources to employ state-of-the-art computer systems in space. NASA leads in only two restricted areas of computer science--massive aerodynamic calculations and highly reliable aircraft control systems. Even DoD cannot sustain state-of-the-art equipment comparable in overall performance to that available to the worldwide communications and computer industries. Thus to expedite development of the Space Station, NASA must encourage the maximum direct utilization in space of technologies developed for terrestrial markets.

Debate over "people versus machines" in space has overlooked a critical point. Since current technology serves the needs of people, a totally machine-based space program would require the complete reworking of those technologies. Conversely, "man-rated" space laboratories could be designed to accept a far wider range of terrestrial devices with minimal additional development. The Space Station can be intentionally designed to accept increasing flows of terrestrial technologies.

Designing space systems to use new terrestrial products will simplify acquisition of state-of-the-art systems in space and promote faster development of devices and systems. A wider range of people will become familiar with space operations, and those operations will be more vigorously explored and exploited outside NASA.

Space offers more than access to vacuum and very low gravity. As facilities grow, greater control will be provided over almost all basic physical conditions than is possible on Earth. Research and development in space will grow in scope, accelerated by cheaper transport to space, decreasing costs of operating space facilities, and the needs of burgeoning worldwide R&D. The Space Station should be designed to encourage this growth.

6.3.2 Advanced Machines and People

If space ventures play an expanding role in the world economy, space systems should not be designed just as pieces of hardware to perform particular tasks. Rather, they should be viewed as part of a process to eventually move much human activity permanently off Earth. Such ventures will call for new approaches in management and new uses of machines.

Engineering Styles

A question frequently raised about technological problems is "If we can go to the moon why can't we...?" The usual answer is that we do not have the resources to attack a wide range of problems at such an intense level. Apollo was the largest human-intensive systems effort in this century. It required, for several years, approximately half the nation's research and development personnel.

A return to the moon would be a far smaller effort today. This is not simply because we have already been there, because we now have the shuttle, or even because the Space Station could stage lunar missions. It is also because we have new engineering styles with far greater capabilities.

The world is realizing that new, computer-intensive methods can be used to speed engineering projects and permit people in service activities to operate far more efficiently. The National Research Council endorses the use of the Space Station program to encourage development of nationwide protocols for coordinating design, development and manufacturing of products as complex as Space Station (NRC, 1984b).

Our present transition from strictly human to computer-aided teams involves major changes in how people organize themselves and attack problems. Traditional large engineering projects require strictly organized hierarchies. Generally, most workers do not gain deep understanding of an overall project, experiment with the conceptual design, or influence more than a restricted area of the activity. In the near future, however, extensive access need not be restricted to small groups at the top. NASA could promote tools of engineering communications and design that would directly connect designers, builders, and users to the complete process. Such new control of information may be as basic to human advancement as was the 19th century introduction of mass production.

Nearly paperless and widely accessible systems would reduce costs and shorten times to completion of complex projects. They would contain detailed documentation of development stages. More important, however, they woud open complex projects to a far greater pool of innovative thinking and knowledge throughout the nation.

It should not be assumed that current man-machine interface techniques, developments in machine intelligence, human factors engineering principles, and social science maxims could adequately support such large, sophisticated and dynamic systems. Technology advancement is needed to develop better techniques for letting people interact with whole systems. Man-machine science must be multidisciplinary.

Expanding the NASA Charter to Demonstrate Advancing Service Automation on Earth

In modern America, less than 20 percent of the population and cash flow is even indirectly associated with materials industry activities. Most Americans are in the service economy. It is not unreasonable to expect that, by early in the next century, fewer than 5 percent of the people in advanced countries will work directly with materials industries.

NASA is an intensely service-oriented organization, and is the high technology component of the federal government most open to public view. Its personnel, support contractors, and research communities explore and apply advanced technology openly in highly visible missions. Thus NASA is a natural choice to lead in the demonstration of advanced automation in a service industry.

NASA could be given a charter by Congress, and additional resources, to demonstrate the application of available advanced automation hardware and systems within the federal government. Long-term goals might include increased efficiency, reduced costs, and opening of the Agency even more to the nation. NASA should encourage grants and contracts to develop new conceptual tools and should evaluate and widely disseminate the results--even to other organizations of the federal government. The immediate goal of this program might be to bring NASA to the state of the art in office automation and create a *paperless NASA*.

Routine tasks (such as time keeping, travel arrangements, conferences, report dissemination, resource evaluations, spreadsheets, and message relays) would be conducted electronically. A mid-range goal could be the use in management of expert systems that could assist in resource allocation at all levels, assist in crisis management (Smith, 1984), answer external inquiries, and increase the use of machine-aided management. These expert systems should free government and contractor personnel for more creative work.

Additional electronic tools are needed for the management and scheduling of large complex systems such as the Space Station. Much is now done by hand or via many meetings which require extensive travel. New approaches are needed for cost accounting. For example, overhead allocations for some systems are based on man-hours (labor) even as labor involvement is approaching zero. Advanced computer management aids would have constantly changing world models and conduct natural language dialogues.

The Los Alamos National Laboratory is developing a multi-functional, integrated information system (INFORM). Over 1,600 employees use electronic mail, a budget system, an organizational directory (on-line, up-to-date telephone book), a bulletin board, an electronic authorization system (limiting access to those designated), and travel planning aids. The system has already eliminated much paperwork, decreased the time needed to obtain information or approvals, and promises to enhance the quality and quantity of information available for study and automated analysis.

Applying even more ambitious advanced service industry automation to NASA will directly advance automation of the Space Station. All such activities will *expedite the transfer of major NASA activities to space* over a period of time.

Human Factors and High Technology

Human factors will be a critical concern in designing automation and robotics for the Space Station. Interactions between complex machines and their human operators can be very important. In some situations (i.e., in nuclear power plants and space stations), lapses can be catastrophic.

There are three major problems in human/machine interactions:

- When failures (either human or machine) occur, human operators may have to respond very quickly.
- Human-machine interactions often promote boredom, error, and exhaustion.
- Systems developed by and optimized to an intelligent, highly motivated staff do not always remain under the control of such people. When innovators move on to new challenges, the old facilities may not be staffed as capably.

These are symptoms of inadequate design, and should be avoided through the use of human factors engineering.

New mangement problems will arise as the number and variety of people going into space grows. This trend began with the division of the astronaut corps into pilot, mission specialist, and military, industrial, and academic payload specialist categories. It is a recently declared national goal to take selected representatives of the public into orbit onboard the shuttle.

Such programs may become routine after IOC. With transportation breakthroughs, achievements in recycling and life-support autonomy, and larger scale space structures, the volume of traffic will rise. While it is premature to plan for a "tourist trade," it would be wise to consider some implications of non-astronaut visitors to the Space Station.

Untrained space visitors will require basic systems to carry more of the responsibility for safety and reliability. Space Station critical systems will not only have to withstand normal wear and tear, accidents, and degradation, but will also have to perform if damaged or misused.

Visitors will deal with many advanced machine systems not in general use. These include closed life support systems, devices for variable (including zero) perceived gravity, research facilities, or advanced language systems (especially for multinational crews). Station automation can relieve resident staff from the time-consuming responsibility of providing visitor services. Automated devices will, for example, give simple instructions, screen requests, and warn of danger. Automation and robotics capabilities that can serve and protect visitors, and also keep them from interfering with critical experiments and operations, should be part of the Space Station's design.

6.3.3 Extending Society's Reach

Commercial airlines have revolutionized global travel. Traveling 10,000 meters above the ground at 70 percent of the speed of sound, jet aircraft routinely operate safely in far more hostile conditions than will the Space Station. Air travel is so common that over 30 percent of the people in the advanced nations have flown. At any time, as much as 0.01 percent of the world's human population may be in jet aircraft. Comparing this to modes of travel only 50 years ago puts into perspective the likelihood of large-scale, routine travel to orbit. Rocket-propelled aircraft will eventually routinely operate between Earth and orbit (NRC 1984a). Transportation breakthroughs (see section 6.4) may someday make near-Earth orbits as traveled as the intercontinental airways of today.

Involvement of an ever widening variety of people in space will result in the creation of new, profitable space activities. More individuals and organizations will see space as a place with resources and potential for profit. Industry off Earth can acquire dependable solar energy at low cost. Major materials can be obtained efficiently from the moon and later the asteroids as space systems spread beyond the earth-moon system. New wealth can be created. New service industries will arise. The communication satellite industry is an example. A&R is the key that will allow the U.S. to expand its present lead in off-Earth industry.

Defense applications will play a major role in future space development, but they will usually be secret operations. There must also continue to be activities visible to the public. It is important that NASA keep our growing presence in space accessible to civilian Americans. For example, electronic communications from Earth to space can provide civilian workers opportunities to operate factories, robots, or experiments in low-Earth orbit or on the moon.

6.4 THE FUTURE: EXPECTATION VS. POSSIBILITY

We have seen that the Space Station cannot be defined as a single image in time or in space, or as a narrow community of researchers, users, and managers. No single image will ever describe it completely. The only certainty seems to be that it will not be much like anyone predicts.

Prior chapters of this study have tried to identify reasonable expectations for the year 2010. But that is not enough. The conceivable and the hypothetical should also be given some attention.

Of course, the Space Station program should not rely on speculative major breakthroughs in critical areas. Nevertheless, it should not ignore unproven technologies. For odds are great that at least one or two of the concepts discussed on the following pages will be practical within thirty years. A great society cannot afford to let breakthroughs take it by surprise.

Lift cost to low-Earth orbit is critical in deciding which space travel schemes are practical. A breakthrough in dollars-per-kilogram to LEO would bring many "science fictional" concepts within the reach of profit-minded investors.

It is reasonable to expect travel from Earth to orbit will become more routine, frequent and far less expensive than with the present version of STS. In the extreme case, one can conceive a fleet of small vehicles which could transport people and goods to LEO at only ten times the cost of the minimum energy required to move them there. That energy is about 10 Kw-Hr per kilogram. Assuming a unit cost of $.10 per Kw-Hr, this would imply a cost to orbit of 10 to 20 dollars per kilogram with the new vehicle, or only a few times the present price of transoceanic air travel.

Current trends will force advances. For instance, STS effectiveness will grow in part through increasingly automated operations, more frequent usage, evolved versions, and economics of scale. Intense debate is underway among NASA, the Air Force, and private groups concerning the use of the STS and expendable launch vehicles. Military and commercial long-range aerodynamic flight may evolve into semi-ballistic operations. Proto-scale industrial operations in space may develop into much larger-scale activities using materials transported via shuttle excess lift capacity, or derived from space-salvaged shuttle external tanks or off-Earth sources.

Every mission of our Space Transportation System lifts over 350,000 pounds to space. This is seven times the shuttle's rated internal cargo capacity. Launch systems derived from STS can carry to orbit far greater payloads of people, components, and systems or bulk materials. Lift capacity of this magnitude can support diverse, large scale activities. Priority must be given to identifying plausible goals in space of sufficient importance that the associated traffic could itself sharply reduce the cost of Earth-to-orbit travel. Other possibilities are worth citing.

Tethered systems seem to offer a whole new generation of opportunities in space operations. The ability to exchange momentum between two co-orbiting masses, to provide gravity gradient attitude stabilization and milli-gravity work environments, and to electrodynamically apply orbital torque against the Earth's magnetic field, are all exciting concepts. Some have already been incorporated in Space Station baseline design. Others merely await experimental confirmation within the next few years. (In almost every way, tethered systems appear to benefit from advances in automation and robotics.) It would be short-sighted to preclude such new capabilities in the IOC design.

There are other examples, many of them involving advanced automation and robotics. The nation may follow the Space Station with more ambitious activities featuring utilization of *the moon and near-Earth asteroids and perhaps eventually visits to Mars.* As mentioned earlier, these endeavors may fundamentally alter our priorities, and early space infrastructure should at least not obstruct them unnecessarily.

Electronic communications and computers provide a second portal to space, one which complements travel. The present conception of the 2010 Station proposes dramatic advances in these areas. People on Earth can operate complex machinery in space, on the moon, or on asteroids. Systems may grow rapidly in space under remote control from Earth.

The area of *space industrialization* is ripe for breakthroughs. If there is a sudden, major demand for orbital workspace, factory volume, mass, or raw materials, will the Space Station be able to adapt quickly? Could it accommodate attachments? Unexpected new facilities? What will be the automation requirements?

Again, planners cannot *count on* breakthroughs, but they should have contingency plans that allow for them. Dr. R. Frosch (p. 95 in OTA 1984b) has suggested that machines may someday be designed to make copies of themselves, using solar power and only local materials. A few such machines placed, for example, on the moon, could increase exponentially to a large population in a short time. They could then be reprogrammed to produce other types of manufacturing systems, solar power systems, propellants, structures, other goods, and services. Exponentially growing machine systems are simply the ultimate extrapolation of industrial processes developed over the past 400 years. We cannot build such systems now, even though they are possible in principle. However, small amounts of goods and materials can be imported to the moon and combined with common lunar materials to produce a wider range of machines and goods than could be produced locally. Mass imported from Earth could be multiplied into a much larger mass of almost entirely lunar products. Effective multiplication would increase as our off-Earth skills evolve.

Another potential breakthrough that might dramatically alter the balance between pipe dream and practicality, would be advances in automated *life-support technology*, allowing substantially greater autonomy. This might vastly reduce the cost of large manned stations, manned deep-space missions, or a permanent base on the moon. This area, perhaps second only to lift cost in potential importance, will benefit strongly from progress in automation and robotics.

The Space Station and associated systems should enable us to take advantage of such opportunities.

6.5 BROADER OPPORTUNITIES AND AUTONOMY

The Space Station will be many things over time, in space, and in society. It is a means to a variety of ends, not an end in itself. Much of what we predict today will bear little resemblance to future realities. Thus we must keep broader opportunities in mind while designing a space infrastructure. It must be practical and efficient by today's standards, but be capable of adapting to significant change.

6.5.1 Recommendations for Growth

- Consider the Space Station as a means to a growing system of human activity in space.
- Planners should not have a single, specific image of the Space Station. The space infrastructure will undoubtedly
  - change dramatically with time,
  - be widely dispersed in space,
  - be interwoven with Earth society,
  - accommodate a wide range of missions and goals,
  - be strongly dependent on the success of A&R.
- With this in mind, designers should emphasize
  - flexibility,
  - use of interchangeable parts,
  - economies of scale (i.e., lowering costs over large production runs),

- potential use of Space Station derivative modules in other ventures and locales (e.g., lunar orbit or surface, asteroids, moons of Mars),
- potential recycling of retired space hardware, external tanks, organics, volatiles, and orbital momentum,
- new space industrial services,
- potential for receiving and using new resources, such as materials from the moon and beyond.

- Immediately start developing a *space shop* capability for on-site repair and even small-scale fabrication.
- Provide high-quality communication and manipulative links with Earth whereby Earth-bound personnel can access, assist, direct, and conduct complex tasks in orbit.
- The implications of involvement of a wide variety of citizens in space, by proxy or in person, should receive close scrutiny.
- NASA should be chartered to lead in the demonstration of advanced service industry automation within the federal government. It should receive extra, continuing resources to do so as it succeeds.
- Promising technologies for reducing lift transportation costs should be pursued even at some risk, since rapid progress in this area will have substantial benefits. IOC design should not preclude expansion, retrofit, use of tethers, or resupply by expendables.
- Design the IOC not only to welcome *expected technological advances* but to anticipate and be adaptable to *possible major technological breakthroughs.*

6.5.2 Recommendations Concerning Autonomy

Some degree of autonomy from Earth logistical support will be necessary. Efforts to increase autonomy will lead to augmentation of space infrastructure as a portal to new opportunities beyond Earth. To that end, the Space Station program should have the following attributes:

- Advanced automated life support techniques for semi-closed system autonomy merit substantial, reliable, long-term investment. New automated approaches should be encouraged.
- Initial capabilities to *process bulk materials* and components into other shapes, compositions and applications will help industrial concerns interested in space processing, and will also provide experience working materials in space.
- Capabilities to process materials and manufacture basic goods *for use in space* should be consistent with our growing abilities to deliver materials to orbit.
- Proto-scale capabilities for initially limited manufacturing, repair, maintenance, and upgrading of orbiting devices and facilities should be established. Problems of inventory and resupply should be analyzed with a mind toward optimized on-site autonomy.
- Space Station automation should be planned from the start to create and capitalize on use of lunar materials and mutually supportive operations in Earth orbit and on the moon.

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Chapter 7

ADVANCEMENT AND IMPLEMENTATION

7.0 RECOMMENDATIONS

The Congressional mandate anticipates tremendous potential benefits from developing automation and robotics for the Space Station, as well as the high degree of technology advancement required to achieve these benefits. The United States can regain its preeminence in industrial technology and create new concepts of manufacturing and human service via robotics. Preceding chapters have described the enormous opportunities to exploit space to achieve new knowledge, products, and services, and to help improve life on Earth.

These goals will only be fully realized if automation and robotics are adequately advanced and implemented, not only in the Initial Operational Capability (IOC) Space Station, but far beyond it as well. As described earlier, this requires a large, long-term program. The Panel makes the following major recommendations which we believe to be of the highest priority if the Space Station program is to achieve the goals set forth by Congress (from Chapter 1):

Establish management structures that ensure rapid, ongoing advancement of Automation and Robotics (A&R)

Recommendations

11. Establish management structures in NASA to ensure that
    a) the needed A&R technology advancements occur unimpeded by Space Station operational or budgetary problems.
    b) there is a strong linkage between the technology advancement program and Space Station A&R implementation activities.
    c) the goals for Space Station A&R technology advancement reflect a consideration of broader applications (including terrestrial).
    d) the A&R technology advancement and implementation activities have visibility and accountability to the highest levels of NASA and to Congress.

12. Without presuming to recommend a specific organizational structure, the Panel further suggests strongly that NASA accomplish Recommendation 11 by providing
    a) an organization, managed outside the Office of Space Station, to lead the A&R technology advancement activity.
    b) the A&R technology advancement activity with a line item no lower than a first level breakout of an Associate Administrator's budget.

   c) a second organization, administered within the Office of Space Station, charged with promoting smooth flow of capabilities from the A&R advancement activity to Space Station operation, and with conducting required prototyping and testing activities.

13. Create an external review panel consisting of experts from universities, industry, and government to
   a) conduct in-depth review of NASA A&R activities.
   b) advise NASA.
   c) present annual reports to Congress.

7.1 ACHIEVEMENT OF A&R BENEFITS

To achieve the benefits of automation and robotics for the Space Station, NASA must perform the following four basic steps:

Step 1 - Provide the advancing technology base.

Step 2 - Conduct early demonstrations (ground and flight) of key new capabilities.

Step 3 - Develop and test prototypes.

Step 4 - Achieve operational implementation.

These steps have different time frames and involve different degrees of technological risk. Under the financial and time constraints of the Space Station program, how should time and money be distributed among them? For example, the first step has a high technological risk, since only a fraction of the approaches investigated ultimately lead to operational devices. And time frames can be very long, 10 to 20 years in many cases; technology advancement activities begun now will be directed primarily toward post-IOC implementation. Yet, these activities are essential to future operations; without them, the Space Station will not achieve its full capabilities. A&R experts must be funded to pursue new ideas to meet long-range goals, and chartered to develop and implement advanced A&R on the Space Station.

At the opposite end of the advancement sequence, the implementation activities in the fourth step have high public visibility, involve low risk, and must meet rigid time schedules. The manager of the Space Station program must ensure that the Station is built on schedule and works satisfactorily.

NASA must create A&R management structures which makes certain that

- All four steps of the effort are pursued vigorously.
- Adequate interaction is developed among the four steps.
- The quality of the effort is maintained at a high level.
- The Congressional mandate is met.

The Panel believes that the implementation and deployment of A&R is principally the concern of the Office of Space Station but will be driven by the capabilities which arise from fundamental technology advancement. Thus, this chapter primarily addresses organizational characteristics associated with the first three steps of A&R activity.

7.1.1 Ensuring the Achievement of A&R Technology Advancement

A&R Organizational Considerations

Previous chapters have identified many specific applications of automation and robotics for the Space Station program. Realization of most of these will depend upon an active, long-term NASA program to advance the state of the art of A&R technology. Cost estimates for the technology advancement program, including the concept demonstration stage, are presented in Chapters 1, 3 and 4.

To carry out the technology advancement program, NASA must provide the following:

- An adequate, stable budget.
- A focus on long range activities and freedom from daily pressures of implementation.
- Goal-setting mechanisms that give a strong voice to both the implementation organization of the Space Station effort and the A&R technology experts.
- A mixture of in-house and externally funded activities.

The technology advancement activities will call for highly trained personnel. It will take several years to build the needed level of staffing, both internal and external. Personnel with the appropriate training are in high demand, and stable, adequate funding is necessary to keep these people. It is, therefore, very important that funding for technology advancement be maintained, regardless of delays or costs in Space Station implementation. The funding patterns shown in Chapter 1 reflect this.

Effective A&R for the Space Station requires long-term fundamental studies directed principally toward post-IOC capabilities. The time frame of these studies clearly goes far beyond IOC construction and implementation. The implementation organizations and the technology advancement organization should participate in the development of long-range goals but not in coordination of day to day activities. While close attention must be paid to Space Station Office needs, technologists should be free to concentrate on leading A&R concepts without being directly involved in the daily pressures of implementation and deployment. The A&R implementation (Recommendation 12c) and the A&R technology advancement (Recommendation 12a) organizations can independently track Space Station activities to identify new applications.

A key activity in Step 1 will be to chart a course and plan the utilization of resources. In setting long-range goals, all organizations of the Space Station effort should indicate specifically what they want and need automation and robotics to do. The A&R technology advancement organization must then identify and study the critical areas necessary to achieve these goals. The study programs should involve both internal and external work.

NASA should build a strong internal capability in A&R. It should maintain contact with industries and universities and evaluate A&R technologies so that NASA can be a "smart buyer" and a "smart patron" of external technology. It should be able to integrate component technologies into demonstration systems and support R&D and flight operation organizations.

NASA must also invest heavily in external technology advancement. Severe manpower shortages in important technical areas make acquisition of qualified staff difficult. Many critical capabilities in both universities and industry are available only through external contracts. NASA should consider establishing several technology advancement centers at major universities.

The technology advancement organization must also carry out space demonstrations of principal technologies. Such demonstrations will not be expected to space-qualify equipment but will be used primarily to illustrate new A&R concepts. They might also be an excellent method of encouraging technical exchange with other organizations in the Space Station effort.

Suggested Organizational Constraints

The Panel believes that the key to ensuring the rapid and ongoing advancement of A&R technology for space applications (Step 1) lies in assigning this responsibility to a single organization within NASA. This A&R technology advancement organization should also direct the concept demonstrations (Step 2). The Panel believes strongly that this fundamental technology advancement should be separated at a high level of management from prototyping, testing and implementation. Otherwise, there is a danger that resources for technology advancement could be redirected toward high-pressure short-term goals. This would delay advancements in key technologies. In particular, the Panel believes that the responsibility for A&R technology advancement should lie outside the Office of Space Station. These considerations give rise to Recommendation 12a.

The Panel considered several models the technology advancement organization might use to manage contracts. One is the Defense Advanced Research Projects Agency (DARPA) in which a few highly qualified technical people define major program areas, accept and review proposals, and make contract decisions. The individual military services bring ideas to DARPA for funding of work to be conducted jointly. This program has yielded important results in machine vision, artificial intelligence, expert systems, microelectronics, and new computer architectures. Yet DARPA itself does not administer its contracts; the services award and manage them.

A similar model could work well for NASA. A lead center could be assigned to work with the A&R technology advancement organization to provide both technical expertise and contracting services. This will allow NASA to put the technology advancement organization into operation quickly and with a minimum of overhead.

A lead center can also serve as a repository for facilities to be shared by NASA and its contractors. For example, a knowledge engineering laboratory would be extremely useful to both NASA and a broad range of university and industry contractors. The laboratory would contain several knowledge bases and provide computer simulations of key problem domains. Such knowledge bases and simulations can take many man-years to develop. Having them in a central, shared facility can save a great deal of effort, and also provide a common base for comparing techniques developed by different investigators.

Shared facilities will also be necessary in areas such as massively parallel computer systems, computer aided design (CAD) databases of hardware, and complete dynamic simulations of the Space Station. The centralized facilities must be physically accessible to many users. Workers in the wider A&R community must be able to access the centralized facilities and each other via a NASA SPAN or ARPANET.

7.1.2 Ensuring Linkage between A&R Technology Advancement and Implementation

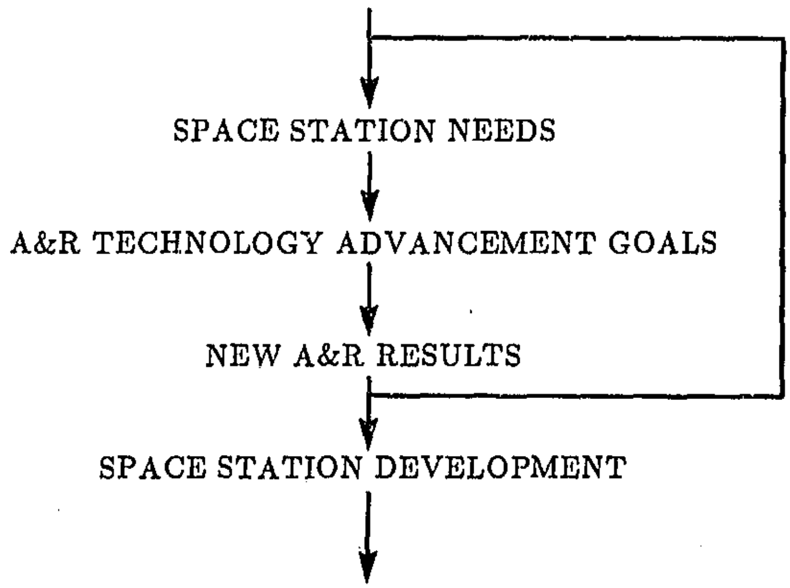
It would be preferable to have the A&R technology advancement and the implementation of advanced systems in the Space Station be conducted by separate organizations. However, they must cooperate in setting overall goals, understanding the potentials of new concepts, and in bringing suitable new concepts into the operation of the Space Station.

Coupling Advancement and Implementation

A&R technology advancement activities can be closely coupled to the Space Station's needs by an implementation organization in the Office of Space Station. Exhibit I depicts the desired situation.

Exhibit I

Relationships between new A&R technology advancement and implementation activities



The A&R technology advancement organization should set joint goals with other NASA entities. All major Space Station development and operations groups should have a strong voice in setting these goals. Also, reports from the external review panel (see section 7.2) should weigh heavily in planning activities. The Space Station implementers do not need to concern themselves with the daily activities of the A&R technology advancement organization. They must, however, participate in the general technology advancement. Frequent joint technical progress reviews will ensure mutual awareness of activities and promote technical exchange.

Ensuring A&R Technology Insertion

There must be a mechanism for the efficient flow of advanced technology into Space Station operations. A large corporation typically has a research laboratory, an engineering department, and a manufacturing department. The engineering department often serves as an intermediary between research and manufacturing. The Panel suggests a similar arrangement in the Space Station program, to be administered by the Office of Space Station. This gives rise to Recommendation 12c.

The most practical ideas must be extracted from the advancing technologies. Someone must assist the researchers in maintaining practical goals, and help those actually building and operating the Space Station learn to understand and use the new technologies. The educational process is particularly critical.

In the categories of technology development described earlier, Step 1 is the initial creation, performed by scientists and research engineers, and Step 4 is the ultimate implementation step performed by Space Station construction engineers. In between, advanced development engineers will be responsible for the space demonstrations in Step 3. The concept demonstrations of Step 2 must be joint projects between research engineers and advanced development engineers. Such projects are also an excellent way to pass in-depth knowledge of new A&R concepts to those who will be responsible for their further development. Similarly, involving the Space Station construction engineers in prototype testing (ground, aircraft, and shuttle flights) will give them the detailed knowledge they need to implement new A&R capabilities.

A matrix relationship between the two new organizations would encourage greater flexibility in moving new ideas into operation. Developers could temporarily move into the advanced development arena to participate in prototyping and space-qualifying tests. Consider, for example, the development of an Astronaut's Apprentice. This project would begin with an autonomous robot *go-fer* on the IOC using off-the-shelf technology. The project would evolve into an autonomous system for operation and repair of the core Space Station. This would eventually leave the crew almost entirely free to concentrate on user and payload functions (see Appendix 2-A).

7.1.3 Ensuring Additional Responsibility for Broader Applications

A major aim of the Congressional mandate is that A&R technology developments sponsored by the Space Station program should benefit the nation's civilian economy through advances in manufacturing and service industries. Thus, while the A&R technology base will primarily benefit the Space Station, the technology advancement organization must consider non-NASA applications in its planning. It must also see to it that the advancements reach the civilian economy.

The Space Station program can promote the use of terrestrial A&R in space by designing the evolving Space Station to readily accommodate terrestrial technologies. Increasing A&R technology transfer between space and Earth applications should be encouraged throughout the program.

7.1.4 Ensuring Visibility and Accountability

Congress has mandated the accelerated use of automation and robotics in the Space Station. Thus, NASA activity in these areas should be both visible and accountable to the highest levels of NASA, to Congress, and to the nation as a whole. This will help establish the importance of A&R technologies and encourage broad participation in their advancement. It will also encourage implementation of the technologies within NASA, and their transfer to private industry. The accountability at high levels should provide budgetary stability for the technology advancement activity.

The Panel suggests that placing the budget for the A&R activity at a prominent high level in NASA's budget (as indicated in Recommendation 12b) is an effective way to ensure this visibility and accountability.

7.2 EXTERNAL REVIEW PANEL

The automation and robotics program must be maintained as a top quality activity. To ensure this, an external review panel is recommended, to be drawn from industry, academia, and government. This panel would advise the government and the nation on the best near- and long-term A&R goals and on how to achieve them. The panel activities can also encourage other national communities to help bring advanced A&R to use in space and on Earth. It may be necessary to encourage the growth of new A&R communities.

7.2.1 Purpose and Function

The external review panel should establish goals and priorities for both Space Station and national interests. Through its committee selections, the review panel should ensure broad exposure in industrial, academic, and governmental sectors and the subsequent transfer of knowledge.

The review panel should perform the following minimum functions:

- Conduct an annual peer review of A&R research and technology to maintain the high quality of the program.
- Actively advise NASA on A&R technology advancements pertinent to Space Station. In particular, the panel should review and expand the Space Station A&R implementation plan.

- Annually report to Congress on technology advancements in automation and robotics.

7.2.2 Implementation

Several models exist for the external review panel, including panels operated by the National Research Council (NRC), the Lunar and Planetary Review Panel operated for NASA, and panels created by professional societies.

For example, NRC's advisory Space Science Board whose purpose is to counsel the federal government on goals and priorities for space science, appoints committees to prepare strategy reports. Their findings and recommendations are directed principally to NASA management and, through them, to the Executive branch of the government. The Board also communicates its recommendations to Congress through letters and individual testimony, and makes its reports available to the public on request. The main drawback of this approach is that NRC panels typically meet too infrequently to track and advise on rapidly changing technologies.

Other implementation options should be considered. For example, since the review panel would be concerned primarily with technology issues, it could be organized within the National Academy of Engineering. Another approach might be to establish it through joint sponsorship by universities, industries, and governmental agencies (such as NASA, DARPA, and the National Bureau of Standards) that have a strong interest in A&R technology. A properly constituted external review panel can vitalize the advancement of automation and robotics within NASA and link NASA to the relevant national communities.

7.3 A CHALLENGE

The Automation and Robotics Panel concludes that the United States Congress was correct to broaden the challenges assigned to NASA, especially in its approach to advanced A&R technologies.

NASA is world renowned for its accomplishments in space. Advanced automation and robotics can make the Space Station, in particular, into a toolset for America to use for growth beyond the Earth. Space Station automation and robotics will also directly advance technologies and procedures that benefit industries and individuals here at home.

Can NASA and its affiliates in the Space Station program meet these new challenges? If so, the nation's goals and capabilities, on and off Earth, will expand, last longer, and involve more people. These groups face a demanding challenge during the short definition portion (phase B) of the Space Station program. The nation should carefully scrutinize their accomplishments. They are defining the tools for our permanent growth beyond Earth. These tools should be versatile, cost-effective, safe, and supportive of the highest creativity.

GLOSSARY

Ada - High-level programming language developed by the U.S. Department of Defense for use in embedded computer systems.

ARPANET - A network linking computers sponsored by the Defense Advanced Research Projects Agency (DARPA).

Artificial Intelligence (AI) - A discipline devoted to developing and applying computers to produce intelligent behavior.

Autonomous - Capable of independent action.

Backtracking - Returning to an earlier point in a search.

Backward chaining - A form of reasoning that works backward from a goal toward the required conditions.

Bottom-up control structure - A problem-solving approach that reasons forward from current or initial conditions.

C - High-level programming language developed at Bell (AT&T Information Systems) Laboratories for systems programming.

Cis-lunar - Between the earth and the moon.

Cognition - An intellectual process for gaining knowledge about perceptions or ideas.

Common sense reasoning - Low-level reasoning based on experience.

Computer architecture - The way in which computational elements are connected to perform an overall function.

Computer graphics - Visual representations generated by a computer.

Computer network - An interconnected set of communicating computers.

Computer vision - Perception by a computer based on visual sensory input.

Concurrent programming - Allows multiple processes to occur simultaneously.

Core network - Space Station computer capable of handling basic survival and housekeeping functions.

Cryogen - Liquid that boils at a very low temperature (typically less than 110 K) at atmospheric pressure.

Database - An organized collection of data.

Database management system (DBMS) - A system designed to store and retrieve information.

Data-driven - A forward reasoning, bottom-up approach to problem solving.

Data structure - The form in which data in stored in a computer.

Debugging - Correcting errors in a system or computer program.

Decision support system (DSS) - Computer program that provides advice or analysis aimed at helping a professional make complex decisions.

Deductive reasoning - Working from premises to a conclusion.

Default value - A value to be used when the actual value is unavailable.

Distributed System - Many communicating functional elements at several locations.

Editor - A computer program used to enter and correct text.

Emulate - Perform like another system.

End effector - The tool or "hand" at the end of a robotic arm.

Ergonomics - The study of human factors in the workplace.

Expert system - A computer program that uses knowledge and reasoning techniques to generate advice and make limited decisions normally requiring the abilities of a highly trained person.

Fail operational - A system which continues to operate following failure of subsystem(s).

Fail safe - A system which remains safe following subsystem(s) failure.

Fiber optics - Thin glass fibers used to link optical communication systems.

Fiducial point - Mark used for reference or measurement by an optical instrument.

Fifth Generation Computer - A non-Von Neumann, intelligent, parallel processing form of computer now being developed in Japan.

Gigabit - One billion bits.

Go-fer - A robot capable of responding to simple requests for parts and materials.

Heads-up display - A simulated visual display which can be viewed while looking straight ahead and changed by movements of the operator's head.

Hook - Software that serves mainly to allow later additions or extensions to a system.

Hybrid (teleoperator-robot) system - See telerobot.

Knowledge bases - A database used in artificial intelligence applications, consists of facts, inferences, and procedures required to solve a problem through reasoning.

Knowledge engineering - AI use of knowledge bases to solve problems.

Knowledge representation - The form of data structure used to organize the knowledge required to solve a problem.

LISP - List Processing Language, a computer language widely used in AI applications.

Local area network - A communications network linking computers and other elements that is geographically restricted to within a small area such as a single building.

Machine vision - See computer vision.

Macromodular - Consisting of separate large, independent units.

Menu - Listing of the current options available to a system operator.

Micromodular - Made up of simple building blocks.

Natural language interface - Communicating with a computer using human language.

Node - A connection point in the network.

Object-oriented programming - A programming approach focused on objects that communicate by passing messages.

Operational network - Space Station computer network capable of handling user needs over and above core needs.

Orthographic representation - Perpendicular projection of a three-dimensional object on a two-dimensional surface.

Parallel processing - Simultaneous processing of inputs.

Pattern matching - Comparing inputs to images or templates in a database.

Perception - The process of classifying data into predetermined categories.

Portability - The ease with which a computer program developed in one programming environment can be transferred to another.

Programming environment - The total setup used to develop programs, including languages, editors and other programming tools.

PROLOG - Programming in Logic, a logic-oriented AI language.

Protocol - Set of conventions governing the format and timing of data exchange between communicating systems.

Real-time system - System that controls an ongoing process and gathers inputs and produces outputs at the times required for effective control.

Retrofit - To add hardware to an operational system or structure.

Scar - Hardware that serves mainly to allow later additions or extensions to the system.

Sensor fusion - Combining information from one or more sensor.

Signal processing - Analysis of real-time data from sensors.

Software tool - A program used mainly in the development of other progr ns.

Space-qualified hardware - Elements certified as capable of operating in an unprotected space environment.

Speech recognition - Recognition by a computer of spoken words.

Speech synthesis - Development of speech from text or other representations.

Symbolic processing - Use of logic and reasoning to deal with relationships between non-numeric objects.

Symbolic programming - Writing of programs to perform symbolic processing.

Telerobot - An abbreviation of hybrid teleoperator/robot, a device capable of some independent (autonomous) operation but generally requiring remote operator control for most tasks.

Teleoperator - A manipulator that can be controlled continuously and in detail by a human operator. either remotely or "hands on."

Telepresence - Making the remote operator of a system feel as if he or she were actually present in the workplace through sensory inputs and feedback.

Terabyte - One million megabytes, 10^{12} bytes.

Top-down approach - A goal-directed approach to problem-solving.

Von Neumann architecture - Standard computer architecture based on stored programs and sequential processing.

World model - A representation of the current situation.

ACRONYMS AND ABBREVIATIONS

A&R	Automation and Robotics
AI	Artificial Intelligence
ANSI	American National Standards Committee
ARP	Automation and Robotics Panel
ASCII	American Standard Code for Information Interchange
ATAC	Advanced Technology Advisory Committee
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAI	Computer Aided Instruction
CAM	Computer Aided Manufacturing
CAT	A Small, Furry Animal
DARPA	Defense Advanced Research Projects Agency
ECLSS	Environmental Control and Life Support System
EMU	Extravehicular Mobility Unit
ET	External tank of the STS

EVA	Extravehicular Activity
GaAs	Gallium Arsenide
GEO	Geosynchronous Earth Orbit
GPS	Global Positioning System
H/W	Hardware
IOC	Initial Operational Capability
IVA	Intravehicular Activity
LEO	Low-Earth Orbit
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NBS	National Bureau of Standards
NDE	Non-Destructive Evaluation
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OAST	NASA Office of Aeronautics and Space Technology
OMV	Orbital Maneuvering Vehicle
OSS	NASA Office of Space Science and Applications
OTA	Congressional Office of Technology Assessment
OTV	Orbital Transfer Vehicle
PC	Personal Computer
RMS	Remote Manipulator System
ROV	Remotely Operated Vehicle
RRM	Replaceable Reconfigurable Module
SPAN	Scientific Program Access Network
STS	Space Transportation System
S/W	Software
VHSIC	Very High Speed Integrated Circuit
VLSI	Very Large Scale Integration