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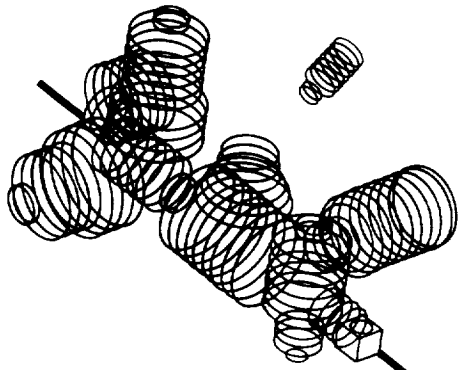
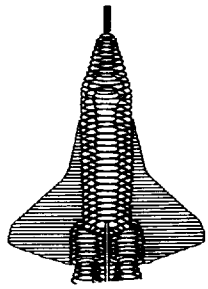
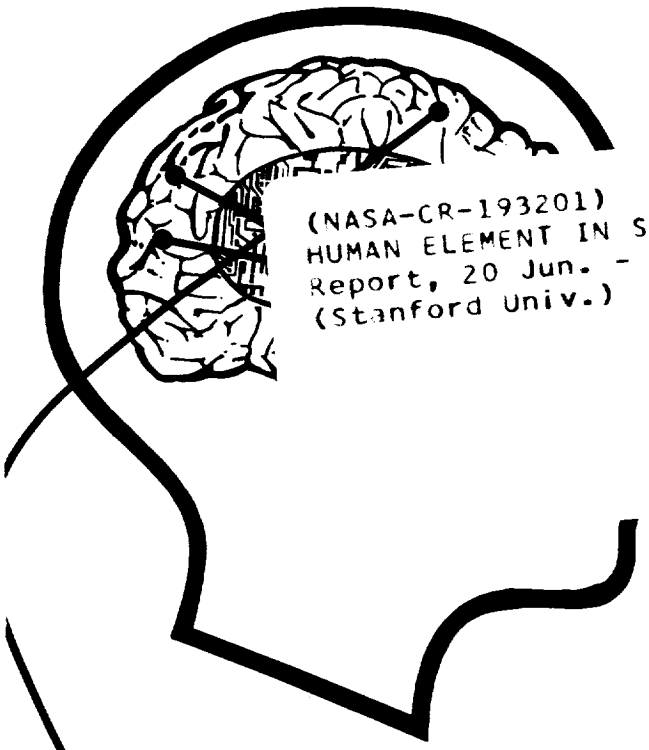
# AUTONOMY and the HUMAN ELEMENT in SPACE







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**FINAL REPORT**

# AUTONOMY and the HUMAN ELEMENT in SPACE

**FINAL REPORT OF THE 1983 NASA/ASEE SUMMER FACULTY WORKSHOP**

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# TABLE OF CONTENTS


| | Page |
|---|---|
| TITLE PAGE | i |
| TABLE OF CONTENTS | iii |
| LIST OF PARTICIPANTS | vii |
| LIST OF TABLES | ix |
| LIST OF FIGURES | x |
| ACKNOWLEDGMENTS | xi |
| 1. INTRODUCTION | 1 |
| 1.1 Study Objectives | 1 |
| 1.2 Dimensions of Autonomy for the Space Station | 2 |
| 1.3 Autonomy Relations in Space Systems | 4 |
| 1.4 Organization of This Report | 4 |
| 1.5 References | 5 |
| 2. AUTONOMY IN THE SPACE STATION CONTEXT | 7 |
| 2.1 Space Station Description | 8 |
| 2.2 Space Station Users and Uses | 8 |
| 2.2.1 Space Operations | 8 |
| 2.2.2 Commercial Operations | 9 |
| 2.2.3 Space Sciences and Research | 9 |
| 2.2.4 National Security | 9 |
| 2.3 References | 10 |
| 3. HUMAN-MACHINE SYSTEMS | 11 |
| 3.1 Manned Extravehicular Activity (EVA) | 11 |
| 3.1.1 Safety | 11 |
| 3.1.2 Mobility | 12 |
| 3.1.3 Tools, Supplies and Information | 13 |
| 3.1.4 Working in Space | 13 |
| 3.2 Teleoperation and Telepresence | 13 |
| 3.2.1 Past Telepresence Applications | 14 |
| 3.2.2 Space Telepresence | 14 |
| 3.2.3 Teleoperated Intravehicular Activity | 15 |
| 3.2.4 Teleoperated Extravehicular Activity | 15 |
| 3.2.5 Space Station and Telepresence | 16 |
| 3.2.6 Telepresence Technology and Development Program | 17 |
| Teleoperation Technology Requirements | 17 |
| Telepresence Development Program | 18 |
| 3.2.7 Supervisory Control: The Bridge to Robotics | 18 |
| 3.3 Robotics | 19 |
| 3.3.1 Robot Control, Sensors, and Power | 19 |




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Page


3.3.2 Mechanical Classes of Robots Possibly Useful in Space ..... 20
Humanoid Manipulators 20
Cartesian Manipulators 20
Spherical Manipulators 20
Cylindrical Manipulators 20
Tentacle Manipulators 21
Non-Servo Pick-and-Place Manipulators 21
Mobile Crawlers 22

3.3.3 Space Station Robot Applications ..... 22
Assembly Tasks 22
Manufacturing and Laboratory Testing Tasks 23
Satellite Servicing Tasks 23
Space Food Services 23
Space Health Maintenance 23

3.3.4 Generic Capabilities Required for Space Station Robots ..... 24

3.3.5 Needed Development of Space Robotics Technologies ..... 24
Background on RMS 24
Future Capabilities of RMS 24
Zero-Gravity Manipulator Mechanics 25
Locomotion for Mobile Robots in Space 25
Manipulator Designs for Space 26
Sensors for Robots in Zero-G 26
Spatial Reasoning for Zero-G 26

3.3.6 Spinoffs from Advanced Robotics Development ..... 26

3.3.7 Summary and Recommendations ..... 27

3.4 Human-Machine Symbiosis ..... 27

3.4.1 Function Allocation ..... 27
3.4.2 Choosing Tools ..... 29
3.4.3 Humans and Machines: The Element of Trust ..... 29

3.5 References ..... 30

4. MONITORING AND CONTROL ..... 33

4.1 Supervision: Locus of Control Autonomy ..... 33

4.1.1 Computer-Based Supervisory Process Control ..... 34
Monitoring for Supervision 34
Annunciators and False Alarms 35
ECLSS: A Case Study 36

4.1.2 Automated Problem-Solving and Fault Diagnosis ..... 36
Expert Systems: Basic Structure 37
System Evaluation and Fault Diagnosis 37
Intelligent Assistants 38
Software Reliability, Credibility, and Confidence 39

4.1.3 Natural Language and Station Information Management ..... 39
Natural Language Systems: Background and Brief Tutorial 41
Natural Language in Database Management 42

4.2 Technology Systems: Task Performance Autonomy ..... 44

4.2.1 Sensor Technologies for Space Operations ..... 44

4.2.2 Space Station Displays ..... 45
Selection of Sensory Mode 45
Speed and Load in Displays 46
Visual Displays 46
Symbolic and Pictorial Displays 46
Head-Up, Historical and Predictive Displays 47
Location and Patterning of Displays 47
Display Technology for the Space Station 47

Page


4.2.3 Space Station Controls ..... 48
Design Considerations for Controls 48
Control Technology for the Space Station 49

4.2.4 Space Station Computer/Controller Network ..... 50
Computation 51
Station Network Configuration 51

4.3 Ground vs. Space: Locale of Control Autonomy ..... 52

4.3.1 Ground-Based Functions ..... 53
4.3.2 Space-Based Functions ..... 54
4.3.3 Shared Ground/Space Monitor and Control Functions ..... 54

4.4 References ..... 55

Appendix 4A. Computer Science & Artificial Intelligence Control Structures for Space Station 59

5. HUMANE SPACE STATION ..... 63

5.1 Humans in Space Settings ..... 64

5.1.1 Emotional Difficulties of Space Station Habitation ..... 64
Loneliness 64
Station Recreation 64
Anchorage and Exploration 65

5.1.2 The Design of Setting Factors ..... 66
The Physical Dimension 66
The Perceptual Dimension 67
Physiological Dimensions: Calcium and Sunlight 68
Social and Temporal Dimensions 69

5.1.3 The Reciprocal Roles of Settings and Behavior ..... 69

5.1.4 Setting Design for the Space Station ..... 70

5.1.5 Fundamental Issues ..... 71

5.1.6 Summary of Space Settings ..... 72

5.2 Crew Communications ..... 73

5.2.1 Face-to-Face and Telemediated Communication ..... 73
The Function of Human-to-Human Communication 73
Face-to-Face Contact 73
Telemediated Contact 74
Evaluation of Media 74

5.2.2 Space Station Interpersonal Communication ..... 75
Onboard: Within-Crew Communication 75
Local Calls: Communication in Near-Space Neighborhood 75
Long Distance: Station-Earth Communication 76
Terrestrial Networking: Communicating on Earth 76
Conclusions 77

5.3 Space Station Organization ..... 77

5.3.1 Space/Ground Autonomy ..... 78

5.3.2 A Primer of Organizational Design for Effectiveness ..... 79
Scientific Management Principles 79
Human Relations Management Principles 80
Contingency Approach to Design 81
Framework for Space Station Organizational Design 82

5.3.3 Space Station Applications of Organizations Research ..... 82
Computers in Organizations 82
Professional Workers and Technology 83
Simultaneous Loose and Tight Coupling 84

Page


5.3.4 Models for Space Station Organizational Design ..... 84
Effectiveness of Alternative Models 86
Semantics as Symbols 86
Skewed Sex Ratios and Tokenism in Crew Selection 87

5.3.5 Organizational Aspects of the Human-Machine Interface ..... 87
An Augmented Human Factors Perspective 87
Human Factors Engineering and the Organization of NASA 88
Space Station Human-Machine Interface 89
Lessons from Lordstown for the Space Station 89

5.3.6 Summary of Needed Areas for Study ..... 90

5.4 References ..... 91

6. METHODOLOGIES FOR AUTONOMY ..... 97

6.1 Simple Matrix Methodology: The ARAMIS Study ..... 97

6.2 Expert System for Task Allocation: SSTAAMMER ..... 102

6.3 Decision Matrices: The Geometry of Uncertainty ..... 104

6.4 Ethnography and Terrestrial Cultural Analogs ..... 104

6.4.1 The Eskimos: Cultural Adaptation to Isolation and Withdrawal ..... 104
6.4.2 Isolation and Confinement ..... 106

6.5 Trend Mapping Methodology ..... 106

6.6 References ..... 107

Appendix 6A. Sample Run, Decision Rules, and Program Listing for the SSTAAMMER Expert System 109
Appendix 6B. Autonomy Measure Function and Symmetry Relations ..... 121

7. EVOLUTION OF SPACE STATION AUTONOMY ..... 123

7.1 Near-Term Station Evolution ..... 124

7.1.1 Near-Term Capabilities of the Space Station ..... 124
7.1.2 Factors and Options in Near-Term Evolution ..... 125

7.2 Commercialization of the Space Station ..... 125

7.2.1 Materials Processing in Space (MPS) ..... 126
Product Areas for MPS 126
Role of the Space Station in Support of MPS 127

7.2.2 Communications Satellites ..... 127

7.3 Advanced Stations and the Evolution of Autonomy ..... 128

7.3.1 Second-Generation Stations, Lunar Bases, and Beyond ..... 128
7.3.2 Autonomy and the Human-Machine Symbiosis ..... 129
7.3.3 The Space Station as an Autonomous Intelligent Organism ..... 129

7.4 References ..... 129

Appendix 7A. A Day in the Life of a Space Station Crewman ..... 131
Appendix 7B. Design Concepts and Desirable Station Features ..... 138
Appendix 7C. Space Platform: The Unmanned Alternative ..... 142

8. CONCLUSIONS AND RECOMMENDATIONS ..... 149

GLOSSARY ..... 151

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# LIST OF TABLES


| Table | | Page |
|---|---|---|
| 4.1. | Nature of, Interface Character of, and Control Locations for Representative Systems | 53 |
| 5.1. | Communication Channels Available as a Function of Communications Media | 74 |
| 5.2. | Functional Allocation of Crew Scheduling Activities | 79 |
| 5.3. | Characteristics of Alternative Organizational Design Models | 85 |
| 6.1. | Critical Factors in Selecting Autonomy Decision Methodologies | 98 |
| 6.2. | List of ARAMIS "Areas" and "Topics" | 100 |
| 6.3. | ARAMIS Decision Criteria Comparison Chart and Average Sums | 101 |
| 6.4. | Conditions on the Space Station, Sociological Study Groups, and Cultural Analogs | 105 |
| 7.1. | Space Station and Space Platform: Cost Estimate Comparison | 146 |
| 7.2. | Space Station and Space Platform: Economic Benefits Estimate Comparison | 147 |

# LIST OF FIGURES


| Figure | | Page |
|---|---|---|
| 1.1. | A Three-Dimensional Model of Autonomy | 3 |
| 3.1. | M.I.T. Free-Flying Hybrid Teleoperator | 14 |
| 3.2. | Remote Orbital Servicing System (ROSS) Teleoperated Servicer Kit | 14 |
| 3.3. | Telepresence Communications and the TDRSS Time Delay Problem | 16 |
| 3.4. | An Example of Advanced Supervisory Control | 19 |
| 3.5. | Mechanical Classes of Robot Manipulators | 21 |
| 3.6. | Space Station Module with Cylindrical-Coordinate Manipulator Automation | 22 |
| 4.1. | Data Representation Alternatives for Space Station Database Management Systems | 40 |
| 4.2. | Space Station Monitoring and Control Architecture: Hierarchy of Intelligent Monitor and Control Systems | 50 |
| 4.3. | Schematic of First-Order Logic Blackboard | 60 |
| 5.1. | Research Framework for Studying Communication Modality Effects on Task Performance | 77 |
| 6.1. | ARAMIS Study Method: Space-Project-Task/ARAMIS-Capability Matrix | 99 |

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From the outset the workshop was greatly assisted by an intense series of presentations and briefings by very able outside visitors -- experts on various aspects of space, space technology, computing, artificial intelligence, robotics, and teleoperator systems. Their names appear in the list of participants.

The group wishes to thank Dan Hays, Sam Topham, and JoAnne Freeman for their special service as team leaders during successive trimesters of the summer workshop, and the other fellows and associate fellows who, in addition to the three leaders, acted as chapter or section editors during the course of the study. The group especially thanks Doug Wong for working as computer system coordinator in addition to his workshop research responsibilities. We also thank our co-directors, Dr. Richard D. Johnson of Ames Research Center and Professors Daniel Bershader and Lawrence Leifer of Stanford University, our ex- cellent secretarial staff including Teresa Storm, Margaux Syvertson and Theresa Warren, and our general editor Robert A. Freitas Jr., for their contributions and assistance.

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# CHAPTER 1

# INTRODUCTION

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NASA is contemplating the next logical step in the U.S. space program -- the permanent presence of humans in space. As currently envisioned, the initial system, planned for the early 1990s, will consist of manned and unmanned platforms situated primarily in low Earth orbit. The manned component will most likely be inhabited by 6-8 crewmembers performing a variety of tasks such as materials processing, satellite servicing, and life science experiments. The station thus has utility in scientific and commercial enterprises, in national security, and in the development of advanced space technology.

The technical foundations for this next step have been firmly established as a result of unmanned spacecraft missions to other planets, the Apollo program, and Skylab. With the shuttle, NASA inaugurates a new era of frequent flights and more routine space operations supporting a larger variety of missions. A permanently manned space system will enable NASA to expand the scope of its activities still further.

Since NASA's inception there has been an intense debate over the relative merits of manned and unmanned space systems. Despite the generally higher costs associated with manned components, astronauts have accomplished numerous essential, complex tasks in space. The unique human talent to evaluate and respond inventively to unanticipated events has been crucial in many missions, and the presence of crews has helped arouse and sustain public interest in the space program. On the other hand, the hostile orbital environment affects astronaut physiology and productivity, is dangerous, and mandates extensive support systems. Safety and cost factors require the entire station complex, both space and ground components, to be highly automated to free people from mundane operational chores.

Recent advances in computer technology, artificial intelligence (AI) and robotics have the potential to greatly extend space station operations, offering lower costs and superior productivity. Extended operations can in turn enhance critical technologies and contribute to the competitive economic abilities of the United States. A high degree of automation and autonomy may be required to reduce dependence on ground systems, reduce mission costs, diminish complexity as perceived by the crew, increase mission lifetime and expand mission versatility. However, technologies dealing with heavily automated, long-duration habitable spacecraft have not yet been thoroughly investigated by NASA (Sagan, 1980).

A highly automated station must amalgamate the diverse capabilities of people, machines and computers to yield an efficient system which capitalizes on unique human characteristics. The station also must have an initial design which allows evolution to a larger and more sophisticated space presence. In the early years it is likely that AI-based subsystems will be used primarily in an advisory or planning capacity. As human confidence in automated systems grows and as technology advances, machines will take on more critical and interdependent roles. The question is whether, and how much, system autonomy will lead to improved station effectiveness.

## 1.1 Study Objectives

This report describes a study of autonomy in space and its effective use in an evolving, permanent extra-terrestrial human presence. The ten-week summer workshop was conducted at Stanford University from June 20 to August 26, 1983 with the assistance of Ames Research Center. The study brought together an unusually diverse interdisciplinary group of eighteen university professors and two graduate students from institutions throughout the United States, representing such fields as physics, psychology, chemical and industrial engineering, urban ecology and environmental planning, business and management, anthropology, and computer sciences. The workshop was sponsored jointly by NASA, through the Office of Aeronautics and Space Technology (OAST), and the American Society for Engineering Education as part of their continuing program of summer faculty fellowships, and was co-directed by Richard D. Johnson of NASA/Ames Research Center and by Daniel

Bershader and Larry Leifer of Stanford University.

The workshop sought to generate recommendations on autonomous systems and human functions as well as on a space technology program directed toward symbiotic use of machines and humans. The study addressed four overall topic areas dealing with interactions between autonomous machines and humans for a space station: (1) supervision/management of autonomous systems, (2) teleoperation of remote systems (telepresence), (3) extravehicular activity, and (4) the human as a subsystem.

NASA also needs a methodology to assess and to help assign functions between machine and human elements on the space station. While for some functions it will be a question of whether to have a human or a machine perform the work, it is likely that symbiotic combinations of these elements can offer enhanced capability. It is therefore desirable to search for human-machine combinations utilizing the best features of each, so that synergistic capabilities beyond human or machine abilities alone can be obtained.

The principal objectives of the 1983 summer study were to examine the interactions of humans and highly automated systems in the context of specific tasks envisioned for the space station, to search for optimum combinations of humans and machines, and to develop methodologies for selecting human-machine systems.

By the end of the study, workshop participants concluded that machines will not replace humans in space and that artificial intelligence (AI) systems will not have major impact on initial station design. However, several specific areas of human-machine interaction appear promising, both for increasing station effectiveness and for reducing ground personnel requirements. Therefore, study fellows recommend that significant funding should be directed toward the development of selected EVA, teleoperator, robotic, and AI systems, and toward design studies of work-setting, communication, and organizational factors in highly automated environments.

All views expressed in this report are due solely to the workshop participants and do not necessarily reflect official NASA positions. Also, as of the publication date of this report, the Space Station project has been funded and design considerations have evolved considerably beyond their status in 1983 at the conclusion of this study.

## 1.2 Dimensions of Autonomy for the Space Station

As a principle for designing relations among parts of systems or organizations, autonomy itself has no intrinsic value. It is important only insofar as it enhances or detracts from effectiveness. If component or system effectiveness improves as a result of greater autonomy, then more autonomy would be judged desirable. Conversely, increased autonomy which detracts from effectiveness is undesirable. The autonomy issue arises naturally when parts of a system -- such as the multicomponent space station -- are physically distant.

What is autonomy? One operational definition currently used by NASA engineers is: "The ability to function as an independent unit or element, over an extended period of time, performing a variety of actions necessary to achieve predesignated objectives, while responding to stimuli produced by integrally-contained sensors" (Hodge, 1983). In the broader context of space habitation, exploration, and industry, autonomy refers to the network of control relationships that inevitably forms when people and machines are coupled in a common venture. Autonomy is a property not of things but rather of the relatedness of things. Autonomy thus describes the degree and nature of independence from control that an entity has with respect to any other in an organized system.

The autonomy concept is applicable to elements in any system that performs a task. These elements may be astronauts, machines, computers, sensors, or some larger or hierarchial combination of components, and each may be either a controlled object or a source of control for other elements. A three-dimensional geometrical model of autonomy for the space station, incorporating the essential concept of independence from outside control, was developed during the workshop to help focus the research effort (Figure 1.1).

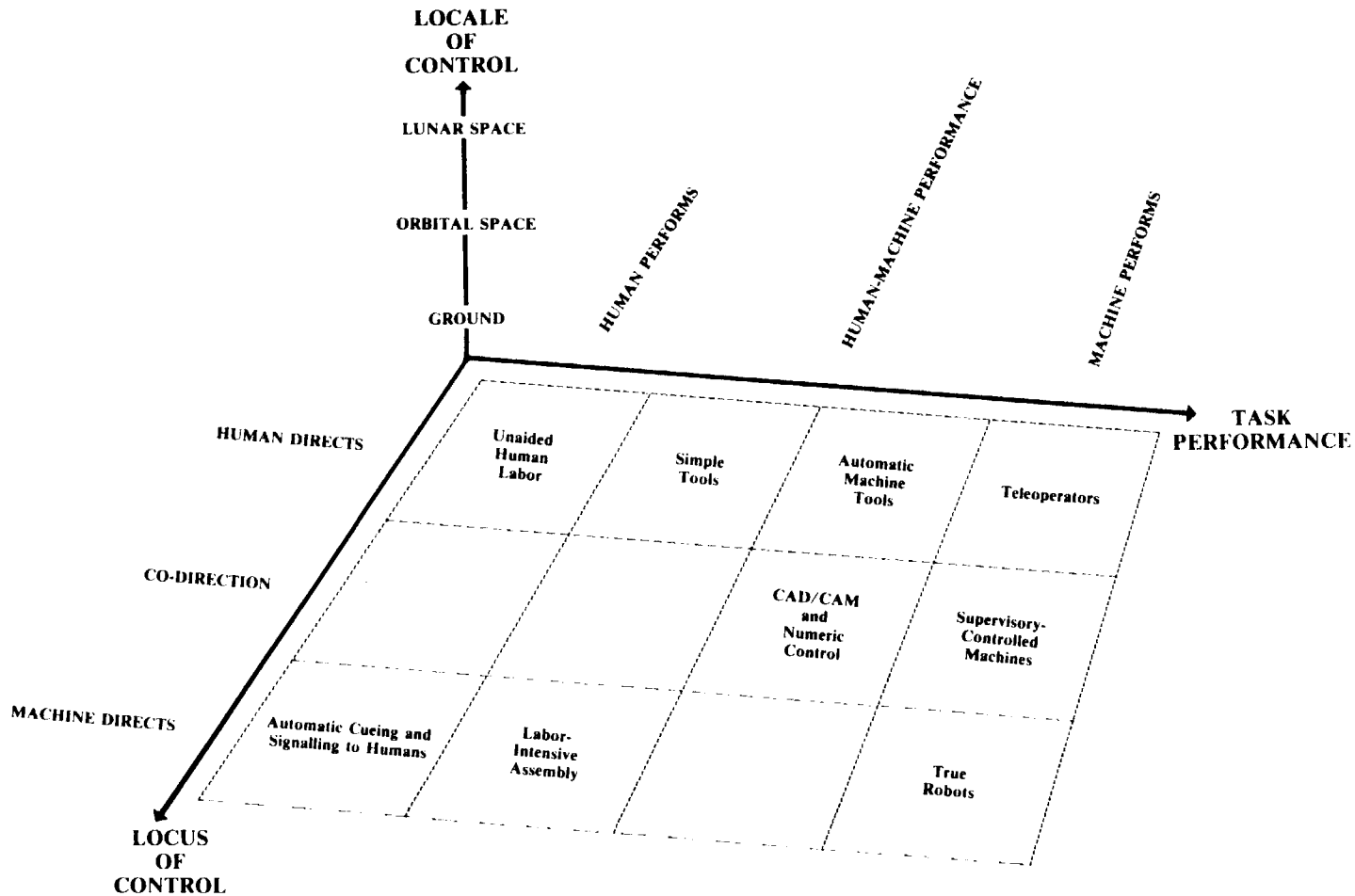
The first dimension of autonomy measures the <u>locus of control</u> for tasks -- that is, do humans or computers exercise the controlling intelligence, and to what degree? NASA sometimes equates autonomy with a machine system in which real-time human control is absent, or with the degree of technological development of autonomous machines and the practical applicability of these types of machines to space. These issues are an important subset of the comprehensive autonomy concept developed here.

Along a second dimension of autonomy lies the allocation of physical <u>task performance</u> to humans or machines. The more done by machines, the more "automated" the station. For instance, should humans in EVA suits or mechanical teleoperators execute a given task? Should monitoring and control functions be physically performed by people or by largely computerized systems? How much automation or machine assistance should be inserted into work and life on a space station?

The third dimension of autonomy, <u>locale of control</u>, distinguishes between Earth-based and space-based control. As control moves outward into space, the station becomes increasingly autonomous from the ground. Should the site of a particular monitoring, supervisory, decision or control task be in space, on the ground, or some combination of both? To what degree should the crew be organizationally autonomous from the ground?

Figure 1.1 offers a few typical examples of human-machine work systems in the Control/Performance plane. Unaided human labor (people direct and perform the work) represents the highest degree of human autonomy. True robots (self-guided work performance, using advanced machine intelligence) represent a high degree of machine autonomy. The mixed cases are more interesting. For instance, as humans employ increasingly complex tools, task performance is gradually assumed by machines even though the locus of control remains with the human. Teleoperator systems are an example of machines performing physical tasks under remote control by humans. Another mixed case is when humans do a task but are directed by machines. For example, in a labor-intensive assembly line humans perform physical labor but the pacing and timing of the assembly line is frequently computer-controlled.

FIGURE 1.1. A THREE-DIMENSIONAL MODEL OF AUTONOMY



## 1.3 Autonomy Relations in Space Systems

While a detailed analysis of autonomy models and theories is beyond the scope of the present study, the conceptual nature of autonomy was examined during the workshop. In the context of space station design, autonomy refers to the results of the control relationships among people and machines who join in a common venture.

Autonomy is a property of the relatedness of things. (Technically, it may be viewed as the deviation from restraint of sample element behaviors chosen statistically in a well-organized system.) Autonomy thus is a derived rather than a "primitive" concept. Much as utility arises from the primitive notion of preference, autonomy is derived from the primitive notion of control. The possibility of developing a measure function for autonomy was briefly considered during the workshop (see Appendix 6B).

A space system includes as its elements an assortment of people, machines, computers, and the architectural elements that support them. This system extends from the surface of the Earth to the most distant system component, and from the present to some moment in the past when a communication signal was initiated. Signal travel time induces varying time delays among intercommunicating elements, creating a complexity of component control that must be carefully orchestrated. Instrument pointings, extravehicular activities, station reboosts and platform attitude adjustments must be timed and executed correctly. Autonomy for each element will be appropriate to the role of that element in the matrix of overall system controls, and may be guided by the hierarchy of autonomies proposed in Appendix 6B and by the following basic principles.

First, a control hierarchy should be constructed such that the most autonomous elements experience constraints from the bottom up (e.g., in the order (3) bounding, (2) prioritizing, (1) inclusion/exclusion). The general rationale is to follow an ease-of-control hypothesis: It is usually easier to set limits on performance than to prioritize it or to add/subtract it completely. People also experience less infringement on personal freedom when constraints are placed in this order. For example, when entering a building through a door one is most willing to learn to push (or pull) on the handle, less willing to remember to wipe one's feet before entering, and least willing to request permission to enter. And constraining autonomy from the bottom up retains the greatest amount of unprogrammed system flexibility, thus a broader capability to respond to unforeseen external disturbances.

Second, the type of control most important for an element to express should always be safeguarded by an autonomy type at least one order higher than the control type. The control source needs flexibility to maintain control under a variety of disturbing influences. By exercising this flexibility through a higher-order autonomy, the controller is better able to survive situations that would otherwise circumvent it. While maintaining a variable within bounded limits, the controller is aided by the ability to re-sequence a set of control activities as needed. For instance, when one overpours sugar into a cup of coffee, and the coffee becomes too sweet, one can always dilute it by pouring additional coffee into the cup.

Third, when coupling two performers to execute a common task, their respective autonomies are appropriate if (1) they are coupled only through their outputs, unless one has a higher-order autonomy than the other; (2) the output of any autonomous action of one element does not act as a constraint on the autonomous actions of the other, unless one has a higher order of autonomy; and (3) the constraints placed on the autonomy of the least autonomous performer are of the lowest order necessary to complete the joint performance requirement.

Humans, robots, and intelligent machines in a space operations system are related to each other through the autonomies web of mutual controls they experience. The workshop study effort, detailed in the chapters that follow, has focused on how this web should be organized to enhance performance and effectiveness of the overall system.

## 1.4 Organization of This Report

**Chapter 2** presents tentative space station specifications, capabilities and mission tasks. The purpose of this workshop has been to explore autonomy and its effective use in an expanding permanent human presence in space, at a very fundamental level -- not to design a space station. However, since the station represents the most likely near-term application of autonomy concepts, this study focuses on pragmatic concerns rather than elaborating on theory. Consequently, an appreciation of the space station as currently envisioned is a prerequisite.

The remainder of the report focuses on the combination of humans and machines that will be most effective for the space station, and the degree to which the station and its crew may be independent of Earth-based control. Astronauts will interact with automation and computer systems at three levels: (1) Machines that work alongside people, assisting them in their tasks; (2) machines in the background that support the human presence in space; and (3) machines, in the form of the manned base station itself and indeed the whole station complex, both ground and space systems, which surround and define the human presence. On the basis of this perspective, autonomy and the human element in the context of the station necessarily involves difficult questions concerning human-machine systems (Chapter 3), the essential nature of information-intensive monitoring and control activities (Chapter 4), and space station organizational and social factors (Chapter 5).

**Chapter 3** examines three major types of human-machine systems: (1) Manned EVA (extravehicular activity), (2) teleoperation and telepresence, and (3) robotics. EVA exhibits the least machine autonomy, robotics the most. The characteristics of each technology are reviewed, with an examination of the tradeoffs between potential gains in effectiveness from machine autonomy and technical feasibility and achievability in various time frames. The purpose here is to outline the characteristics of each technology and to make recommendations from the standpoint of autonomy and effectiveness. The chapter concludes with a brief discussion of several important aspects of human-machine relationships -- particularly function allocation, tool-using in general, and mutual human-machine trust.

**Chapter 4** discusses space station monitoring and control functions. The station requires a

control system unlike any that has flown before, as well as sophisticated monitoring to assess its performance, to manipulate its system states knowledgeably under automatic control, and to detect and diagnose abnormal conditions. A larger number of subsystems are planned than for any previous spacecraft. The discussion of station monitoring and control follows the three-dimensional conception of autonomy outlined earlier. If the station can utilize emerging artificial intelligence technologies such as expert and natural language systems, then the full potential of the human presence on the space station may be achieved.

**Chapter 5** focuses on human, social and organizational aspects which may significantly affect station autonomy and effectiveness. This is a somewhat broader context than earlier chapters which focused on direct human-machine interactions in assuring the physical integrity of the station and in doing work in space, and on emerging technologies useful in this enterprise. Factors which most directly impact human performance are physical setting, interpersonal communications, and social organizational design. Effective human performance on the space station depends upon the maintenance of a healthy behavioral ecology. This intricate web of interrelated individual, interpersonal, organizational and setting factors must be carefully balanced if humans are to realize their full potential in space.

**Chapter 6** addresses three broad methodological questions. First, what is the nature of a space station task that determines whether it is appropriate for automation? What types of tasks should be allocated to humans? What combinations of humans and machines will be most effective? Second, what are the decision rules for function allocation between humans and automated systems in space and on the ground? Third, what are the decision rules for determining whether a function can be performed better in space or on the ground? Several specific techniques are briefly described, including simple matrix methodology, human-machine function allocation via expert system, decision matrices permitting representation and analysis of uncertainty, ethnographic methodology using cultural analogs, and trend mapping.

**Chapter 7** offers a quick glimpse of the future. How will the station evolve over the several decades to come? As greater effectiveness is sought in the development of space systems, evolution of station automation should result in a near-autonomous unit. We can imagine a progressive development including a "branch station" in low-Earth orbit for close contact and servicing of expanding orbital activities, becoming, later, the hub of a space city. An interesting ecological relationship could emerge between LEO and lunar activities -- the lunar ecology, sufficiently developed for materials, might serve roughly an analogous relationship to the station as the farm serves to the city on Earth. A near-space waystation or departure facility for manned translunar forays is yet another possibility for far-future stations. The chapter closes with a fictional "day-in-the-life-of" space station scenario and a compendium of numerous proposed design concepts and desirable station features.

**Chapter 8** finishes the report with a brief series of specific conclusions and recommendations.

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# CHAPTER 2

# AUTONOMY IN THE SPACE STATION CONTEXT

Contributions by

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Soon after the formation of NASA, an ad-hoc study group at Langley Research Center formulated a strategy for an evolutionary space program to proceed out of the Project Mercury work (Gilruth and Strass, 1960). This study sparked a debate between those advocating a manned moon landing and those who favored a space station. The early successes of the Soviet manned space program and diplomatic tensions doubtless influenced the decision of President Kennedy to send American astronauts to the Moon, and return them safely to Earth, before the end of the decade (Kennedy, 1961; Logsdon, 1970).

Planning for a post-Apollo space station was revived as the lunar landing program drew to a close -- an advisory Space Task Group created in 1969 to consider NASA's future formally recommended a space station and a space transportation system as major program objectives for the 1970s (Space Task Group, 1969). However, given the political demise of the Saturn V program and the dependency of any future space station program upon the success of the shuttle (for both launch and logistical support), NASA in 1970 replaced the space station with the shuttle as its top priority program.

By abandoning the Saturn V launch system, space station architecture became constrained by shuttle launch capabilities. The original 33-foot diameter station could have been deployed with a single Saturn V launch, but the shuttle-deployed version would require both multiple launches (the volumetric ratio between Saturn V and shuttle payloads is about 7:1) and assembly in space. As a result, NASA was forced to reduce its station capabilities specifications (Memorandum, 1970; MSC, 1970). Recently the monumental successes of the shuttle program have laid a firm foundation for the establishment of a permanent human presence in space.

A consensus has emerged among NASA centers and contractors in current thinking about the space station (Tilton, 1983). Unlike Skylab, the space station will be a permanent facility with its own orbit reboost capability for both orbit maintenance and orbit adjustment, and a planned initial life span of 20-30 years. If designed to enable component changeout and upgrading to utilize advancing technology, the useful life of the space station could be extended indefinitely. There has been some discussion about when people should be introduced into the space station (JSC, 1979; MDAC, 1982; see Appendix 7C), but the general view is that a continuous human presence is essential from the outset for a practical operation. It is believed that the current primitive state of automation technology (particularly in robotics, teleoperators and expert systems) would impose unacceptable constraints upon the mission capabilities of an early unmanned system. There is little disagreement on the means by which the space station will be launched, serviced and maintained. The reusable space shuttle, a cost-effective ground-to-orbit transportation system, may serve as the logistical and personnel support lifeline for the space station well into the next century.

Representing an "evolutionary" approach, the space station will, over time, become increasingly diverse in its function and complex in its configuration. Unlike the biological use of the term which assumes random mutations, evolutionary changes in space station architecture will be anticipated using highly flexible and adaptable system designs. Station evolution will be intelligently managed to ensure systematic technological upgrading, new roles for users, and new directions in applications. The space station must be regarded as a unique domain with unprecedented autonomy from ground support for a number of routine operations. Station crewmembers will experience increasing autonomy of action as the human-machine relationship matures and expands in directions and to a degree only dreamed of by science fiction writers just a few decades ago.

The space station may serve the needs of humankind in ways unimaginable by any other available means. Whether in orbital operations, space commercialization, space science and applications, or national security (see below), the station offers new and diverse exploitable capabilities. Perhaps after centuries of struggling to solve



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age-old human problems we may find many of the answers beyond Earth. The space station could provide the catalyst for our grandest achievements yet.

## 2.1 Space Station Description

America's first permanent space station will be a multi-element dispersed system comprising at least one inhabitable "core" or base station, plus unmanned platforms and associated free flyers. The core will be the most complex if not the largest component of the space station, due to its habitability and operations control requirements. Circling the Earth approximately every 90 minutes with a 6-8 member mixed crew of NASA and private sector (commercial or university-based) mission specialists and astronauts, the station will serve as the space-based control center for virtually all operations of the dispersed orbital system. The station probably will be positioned in LEO at a 28.5° inclination which offers the lowest energy requirements for a Kennedy Space Center launch. The facility will monitor, control and service (as required) a flotilla of unmanned platforms and free flying satellites in orbits with inclinations ranging up to polar (90°) and, eventually, out to geosynchronous range as well.

Actual station physical configurations are still under discussion, but several general design concepts and capabilities will likely be incorporated. The station will be constructed from prefabricated cylindrical modules carried aloft in the 15-foot-diameter shuttle cargo bay and assembled in orbit. Modules may be 14.5 feet in diameter and 20-30 feet long, with multiple access ports at either end and around the circumference to enable docking in any of several attitude-stable configurations.

Several functional module types might be found at the base station (JSC, 1979; MDAC, 1982):

(1) Habitat -- a nonwork module including individual crewmember space for sleep and privacy, communal space for dining and socialization, and recreational space for physical conditioning and various diversions from work routines;

(2) Sick bay -- a first aid, dispensary, medical research, and emergency/trauma treatment area with medical, psychiatric and possibly even security detention facilities;

(3) Core operations -- the nerve center of the base station for a variety of internal and external communications, operations, and life support monitoring and control functions (i.e., the "bridge");

(4) Laboratories -- separate fully equipped life sciences and materials processing facilities for basic research, applications, and commercial uses;

(5) Logistics -- a frequently exchanged module with 3-6 month inventoried expendable supplies and facilities for food preparation, personal hygiene and waste management/storage (for return to Earth); and

(6) Central passageway -- an infrequently replaced structural spine providing a convenient communications and energy bus, a plug-in location for each cylinder ensuring ready access between modules and to the shuttle berthing area, and a "safe haven" if module evacuation becomes necessary during an emergency.

In addition to these modules the station requires berthing ports for shuttle docking, external antennae for communications systems, and a thermal bus analogous to a municipal utility (Ellis and Rankin, 1983). The exact numbers or types of module may be adjusted as crew size and mission complexity changes over time.

System modularity, with its multiple configuration options and ready changeout possibilities, offsets many of the constraints imposed by limited shuttle payload volumes. Another advantage of modular components is that the system can evolve over time, significantly reducing the effects of technological and mission obsolescence. If modularity is extended into the design of the modules themselves (e.g., "plug-to-plug" changeout compatibility enabling continuous response to technological advance), station components can also remain state-of-the-art.

The initial station configuration will be rather spartan, but the ability to replace and add modules as required permits evolution into an environment where people can thrive, not just survive.

## 2.2 Space Station Users and Uses

NASA has been studying and proposing a permanently manned space station as the next logical step since the late 1950s -- first as a post-Mercury program (Gilruth and Strass, 1960), then as a post-Apollo program (Gilruth, 1968), and now as a post-Shuttle program (JSC, 1979; BAC, 1982; MDAC, 1982). However, in each case one or more of five essential preconditions to space station funding (Logsdon, 1982) were missing -- namely, that (1) it must be in the long range national interest, (2) it cannot be accomplished by any other available means, (3) political feasibility, (4) technological feasibility, and (5) it cannot depend upon other yet-to-be-developed expensive programs. The latter three have now been satisfied with the success of the shuttle as a reusable, cost-efficient logistical support and payload delivery system (Hook, 1982), the continuing technological advances in automation systems including robotics, artificial intelligence, and expert systems (Hook, 1982), and the increasingly favorable public and political climate for major space program initiatives (Benedict, 1983). The long-range national interest and the unavailability of alternative means of accomplishment -- the questions of utility -- are now the principal focus of station advocates.

### 2.2.1 Space Operations

Recent proposals for a permanently manned station include a major role as a center for space operations (Hook, 1982) -- for instance, satellite tending tasks (JSC, 1979; Pivirotto, 1983; Tilton, 1983) including maintenance, repair, resupply, testing and checkout, reconfiguration, retrieval, deployment, storage, and reboost. Tending is now possible using the shuttle, but only on a sharply limited basis due to orbiter altitude, storage, stay time, and work space constraints. The

permanently manned space station offers an unpressurized service hangar bay, on-orbit storage facilities, indefinite stay times, and ultimately (with the addition of both manned and unmanned orbital transfer vehicles and teleoperators) the capacity to tend geosynchronous satellites. These are needed capabilities the shuttle cannot directly provide.

Another operations application is on-orbit construction of large space structures (JSC, 1979; Pivirotto, 1983; Tilton, 1983) such as platforms and antennae 100-1000 meters in diameter. The shuttle can efficiently deploy only small, compact ground-built structures. Payload size and weight limitations effectively rule out larger space structures unless delivered piecemeal for on-orbit assembly. The station, if supplied with appropriate construction equipment and raw materials, could provide large-structure deployment, assembly, fabrication and even repair capabilities which do not exist today.

The station can be used as a flight support operations base (Gilruth, 1968; JSC, 1979; Hook, 1982) for manned or unmanned LEO transfer missions, logistical support and geosynchronous sorties, even lunar and planetary missions. It would provide a range of flight support capabilities including assembly, servicing, refueling, maintenance, repair, checkout, launch, recovery and rescue activities. All can be performed more cost-effectively from the space station than from Earth.

A quarantine facility is another possibility (JSC, 1979). A prominent feature of the lunar landing missions was the quarantine procedures for returning astronauts and their lunar samples, although the effectiveness and safety of ground-based facilities has been seriously questioned. With the space station serving as operations base for future lunar and planetary flights, an orbital quarantine facility for both humans and materials returning from such missions is preferable for reasons of safety and cost-effectiveness.

Finally, the space station will serve as a convenient storage facility (JSC, 1979; Pivirotto, 1983) for satellite servicing equipment and supplies, construction equipment and materials, flight support stockpiles, spare parts, processed materials, waste materials, and manpower. Station warehousing and storage will increase cost-effectiveness. Given an increasing volume of space operations activity it is inevitable that the station will become a major orbital transportation node (Pivirotto, 1983; Tilton, 1983), performing extensive space traffic control and scheduling tasks.

### 2.2.2 Commercial Operations

Commercial activities are a second major space station application which is gaining private sector attention in response to the success of the shuttle program. The combined advantages of zero-g and vacuum have given rise to an extensive list of potential materials processing and manufacturing products (MDAC, 1977; Grumman, 1977). These include shaped crystals, semiconductors, pharmaceuticals, biologicals, strategic materials, plastics, films, foils, alloys and mixtures, ultrapure metals, composites, glasses, membranes, metal foam, fibers, microspheres, ceramic/metal, and matrix materials. The shuttle can conduct limited on-orbit experiments and demonstrations, but full exploitation of the materials processing and manufacturing potential awaits a more permanent and expanded human presence in space.

The commercial potential is limited only by the imagination and willingness to invest by the private sector. One important application which achieved early prominence during Skylab is remote sensing. Expanding upon the capabilities of satellites, space station personnel can perform extensive Earth-resources exploration, mapping, and management for both energy and resource sectors of the economy. Meteorological monitoring and general nautical navigation will be greatly improved. The station could serve as a major communications and data processing node (JSC, 1979; Hook, 1982; Pivirotto, 1983). Extensive and sophisticated station communications systems feasibly might function as the data processing node and communications downlink for numerous manned and unmanned commercial operations. This would help avoid costly duplication of facilities and capabilities by the private sector. The station could offer a leased space platform for attached satellites, proprietary laboratory modules for research and development activities, production modules, and so forth, and might even provide commercial space operations services. Driven by increasing private sector and foreign involvement in commercial space operations, station space operations activities (particularly flight support) will inevitably expand to include a growing private sector and foreign market, further exploiting the commercial value of the facility.

NASA station crewmembers may provide laboratory research and development services for commercial enterprises which do not lease or operate their own individual orbital laboratory. Recent shuttle missions have shown that NASA personnel can reliably conduct research and onboard experiments, development activities, testing, calibrating, and laboratory demonstrations which could enable many smaller commercial enterprises to capitalize on the advantages of space operations.

### 2.2.3 Space Sciences and Research

The scientific and research communities will gain access to expanded services because of superior station capabilities (JSC, 1979; Hook, 1982; Pivirotto, 1983). One central activity will be an extensive re-examination, in zero-g and vacuum, of the basic tenets of the natural, physical and life sciences. Much as the terrestrial atmosphere affected astronomy, Earth's gravity may have had unforeseen effects on fundamental assumptions in a number of fields including planetary sciences, astrophysics, life sciences, medicine and engineering. These effects are best investigated using a long-duration on-orbit facility, preferably manned or human-supervised.

### 2.2.4 National Security

The defense and national security uses for the space station have received relatively little public comment but have been the subject of considerable private speculation. The station is unlikely to be used as a weapons platform because of its high visibility and predictability (hence vulnerability), but there are many defense and

intelligence applications not compromised by such characteristics.

For example, a surveillance platform for strategic monitoring of terrestrial operations would benefit from integration with domestic and international civilian station operations if onboard security can be maintained. A lone intelligence-gathering surveillance platform might invite assault, but domestic and international civilian populations on the space station might provide some protection during peacetime operations.

Station modules could also be used as laboratories for materials and weapons systems research and development. Given the increasing foreign presence in space, ever-accelerating as more countries join the space club, weapons research for ground and space applications may be deemed essential for American national security -- even if only for the near-term objective of space station defense.

The possibility that the space station could be used as a base for tactical defense or space intelligence operations is directly related to the increasing foreign presence in space. An orbital base for strategic operations is highly risky, but limited peacetime tactical operations could be launched from an integrated domestic or international civilian station complex with far less chance of retaliation than if conducted from an isolated or free-standing platform.

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# CHAPTER 3

# HUMAN-MACHINE SYSTEMS

Contributions by

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The issue of machine autonomy -- the degree to which a machine is independent of man -- is an important aspect in the design of human-machine systems for the performance of physical tasks. From a pragmatic point of view, autonomy is significant because differing patterns of human or machine independence will produce varying amounts of overall system effectiveness in specific circumstances.

This chapter examines three major types of human-machine systems: (1) Manned EVA (extravehicular activity), (2) teleoperation and telepresence, and (3) robotics. EVA exhibits the least machine autonomy, robotics the most. The characteristics of each technology are reviewed here, together with an examination of the tradeoffs between potential gains in effectiveness from machine autonomy and technical feasibility in various time frames. The purpose is to outline the characteristics of each technology and to make recommendations from the standpoint of space station autonomy and effectiveness.

The chapter concludes with a brief discussion of several important aspects of human-machine relationships -- in particular, function allocation, tool-using, and mutual human-machine trust. Formal human-machine and ground/space allocation methodologies are discussed later, in Chapter 6.

## 3.1 Manned Extravehicular Activity (EVA)

Manned EVA encompasses all the activities of people in space who are outside of a pressurized environment. EVA has been accomplished by United States astronauts since the Gemini program, and is becoming a more frequent function supported by the shuttle. During the lifetime of the space station manned EVA will become routine, often performed on an eight-hours-a-day, seven-days-a-week basis.

There are two primary drawbacks to manned EVA for space activities as opposed to a telepresence system (section 3.2) (Howard _et al._, 1982). First, people require a large amount of task-related time for EVA preparation and cleanup, as well as personal time for eating, sleeping, and recreation. Second, there are high recurring costs associated with supporting the EVA crewperson.

The main advantage of manned EVA lies in the great versatility of human beings and in their ability to deal intelligently with unexpected situations. While telepresence and robotics may eventually aid and augment the EVA astronaut, they will not in the immediately foreseeable future be able to accomplish all of the functions which can now be performed by manned EVA.

Three basic conditions must be met for an EVA operation to be accomplished effectively: (1) The safety of the EVA astronaut must be assured; (2) the mobility and dexterity of the person in EVA should not be hindered by the required gear; and (3) the necessary tools, supplies, and information must be available to adequately perform the desired tasks (Howard _et al._, 1982).

### 3.1.1 Safety

The Extravehicular Mobility Unit (EMU) allows humans to function in an unpressurized environment. The EVA crewperson plus the EMU comprise a true symbiosis of human and machine -- neither could operate without the assistance of the other. The EMU is comprised of several subsystems. The Space Suit Assembly maintains the pressure required for safe operation in a vacuum environment, and provides mobility and protection from radiation, micrometeroids, and the extremes of temperature encountered in space (King and Rouen, 1982). The Life Support Subsystem maintains a pressurized flow of breathable air to the operator and removes metabolic heat. Other EMU subsystems include waste control, communications, and limited food and drink. The EMU can also provide life support functions for short periods in the event of a loss of power or suit puncture. The development of an inflatable medical refuge would allow longer-term astronaut safety away from the space station, in the event of an emergency.

The Manned Maneuvering Unit (MMU) is a propulsion package attached to the back of the EMU by the EVA astronaut to permit untethered mobility

in the vicinity of the shuttle or the space station. This increases crew safety and eliminates the process of securing, releasing, and controlling tethers which can consume up to 15% of astronaut EVA time. Tests have shown, however, that the present-day MMU probably has insufficient maneuvering capabilities to perform extended space operations, especially if multiple high-velocity translations are necessary (Howard et al., 1982).

A method of tool management is needed which is easy to use and does not interfere with the astronaut. During an EVA, tools and other objects must be prevented from drifting off and, potentially, causing damage. Usually this is accomplished using tethers, but these are cumbersome and can tangle -- a major safety concern since tangles can be difficult to undo with current limited-dexterity pressure suit gloves. Self-rewinding tethers reduce tangling, but exert a force on the tool which must be overcome by the EVA astronaut.

### 3.1.2 Mobility

The mobility and dexterity of an EVA astronaut is primarily dependent upon the characteristics of the pressure suit and the EVA gloves. On current pressure suit designs, much of the area in front of the human torso is occupied by various displays and controls. If this space were cleared of all intrusions, a much greater work envelope would result. Head-up displays could relay time-critical facts such as the amount of power or air remaining for the EVA.

The pressure suits used on the shuttle are much improved over past designs, and further improvements are planned. But it is difficult to work in them because the suits do not maintain a constant volume. When an EVA astronaut moves, he must do work to compress the air inside the suit. This work increases with increasing suit pressure. Lightweight suits with improved joint mobility in the upper body region would be beneficial.

Improving manual dexterity of the pressure suit glove is of primary importance. Current gloves give the astronaut little tactile feedback, an effect worsened by the necessary addition of a thermal protection garment over the suit glove to protect the astronaut from hot surfaces. EVA simulation studies show that the hands are generally the first to tire in extended activities, and require frequent rest breaks to avoid cramping and loss of dexterity. Advanced glove mobility development is underway, aimed at producing a glove operating at 8 psi with dexterity equal to current 4 psi gloves, but even this work will not seriously address major problems in dexterity, tactile sensing, and fatigue.

One alternative to air pressurized gloves is to use the tensile force of an elastic fabric to restrain the skin of the hand, which is otherwise exposed to vacuum. A design for an entire suit was completed in the late 1960's but was discontinued, due to difficulties in matching pressure in the torso and concave areas of the body such as extremity joints. The integration of an elastic glove and a pressurized suit appears highly attractive based on results to date, although there are several potential pitfalls. For instance, it is doubtful that elastic gloves will allow hand surface pressures to exceed 4 psi, thus limiting suit pressure to that level. Also, hand pressure is not related to suit pressure, so the astronaut's hand is constricted during suited intravehicular activities (IVA). A further concern is that the necessary bulky thermal protection overgarment may negate any gains in glove dexterity.

Astronauts should be able to exit the space station immediately after donning the pressure suit. On the shuttle, astronauts spend 3-4 hours breathing pure oxygen to clear the nitrogen dissolved in their body tissues. This is necessary to prevent the bends, a painful and potentially dangerous physiological condition, from occurring upon dropping the pressure from 14.7 psi (cabin) to 4.3 psi in the suits (King and Rouen, 1982). Prebreathing consumes a significant portion of the EVA timeline and must be eliminated if manned EVA is to become routine. Prebreathing is not required if the suit is held above approximately half the pressure to which the astronaut is already acclimated. Thus, if the station is at 14.7 psi, 8 psi suits are necessary; if the station pressure is maintained at a lower pressure (as was Skylab), 4.3 psi suits can be used.

Suit servicing is another major concern. An 8-hour workday might include two 4-hour shifts with a 2-hour break in between. This requires either that the original suit be serviceable during the 2-hour break, or that a second replacement suit be available. Servicing a suit involves oxygen resupply, battery swapping or recharging, lubricating bearings and sealing gaskets, visual inspection, and some limited testing performed periodically (Elkins, 1982). It is unlikely that an astronaut-worker can perform suit servicing during a break period. Unless suit refurbishment is very highly automated, the assistance of a second person will be needed. To eliminate this costly requirement, an automated suit resupply rack might be employed. Workers would hang their suits on the rack and connect a few gas and electrical lines. All necessary refurbishment operations are then performed automatically so the suit is ready for use in two hours.

With workers performing 4-8 hour EVAs, normal personal hygiene and excretory functions must be comfortably accommodated. Current technology allows for sanitary urination by males only. Female urination, and defecation by either gender, is handled by "fecal containment garments" -- large diapers. These garments have yet to be used on-orbit by any astronaut, as such use is considered to be physically discomforting. A portable space toilet, inflatable to suit pressures, might allow people to function longer and more comfortably in EVA.

New types of physical restraints for crewmembers performing EVA operations are needed. The "cherry picker," for example, is a manned platform presently under development. It would be mounted at the end of the Remote Manipulator System (RMS) and be used to transport EVA astronauts, tools, and mission hardware around the shuttle cargo bay (Nathan, 1982). Current plans require a special RMS operator to control the movements of the cherry picker platform in response to commands from the EVA worker, but a voice recognition system could eliminate the need for this operator and appears to be a promising application of artificial intelligence technology.

Another example of a proposed restraint system applicable to space station EVA is the manned Proximity Operations Module (POM), a free-flying workstation which would utilize the MMU for maneuvering. The POM would offer the EVA worker a foot restraint system that attaches to

various types of surfaces and, after attachment, provides access to a large work area. POM could also capture and maneuver satellites and transport small modules in or about the shuttle orbiter payload bay (Adornato, 1982).

### 3.1.3 Tools, Supplies and Information

Without adequate tools and supplies, the EVA worker cannot perform. The development of EVA tools has generally lagged that of suit design, so there is far more potential for increasing astronaut capabilities by improving tools than by improving pressure suits. Tool development is relatively inexpensive compared to suit design. However, the present procedure for flight certification of hardware (such as EVA tools) is too rigid and takes too much time, is inefficient and tends to discourage innovative ideas and designs (Howard et al., 1982).

Possibly the single most important tool from the standpoint of EVA autonomy would be a system which explains or assists in the use of other tools. A real-time maintenance information retrieval system could provide the crew with information adequate to perform the task at hand. Currently, astronauts must repeatedly practice every step of an EVA operation in an underwater neutral buoyancy tank. The total training time for a single EVA task may run several months, impractical if a variety of manned EVA operations are to be performed on a routine basis.

Using a real-time maintenance information retrieval system, an astronaut would receive instructions from a database containing information about the task at hand. For example, if a satellite servicing task is underway, the astronaut asks the retrieval system for the next step in the servicing operation, or for a schematic drawing of the section of the satellite being serviced, or for the best method to recover from an error. Information is requested through a voice recognition system to allow verbal querying, with the response either broadcast vocally (voice synthesis) or displayed visually on a head-up display. Astronauts would only have to be trained to perform, say, generic satellite servicing tasks, thus increasing the versatility, autonomy, and effectiveness of EVA workers.

Also, if a video image of the worksite is transmitted to station or ground personnel, they can offer additional valuable assistance to an astronaut performing an EVA operation. A small lightweight CCD camera mounted on the pressure suit or helmet, or a free-flying maneuverable television vehicle (MTV), are possibilities.

### 3.1.4 Working in Space

Neutral buoyancy simulation (NBS) shows that EVA astronauts should be able to work productively and routinely in space. An instinctive adaptation to the zero-g environment occurs after 15-25 hours of suited activity in the NBS tank, although astronauts have yet to achieve this level of expertise in actual on-orbit EVA operations. For instance, an unrestrained worker learns automatically to move a high moment-of-inertia item so that the object and the person's body arrive in the proper positions simultaneously.

The only extravehicular construction performed in space to date has been the erection of a sunshade on Skylab II. This was an improvised task at an unplanned worksite, and the results were discouraging (Akin, 1980). But NBS studies suggest that structural assembly can be accomplished productively in space. Whether measured in kg/crew-hour or operations/crew-hour, simulated weightlessness in neutral buoyancy experiments shows a clear advantage over dry land assembly (Akin, 1980). This is because components and workers need not be physically supported during weightless construction. People who have trained in neutral buoyancy and then have performed actual EVA in space report that manned EVA requires much less effort than similar activity during NBS. So productivity will probably be even greater than that predicted by the simulations. One planned experiment will quantify the differences between EVA and neutral buoyancy by having astronauts perform the assembly of a standard structure both in the neutral buoyancy tank and in actual EVA on board the shuttle (David L. Akin, 1983, personal communication).

The ways in which people interact and assist each other at an EVA worksite must also be carefully considered. NASA flight guidelines require many operations to be accomplished by people in pairs -- one person assists with tools and parts, the other performs the operation. It has been shown, however, that productivity is maximized if workers are allowed to function independently (Howard et al., 1982). Further, reducing or eliminating formal step-by-step timelines at a worksite would allow personnel to attempt innovation and new methods to increase productivity.

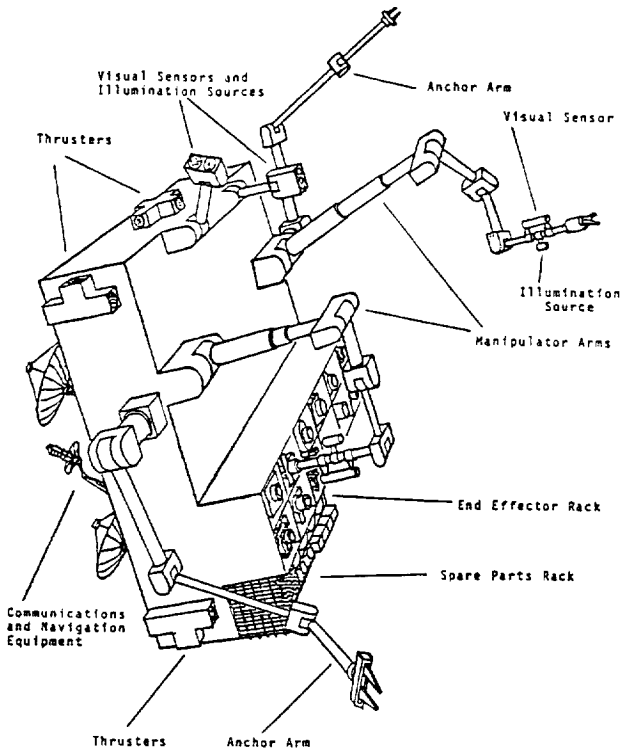
## 3.2 Teleoperation and Telepresence

Teleoperation is the remote operation of a machine. This may be something as basic as pushing a button at a ground control facility to cause space station batteries to begin recharging; or as complicated as a complete mechanical human analog on the station, capable of performing humanlike functions and remotely controlled from the ground. An important subset of teleoperation is telepresence, wherein the operator receives sufficient quantity and quality of sensory feedback to provide a feeling of actual presence at the worksite.

Teleoperation and telepresence have numerous applications on a space station. For example, teleoperation can assist in station maintenance functions, with a ground operator controlling the activity remotely. In many cases it will be prohibitively expensive either to fully automate or to have people perform tasks which would consume valuable on-orbit crew time. Telepresence can be used for space operations requiring human intelligence, control, and dexterity, but which people cannot directly perform due to factors such as cost or safety. Earthbound operators could use a dextrous manipulator arm and vision system for remote laboratory work on the space station. A telepresence EVA system could potentially handle satellite servicing, which might be less expensive than manned EVA and is a very realistic goal for the early 1990s (Thiel and Kurtzman, 1983). Another possibility is remote-directed spacecraft refueling operations, a job regarded by some as too dangerous for EVA astronauts.

Telepresence systems can also expand the range of tasks accessible to humans. Manned EVA is limited to near-shuttle, 6-hour work periods.

**FIGURE 3.1. M.I.T. FREE-FLYING HYBRID TELEOPERATOR**




A telepresence system could operate for more extended time periods even in high altitude orbits, where, for instance, communications satellite servicing and large antenna construction are best performed. Currently, humans cannot work in high altitude orbits due to insufficient life support facilities, the lack of transportation, and excessive radiation hazards.

With the human as operator, telepresence utilizes human judgment and manipulative skills; takes advantage of machine durability, expendability, and performance; and permits the incorporation of autonomous robotic technology as it becomes available. Telepresence thus combines many of the advantages of both human and machine capabilities.

### 3.2.1 Past Telepresence Applications

Teleoperation was initially developed by the nuclear industry in the 1950s and 1960s to perform remote work in high radiation environments. Initial systems employed a "master" control arm whose motions, directed by the operator, were duplicated by a "slave" arm at the worksite. These systems sometimes provided force feedback and a two-fingered end-effector (mechanical hand) with limited dexterity. Increased system dexterity would allow more flexible and human-like operations, and need not require a high degree of precision -- human arms are dexterous but cannot position themselves with the same precision of most nondexterous industrial robots. By the early 1960s, master/slave systems were operational and adequate to accomplish the limited tasks for which they were designed. This achievement halted further teleoperation and telepresence research and development, except for sporadic NASA work in the 1970s. Only recently has renewed interest and funding in telepresence research produced systems with capabilities beyond those of the 1960s.

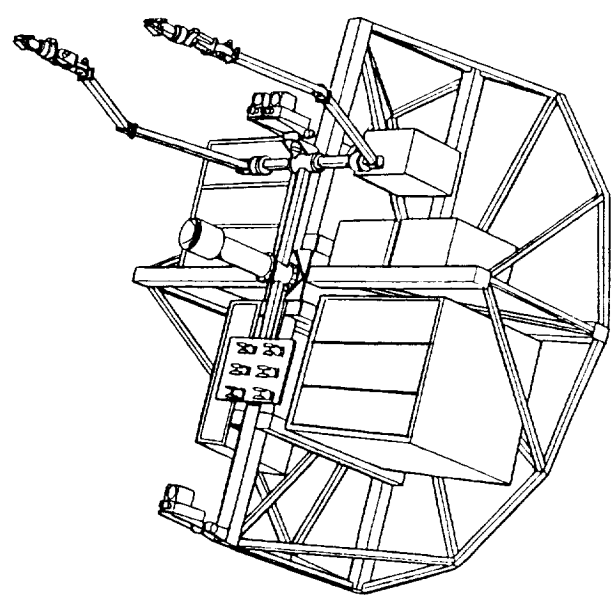
In addition to the nuclear industry, some progress has been made in undersea telepresence. One major current application is remote deep water telepresence diving operations connected with the maintenance and repair of oil platforms. The Naval Ocean Systems Center (NOSC) in Hawaii has developed one of the most advanced telepresence systems in existence. Remote manipulators are controlled by an exoskeletal pair of arms worn by an operator. The system also has a mechanical spine and neck system, and is nearly able to duplicate human upper body movements. Amazingly, while the NOSC system is one of the most advanced today, the technology consists entirely of off-the-shelf or decades-old hardware designed for other purposes.

Biomechanical engineering and robotics may also contribute significantly to future teleoperator development. The difficulties encountered in designing and interfacing humans with prosthetics and other mechanical aids for the disabled are often very similar to the challenge of interfacing humans with teleoperators. And the recent surge of interest and development in industrial robotics has led to the increased development of robotic hardware, such as manipulators and end effectors, which can be adapted for telepresence use.

### 3.2.2 Space Telepresence

Work is progressing on designs for integrated telepresence systems for space use. In 1979, the

**FIGURE 3.2. REMOTE ORBITAL SERVICING SYSTEM (ROSS) TELEOPERATED SERVICER KIT**



Free-Flying Hybrid Teleoperator was conceptualized at the Massachusetts Institute of Technology as a system capable of propelling itself to a repair site and attaching to a structure; carrying tools, spare parts, and a variety of sensors; diagnosing and repairing faults; and communicating with human supervisors. Shown in Figure 3.1, the proposed teleoperator has two manipulator arms for doing work, two anchor arms for fastening itself to the worksite, thrusters for maneuverability, communications equipment, a spare parts and stowage rack, an end-effector rack, TV cameras and illumination sources (Smith and Miller, 1979).

The Remote Orbital Servicing System (ROSS), a Martin Marietta Aerospace concept, could service several satellites using only current technology (Figure 3.2). The ROSS would fit inside the shuttle cargo bay for ease of transportation into space and back to Earth (Schappell, 1982).

The MIT Beam Assembly Teleoperator (BAT) is the first integrated telepresence system which has actually been designed and built for use in a simulated space environment (Shain, 1983). The BAT will perform neutral buoyancy assembly of structures to gauge the feasibility of telepresence and to compare telepresence performance with that of a person in an EVA pressure suit.

### 3.2.3 Teleoperated Intravehicular Activity

The primary goal of using teleoperation and telepresence for intravehicular activity (IVA) within the space station is to allow ground personnel to perform space station functions that are not economical to fully automate but which would otherwise consume valuable crew time. In the initial station configuration, these functions might include relatively simple tasks such as the monitoring and controlling of power levels, commanding battery recharging, maintaining thermal control, supervising the ECLSS (Environmental Control and Life Support System), and so forth. Farther out in the future, more sophisticated telepresence systems could conduct many onboard activities previously requiring the dexterity and physical abilities of a crewperson. For example, in the absence of the principal investigator a humanoid telefactor could execute laboratory research tasks such as preparing slides for analysis, monitoring crystal growth experiments, and performing space station maintenance.

Such capability offers significant advantages (see Appendix 7C), prime of which is the cost savings when continuous human life support (environment, food, hygiene facilities, and psychological well-being) need not be maintained in all station modules. It appears, however, that much more development is needed before this becomes a feasible scenario, because:

(1) No mechanical hand exists today with a dexterity even close to that of a bare human hand. This is probably due to the lack of research funding rather than any fundamental technological difficulty. Marvin Minsky (personal communication, 1983) estimates that an anthropomorphic hand for telepresence applications would cost about $5 million to develop, quite a small sum compared to the total estimated space station commitment.

(2) Even if an anthropomorphic hand already existed, problems caused by transmission time delay between the space station and Earth are large enough to preclude the use of force or tactile feedback to the operator. Without such feedback it is difficult to perform delicate activities, akin to trying to pick up a small object with cold, numb fingers. Transmission time delays (Figure 3.3) will range from 0.5-2 seconds (section 3.2.6), requiring the telefactor operator to adopt a move-and-wait strategy. This greatly reduces productivity.

(3) An alternative to anthropomorphic teleoperators is to redesign all equipment to be operated exclusively by non-dexterous manipulators, ultimately allowing automated functioning through the use of dedicated special-purpose machinery. Such designs are potentially expensive and technologically challenging. However, a fully-teleoperated station or station module might not be required to do everything a manned one could, possibly resulting in significant near-term cost savings. Provisions would have to be made for periodic human visits or for self-maintenance of the mechanical teleoperators, and for telefactor mobility about the station. This alternative is explored more fully in Appendix 7C.

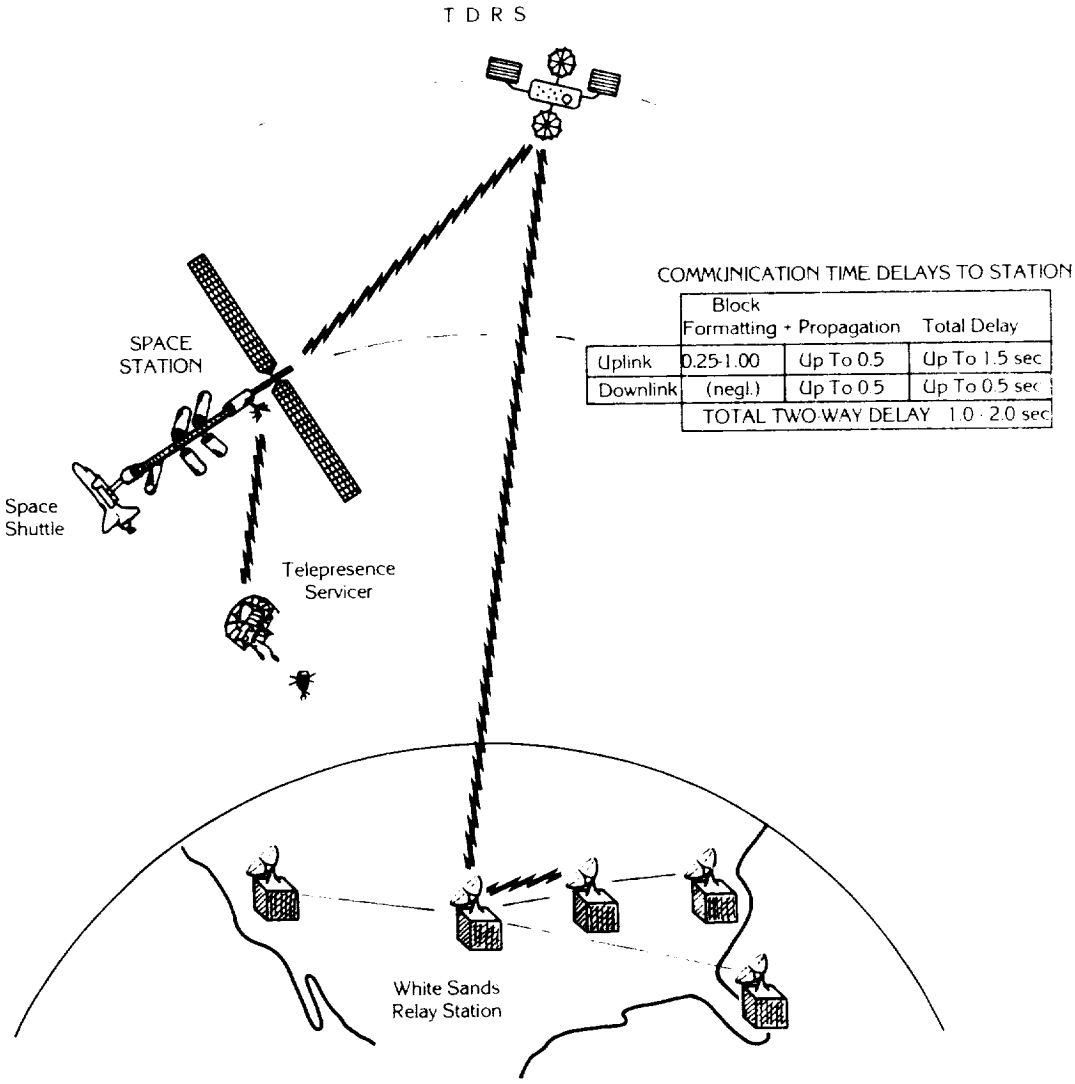
### 3.2.4 Teleoperated Extravehicular Activity

The major application of space telepresence in the near future is activities outside of the space station, such as satellite servicing, structural assembly, and contingency (unplanned) repairs. Thiel and Kurtzman (1983) provide an overview of available telepresence technologies with a focus on those required to support a space telepresence effort. Several space projects are examined in detail to determine what teleoperation capabilities are needed to accomplish tasks such as servicing and assembly. The methodologies of that study are described in section 6.1, but the major conclusions are as follows:

- Telepresence is necessary and desirable.
- Telepresence should be able to match EVA in capability.
- Telepresence is potentially capable of performing satellite servicing, structural assembly, and contingency operations.
- Telepresence is feasible, both operationally and technologically.
- A working telepresence unit could be developed, built, and flown by the early 1990s.
- Advanced telepresence systems will be capable of very complex operations and high levels of autonomy.
- A research and development program should begin immediately.

As a near-term goal, physical performance of telepresence systems should at least match that of humans in EVA. At present, extreme dexterity is not available for EVA pressure suits, so this requirement for teleoperators is not very restrictive. Typical manipulations might involve mechanical and electrical connectors, the grasping and positioning of objects, or the operation of a latch. Note that telepresence systems need not

**FIGURE 3.3. TELEPRESENCE COMMUNICATIONS AND THE TDRSS TIME DELAY PROBLEM**




perform tasks in the same manner as an EVA astronaut -- telepresence might take longer, require more tools, or follow different procedures than manned EVA while achieving similar results.

The basic components of a space telepresence system capable of conducting servicing operations include communications, man-machine interface, vision and other sensors, control, manipulators and end-effectors. Most of these components exist today, but complete operational systems do not. Space adaptation must be included due to the importance and difficulty of space-qualifying hardware. Space telepresence systems could be operational by the early 1990s in conjunction with the first-generation space station, but this will not occur unless development of the necessary hardware and software commences immediately. The successful performance of a single contingency operation during the deployment and assembly of the space station would more than justify the entire cost of the telepresence development program (Thiel and Kurtzman, 1983).

### 3.2.5 Space Station and Telepresence

The space station offers many advantages as a control center for space telepresence. Ground-based telefactor operators suffer intolerable time delays, but station-based operators could service any satellite at the space station or within direct communications range with essentially no time delay, enabling more delicate manipulation. However, the advantages of operating from the space station must be significant to outweigh the high cost of on-orbit crew time. Careful tradeoff studies are needed to precisely determine the types of tasks which can be performed adequately with a time delay, and those which cannot due to the need for sensory feedback or quick response times.

Another advantage of space-based telepresence control is that the station provides a convenient site for telefactor storage, resupply, refueling, and maintenance. The station could serve as repository for satellite replacement items, allowing greater variability in spacecraft parts and servicing applications while eliminating the launch and ground operations that would be necessary if the telepresence unit were ground-based. Since the telefactor stays in orbit, its availability is much higher for work on or near the station. This could become critical during an emergency (Thiel and Kurtzman, 1983).

### 3.2.6 Telepresence Technology and Development Program

The primary technology requirements for a near-term (1990-1992) telepresence system are summarized briefly below. A major non-technological requirement is the utilization of human factors knowledge. For a telepresence system this means minimizing operator workload (as in aircraft cockpit design) and meeting operator expectancies (making the operation seems as "natural" as possible) to maximize use of reflexes and manipulative skills the operator has gained from a lifetime of learning and experience. Virtually all humans, for example, are expert at vision field control, turning the head to look at a desired object or scene. Thus, using operator head position to point a camera on the telepresence servicer may be preferable to manual camera control switches.

Teleoperation Technology Requirements. The recommended vision system uses stereo-optic vision for depth perception with 3D imaging sensing, as in human binocular vision. Helmet-mounted video displays would allow slaving the cameras to the head, so the display screen is always in view regardless of operator head position. This also permits a separate image to be presented to each eye (necessary for true stereo vision), without requiring complex or expensive optics which can restrict operator movement and cause discomfort. Color displays would aid in scene recognition and understanding for both humans and machines. These technologies are well-advanced. For example, a black-and-white stereo helmet-mounted video system has been developed and tested by the Naval Ocean Systems Center in Hawaii, and the addition of color to this system should present little problem. Space-qualified video cameras have been in use since the 1960s.

Manipulator arms with 7 degrees of freedom (DOF) are desirable from a human factors standpoint because they are similar to human arms and thus easily controlled by a master/slave control system. Seven DOF are needed to reach around objects or into confined spaces, and two arms are required for some space operations. Human operators are more comfortable with a pair of 7 DOF manipulators than with one 7 DOF arm and one arm with less than 7 DOF. NOSC Hawaii has built and tested a system with two master/slave manipulators and Martin Marietta has developed a 7 DOF arm for Marshall Space Flight Center that can easily be adapted for space use. MIT is building a manipulator system for neutral buoyancy simulation of space structure assembly and for testing telepresence control technology.

Near-term telepresence systems must be designed to grapple a variety of hardpoints, to manipulate objects, and to use tools. A mechanical hand or hand analogue could in theory perform these tasks, but would require a significant development effort and might not be easily controllable with a communications time delay. Interchangeable specialized end-effectors have been demonstrated in the laboratory and can accomplish all near-term telepresence tasks. The greater versatility of mechanical hands will be needed only in more advanced (post-1995) telepresence systems to perform more complex tasks.

Force control of the manipulator arm is necessary due to the very high stress loads that can accidently be applied without some limit on manipulator force. This control can be a total-force limit which the manipulator cannot exceed, or an applied-force limit specified by the operator. Force feedback, in which sensed force data are transmitted to the control site so the operator can feel and limit it, is probably the most desirable technique. However, time delays prevent the operator from sensing excessive force quickly enough to prevent damage. Experiments have been performed with force-limited manipulators but further research is necessary before this control technology becomes operational. Proximity sensors also are needed, a well-developed technology planned for use with the RMS. Force and torque sensors of various designs are available, and adapting them for space use should present no problems (Bejczy, 1980).

There are three promising techniques for operator control of manipulator arms. Probably the best choice for a near-term telepresence system is the force-indicating hand controller, a multi-DOF joystick which the operator grasps. As forces are applied to the joystick the manipulator moves at a velocity proportional to the applied force. The operator applies forces to the hand controller to "fly" the end of the manipulator to the desired location; if the manipulator is in contact with a spacecraft or component, it applies the same (or proportional) force to the object it is in contact with. The second technique is a master arm, which monitors operator arm position and commands the telepresence manipulator to a similar position. Direct force control is more difficult because the master arm responds to an applied force by moving, thus the operator is not as aware of the forces being applied as with the rigid hand controller. These exoskeletal controllers may use preset force limits instead of continuous operator force commands. The third option, used by the nuclear industry, is a hybrid of the previous two control methods. The operator grasps a hand controller attached to the end of a master arm which moves in response to forces applied to the hand controller by the operator. The actual manipulator arm follows the movement of the master arm. All three approaches are within present technological capabilities.

Teleoperators working on a satellite or at a construction site must be able to apply forces and torques to nearby spacecraft and components. This requires that the telepresence servicer be able to hold steady its position relative to the worksite. Stationkeeping by reaction thrust is difficult, wastes fuel, and may be ineffective with high-torque manipulators. Docking is a viable option but the telepresence system may have difficulty reaching necessary worksite locations if constrained to a single contact point. One solution is a second set of manipulator arms to grapple hard-

points (structural members, booster casings, EVA handrails, RMS fixtures, etc.), less sophisticated than the main arms but permitting the system to grapple at a variety of worksite locations. Also, it is feasible to place the telepresence servicer unit at the end of the RMS, but the need for a Teleoperator Maneuvering System (TMS) or similar device is critical. Without TMS the telepresence system cannot easily operate beyond shuttle altitude or mission time constraints, preventing it from accomplishing many of the missions it could perform and erasing many of its advantages over manned EVA.

Control of the telepresence unit may be achieved using the K-band single-access links provided by the TDRSS spacecraft. Unfortunately, the minimum LEO communications time delay is 0.5 seconds, increasing to 2.0 seconds if the control station must communicate with TDRSS via the NASCOM system (Figure 3.3). Delays may be minimized either by placing the telepresence control station at White Sands, New Mexico where the TDRSS ground control center is located, or by placing it aboard the space station so that the telepresence unit communicates directly with the station bypassing the TDRSS network.

If ground control of telepresence is essential, time delays cannot be completely eliminated and predictive display technology, including recent advances in computer-aided modeling, should be investigated. For instance, the system could maintain a working computer model of a spacecraft which is updated and modified as the structure is altered by servicing. As the operator moves the manipulator, the computer immediately displays the new manipulator link and end-effector positions in relation to the spacecraft, even though the video response from the spacecraft has not yet been received. This makes unnecessary the "move-and-wait" strategies traditionally employed in dealing with time delays. However, several years of technical development work are needed before a suitable operational system can be produced.

Finally, a telepresence system must have adequate storage volume for removed parts and replacement spares, and stowage rack configuration must be compatible with the shuttle and TMS. Instruments must be protected from acoustic vibration during launch. The stowage rack must provide structural support for replacement modules during launch and re-entry, and protection from thermal stresses, contamination, and radiation in the space environment. Designs must utilize lightweight materials, be easily reconfigurable and reusable for a variety of different missions, and be capable of stowing liquids, gases, and providing for the cooling of cryogens.

Telepresence Development Program. In order to provide remote servicing operations during the early 1990s, a space telepresence development program must be started immediately. Much of the necessary technology already exists, but a significant development effort will be required to integrate the technologies into an operational system and to space-qualify the hardware.

The first objective, which should be taken up immediately, is the integration of available technology into a ground demonstration system. This would allow the investigation of human factors and control system designs necessary for the development of an operational system. In parallel with the ground systems integration, an experiment performed in the shuttle middeck would be used to verify the manipulator control system for actual zero-g operations. Ground tests can simulate much of the effects of the space environment, but manipulation of small masses cannot be accurately simulated on the ground -- mass and inertia are dominated by those of the ground simulator and the contact dynamics are extremely difficult to model on a computer. An experiment in the orbiter middeck would allow low-mass manipulation tests in zero-g without requiring the construction of a vacuum-rated system. The results of the middeck experiment and the ground systems integration could be combined into a full-scale demonstration and validation test on a cargo bay pallet. Other experiments aboard the orbiter could be performed as necessary along with continuing ground technology development.

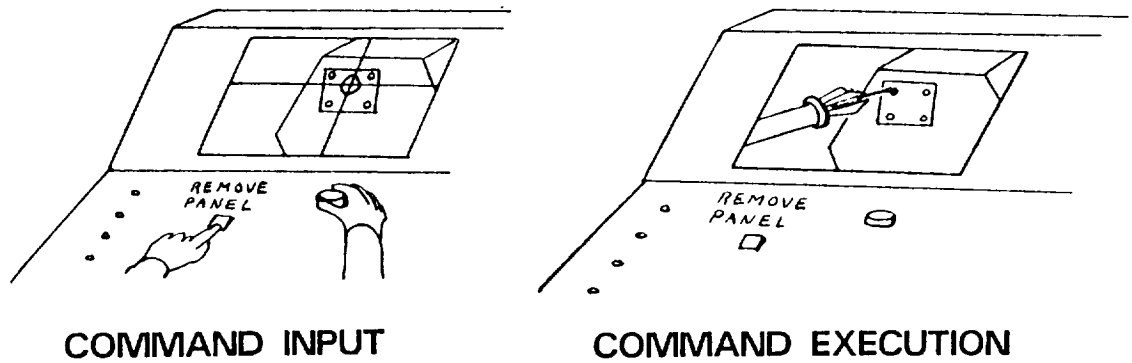
All these efforts lead to a 1990-1992 initial operational system either for use on the TMS or as an attachment to the RMS for early operations. Since the capabilities and expertise of NASA, industry, and academic institutions often overlap, and because each type of organization approaches the problem from a different perspective, each should participate in all phases of the development effort. The actual hardware necessary for a ground telepresence development system need not be very expensive, so NASA should encourage in-house, industrial, and academic ground development systems. A ground development program, coupled with space experiments as necessary, will provide NASA with a highly capable and versatile teleoperation system able to meet both near- and long-term needs.

### 3.2.7 Supervisory Control: The Bridge to Robotics

As telepresence technology evolves, improvements will occur in two major areas. First, the operator will gain a true feeling of being at the worksite (Minsky, 1980), with the telepresence unit possessing many human-equivalent physical and sensory capabilities. Second, telepresence systems will be able to accept higher-level supervisory commands and to accomplish low-level tasks autonomously. Some of the benefits of this latter improvement, known as supervisory control, are that: (1) Problems associated with time delays are virtually eliminated; (2) dependence on communications links and ground commands is reduced; (3) non-anthropomorphic characteristics (such as an infinite wrist roll) are easily incorporated; and (4) tasks which are boring, fatiguing, repetitive, or distasteful to human operators can be performed autonomously.

Supervisory control will initially be implemented for simple tasks, such as changing end-effectors or moving a manipulator arm to a standard position. As confidence and capabilities grow, more complex tasks (often involving the ability to make decisions) will be performed by supervisory control systems. For example, a telepresence operator would give the high-level command "remove panel" (Figure 3.4). The supervisory control system decomposes this command into numerous low-level commands -- it finds the desired panel, figures out the proper manipulator and end-effector motions to remove the panel, and finally stows the removed panel. Eventually an advanced supervisory control system could perform tasks as complicated as "replace component XYZ."

FIGURE 3.4. AN EXAMPLE OF ADVANCED SUPERVISORY CONTROL




Given this command, it would look up the position of the part, open the access panel, remove the module containing the component, replace the component, and return the module to its proper position. At this point the difference between autonomous operation (robotics) and supervisory control becomes blurred. Supervisory control is a key step in the natural progression towards more fully autonomous operations (Thiel and Kurtzman, 1983).

## 3.3 Robotics

Robots probably will play an increasing role in space station activities beyond the near-term. Two principal goals drive robotics research and utilization in industry: (1) Relieving people of tasks which are boring or dangerous, and (2) extending human capabilities to increase overall efficiency and productivity. The Robot Institute of America defines a robot as a "reprogrammable multifunctional manipulator designed to move materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks." However, this definition is based on industrial robot characteristics and does not provide a very useful perspective on robots for space station applications.

Currently and in near-term station designs, work is performed by humans who directly manipulate tools. In teleoperation the effective presence of a human controller is extended to a remote location (which may be dangerous or inconvenient for people) via sensory and control feedback. In supervisory control mode a human commands the machine at a higher level. Supervisory control is an amplification of human control capabilities made possible by providing computational power to interpret and implement high-level commands. When the computer on a remote device gains sufficient artificial intelligence to perform appreciable planning and decisionmaking, it becomes a robot. A completely robotic system would be an autonomous system not directly including man.

Telepresence, robotics and related systems are a means to an end, not an end in themselves. All implementation options for a particular task should be evaluated, with selection based on all relevant factors including available technology and cost. Since these tradeoffs are constantly shifting as goals change and technology evolves, formal task allocation methodologies should be developed (see Chapter 6).

### 3.3.1 Robot Control, Sensors, and Power

A brief description of various aspects and types of robots (Safford, 1982; Weinstein, 1981) is necessary to provide sufficient technical background for the ensuing discussion.

Robots generally employ open loop, servo, or sensory-based control. The simplest type of open loop control is point-to-point control in which only the endpoints of motion along each axis are specified. These endpoints are often implemented via mechanical stops, producing a high accuracy of repeatability (Froehlich, 1981). Between specified endpoint locations the paths of motion are unspecified. A more advanced type of open loop control, called trajectory control, moves the robot arm along precisely predetermined trajectories in accordance with fixed sequences (Heer, 1981).

Servo-controlled robots use feedback loops which employ such internal variables as position, velocity, acceleration, force and torque to permit an arbitrary continuous path trajectory to be followed. When deviation from the desired trajectory is detected, the system automatically adjusts to minimize the error. Open loop and servo robots have already found a large number of industrial applications, but are inadequate for many applications projected for robots in space.

Sensory robots use external as well as internal signals to implement a more sophisticated control function. External sensors may provide signals from cameras, pressure detectors, magnetic sensors, laser range finders, and force-torque sensors. This gives the robot the potential to interact flexibly and effectively with its environment. External-sensed data are the computational starting point for a robot to perform such functions as locating and identifying an object, moving from one site to another while avoiding obstacles, communicating with humans, and detecting and identifying changes in the surroundings. The next major research step in robot sensing will be the most difficult -- extracting useful information from sensory data streams and coordinating this information to achieve an accurate understanding of the environment.

Robot sensors may be classified internal/external, contact/noncontact, and distributed/local. Internal sensors reside within the manipulator and

measure parameters directly from the manipulator such as force and position data to provide kinematic information to the robot controller. Some examples of internal sensors include angle and position, joint forces, velocity and acceleration. Vision is an example of an external sense. The second distinction is between contact sensors which may physically touch what is being sensed (necessary if force is to be measured) and non-contact sensors which do not touch the object sensed. Contact sensors may detect applied force, location, pattern/shape, wrist force, finger force, finger touch, or whisker movement. Mechanisms include piezoelectrics, contact/variable resistance, switches, Hall effect devices, magnetostricture, photoelastics, and fiber optics. Non-contact techniques include electric/magnetic field sensing, acoustic holography, acoustic ranging and imaging, radar and microwave, lidar, interferometry, and optical imagery. Sensors also may be distributed throughout the working environment of a robot, or physically attached to the robot or its appendages.

The three chief methods of providing drive power to a robot are electrical, hydraulic, and pneumatic. The electrical approach generally requires the least energy and is capable of handling the heaviest loads, but is also the most expensive of the three options (Froehlich, 1981) For space applications, electrical is best because of the difficulties in implementing fluid- and gas-based systems in a zero-g closed-cycle environment.

### 3.3.2 Mechanical Classes of Robots Possibly Useful in Space

Seven major types of robots, classified from a mechanical perspective, might possibly be useful in space applications. These, described below,are the humanoid manipulator, Cartesian manipulator, spherical coordinate manipulator, cylindrical coordinate manipulator, tentacle manipulator, pick-and-place non-servo manipulator, and the mobile crawler.

Humanoid Manipulators. Humanoid manipulators are robot arms that resemble the human arm in appearance. However, human arms are very complex actuators with at least 21 degrees of freedom, whereas humanoid robot arms usually have no more than six -- two shoulder rotations, one elbow rotation, and three rotations at the wrist and hand (Figure 3.5(A)). Familiar examples are the space shuttle RMS and the Unimate PUMA, a popular industrial robot. Humanoid arms are often used in work environments where human-like manipulation is desirable. There has been considerable debate over the appropriateness of this design, however. On the positive side, it is often easy to match up a manipulator arm with an industrial workstation designed for human use. The counterargument is that simply automating a human workstation may be suboptimal -- perhaps another kind of station altogether, in combination with another type of manipulator, might be far more effective.

Because of their compatibility with human workstations, humanoid manipulators are widely used in the most common industrial robot applications such as painting and welding. They are also used in pick-and-place operations for manufacturing. For this reason, humanoid manipulators with no more than 6 degrees of freedom have been extensively studied and are well-understood kinematically (Brady et al., 1982). Algorithms for planning trajectories that avoid collisions with obstacles are known (Wallace, 1983a,b), and problems related to feedback and control as well as compliant motion have been at least partially solved (Brady et al., 1982).

Humanoid manipulators have a role in space, as demonstrated by the RMS which is used for deployment and retrieval of shuttle cargo bay payloads. Future RMS tasks include construction of large structures (including the space station itself), delivery of sophisticated end-effectors for satellite repair, and delivery of humans to adjacent worksites in a "cherry-picker" mode of operation. On a smaller scale, humanoid manipulators are proposed for use in satellite repair and servicing (Meintel and Schappell, 1982) and may also be used for space manufacturing and laboratory tasks onboard the space station.

Cartesian Manipulators. Cartesian or rectangular coordinate manipulators typically have three major links, each parallel to one of the three Cartesian axes (Figure 3.5(B)). Sliding or telescoping joints allow the manipulator to place its end-effector anywhere within a right parallelepiped workspace. The Seiko 100 Transfer Robot for industrial automation is a good example of a Cartesian manipulator.

Cartesian manipulators are often used in industrial applications where they may be positioned over an assembly line. In pick-and-place operations, for example, the manipulator need only reach down to pick up and transfer parts. Collision avoidance, control, and planning problems for rectangular manipulators are often easier to solve than the corresponding problems for humanoid manipulators, primarily because the major links translate but do not rotate.

Space applications of Cartesian manipulators are less likely for two reasons. First, their utility is only realized fully in a gravitational environment such as an assembly line. Second, cartesian manipulators have a right parallelepiped-shaped workspace which is not easily compatible with projected space station activities.

Spherical Manipulators. Spherical manipulators are built to work in spherical coordinate systems. Two rotation joints at the shoulder enable angular movement along two axes from the origin; a telescoping or sliding joint at the shoulder allows radial motion of the end-effector throughout the spherical workspace (Figure 3.5(C)). The "Scheinman" or "Stanford" arm is an example of the spherical manipulator class, used in industrial pick-and-place and assembly operations and in some painting and welding applications.

Cylindrical Manipulators. Cylindrical manipulators are designed to work in cylindrical coordinates, which involves one rotational and two translational axes (Figure 3.5(D)). These are of particular interest for application on the space station because individual station components are expected to be cylinders, and cylindrical arms offer a way to use this volume effectively for space manufacturing and laboratory work.

Consider a cylindrical space station module

with a fixed rod along the central axis (Figure 3.6). A manipulator link slides along the axial rod, and may also slide or telescope perpendicular to the rod and rotate in a plane perpendicular to the rod. The manipulator's workstations are positioned around the inside surface of the module within easy reach of the manipulator from a direction normal to their surface. Thus the cylindrical manipulator in the space station realizes the benefits of the cartesian manipulator on Earth. And it is unnecessary to dedicate an entire module to the cylindrical manipulator -- segments of the module may be used in this manner as well. Laboratory and industrial processes could be positioned around the inside wall of the module, to be manipulated by the cylindrical arm. On another part of the inside wall a collection of end-effectors would enable fast changeout and retooling.

Tentacle Manipulators. Tentacle manipulators have the maneuverability of the arms of an octopus (Figure 3.5(E)). They are composed of many small links connected by joints, each with multiple degrees of rotation. Such manipulators were conceived of early in the history of robotics, but few have been built because they proved difficult to realize mechanically and to control. Today at least one company (Spine Robotics) manufactures and markets a tentacle manipulator.

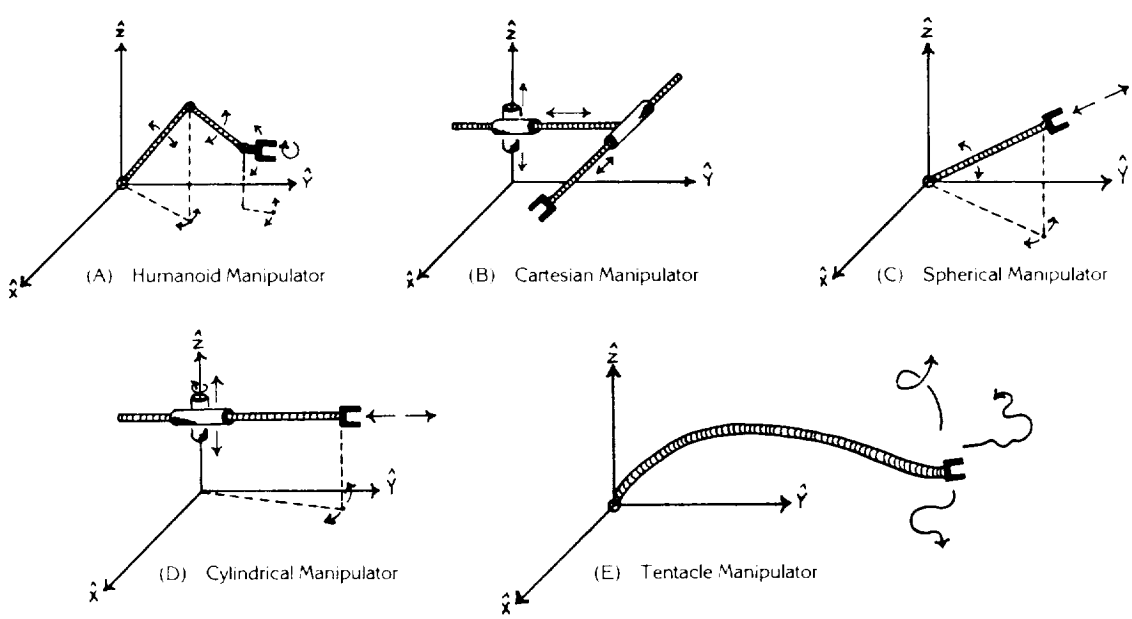
The main advantage of a tentacle manipulator is its ability to position the end-effector in diverse orientations in highly constrained work volumes. In terrestrial applications this is highly desirable for painting, welding and inspection, since the manipulator must reach relatively inaccessible parts of automobile bodies. The single most significant drawback of tentacle manipulators in terrestrial applications is that they typically cannot deliver much force at the end-effector and hence cannot move great masses. In space this is no problem because even very large masses can be transported with small force at low acceleration.

Besides versatile transport in space, a potentially very useful application of station tentacle manipulators is inspection. A TV camera held at the tip of a tentacle could examine many places difficult for humans to inspect such as bulkhead interiors. This could dramatically reduce time spent on disassembly of hardware for inspection.

Non-Servo Pick-and-Place Manipulators. Non-servo pick-and-place manipulators are robots with only limited positioning ability. A typical non-servo manipulator has a single rotary shoulder joint and a telescoping arm attached to that joint. The arm can position the end-effector at just one of two set distances from the shoulder, so the total workspace is characterized by two circles. These robots are the most common in industrial applications and are used for parts transfer, such as from a parts feeder to a punch press.

Just as they have widespread terrestrial applications, non-servo pick-and-place manipulators may also find many applications in space. Non-servo manipulators are less expensive, more reliable, and lighter in weight than servo manipulators. They are less versatile, however, an important consideration in space applications. Also, widespread use of non-servo manipulators on Earth is based on broad terrestrial industrialization, unlike space. Still, potential applications of non-servo manipulators on the space station deserve further study.

**FIGURE 3.5. MECHANICAL CLASSES OF ROBOT MANIPULATORS**



Mobile Crawlers. Mobile crawlers are robots than can move from one place to another across a floor or outdoor terrain via wheels or legs (Raibert and Sutherland, 1983; Moravec, 1983). Capabilities of such devices vary greatly depending on the need for balance, speed and mobility.

On first thought it may appear that crawling robots have little application in a zero-g environment, because existing terrestrial systems require gravity. However, crawling insects rely on surface adhesion rather than gravity for attachment to walls and ceilings. A space station walking robot need not rely on gravity either, provided it dispenses glue with every step (probably too costly and messy) or walks on Velcro tracks laid down throughout the station interior and exterior. A one-legged walker would not work too well in zero-g, since hopping is generally not feasible and may even be hazardous. The fewer the number of legs, the greater the probability that the robot will detach from the surface and float away, so four-legged or six-legged crawlers appear better choices than two-leggers.

The major near-term application of a walking robot in space is inspection. A TV camera could be mounted on the back of the robot and it could crawl into constrained or very distant work volumes that astronauts cannot easily or safely reach. A human (or image analysis program) can interpret what the crawler sees from a remote station, reducing the need for travel and for disassembly of hardware for inspection. Mobile crawlers may also be useful in space construction, able to crawl along space structures to deliver components and to inspect. Crawling robot welders, similar to the robots in the science fiction movie Silent Running, are another possibility.

### 3.3.3 Space Station Robot Applications

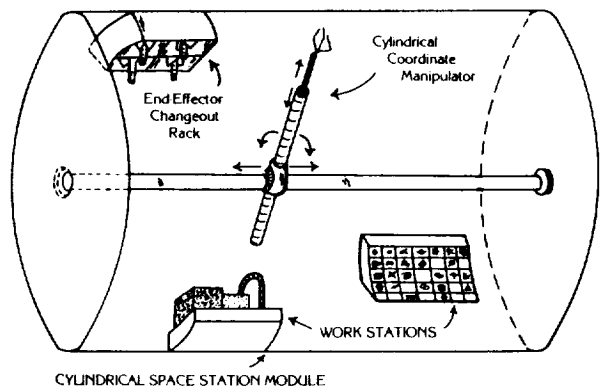
Many types of tasks can be projected for robots in the space station context which may serve to motivate robotics research. Numerous robotics missions and systems have been proposed for future investigation or development by NASA (e.g., Sagan, 1980; Freitas and Gilbreath, 1982). Those most directly associated with the space station include assembly, manufacturing and laboratory testing, satellite servicing, space food services and health maintenance systems. Ultimately, space robots may serve as autonomous planetary surface explorers, perform launch vehicle assembly or nuclear waste disposal in space, or engage in lunar mining, non-terrestrial materials processing, space manufacturing, and possibly even self-replication.

However, early robot assignments will probably involve much mechanical activation and relatively little decisionmaking and planning. Five major task types are summarized below.

Assembly Tasks. Assembly tasks represent one of the principal projected applications for space station robots. An example for the mid-term is the construction of large space systems such as extensive solar collectors, which will involve such subtasks as materials handling, fastening, and subsystem assembly, inspection and repair.

In the farther-term future, there is no reason in principle why the assembly of a space station itself cannot be automated from design through final assembly of the modular units in space. The first step is to employ a computer-aided systems engineering (CASE: Freitas and Carlson, 1982) package to design the space station, right down to the component level. For bulk parts or electronics production the computer-aided designs can be transmitted to robot factories responsible for machining metal parts and electronics assembly, and assembly of the components into modules can be done with an automated factory as well. The economic advantage to automated assembly of space station modules will not be realized for the first few modules built, but such automated assembly will make feasible the construction of many (perhaps hundreds or thousands) of space station modules and reduce the cost of building multiple space stations. Such an arrangement is, in essence, a self-replicating system (Freitas and Gilbreath, 1982).

**FIGURE 3.6. SPACE STATION MODULE WITH CYLINDRICAL-COORDINATE MANIPULATOR AUTOMATION**




Once the modules are assembled they must be joined together in space. One way to accomplish this is to include an RMS system with the first station module. Additional modules are then added by coordinating the shuttle RMS with the station RMS. Many of the operations for assembling the station could be preprogrammed into the manipulator controllers. Fixtures which must be attached to module exteriors can be manipulated by free-flying robotic devices such as ROSS or using special RMS end-effectors.

Manufacturing and Laboratory Testing Tasks. In addition to assembly applications there are many space manufacturing and laboratory tasks which can be performed by manipulators. These include materials handling for containerless processing, welding, chemical and biological specimen transfers, and manipulating materials to be placed into a furnace. Rather than build specialized tools for each of these tasks, NASA could develop a standardized Versatile Space Manufacturing Manipulator (VSMM).

The VSMM will be the space station equivalent

of the terrestrial Unimate PUMA, a manipulator designed to perform a wide variety of manufacturing and laboratory tasks. The VSMM would be about the size of the PUMA, with 0.5-meter links and a shoulder-to-elbow 2-meter reach when fully extended, and outfitted to handle a wide variety of end-effectors and sensors.

Despite its conceptual similarities to the PUMA robot, the VSMM should be designed quite differently for the space environment. It would be senseless to deploy a PUMA on the station because the design is not very mass-efficient. The VSMM would look more like a scaled-down version of the RMS, with long thin links made of lightweight composite materials. VSMM need not be as strong as PUMA because smaller forces may be accommodated in zero-g -- large masses in space can be moved with a small force at slow acceleration. Since the joint torque requirements for VSMM are smaller than PUMA, less massive motors and power trains can be used. A vacuum- and radiation-hardened version of the VSMM is also envisioned to operate in space outside of the pressurized station. It might reduce developmental costs to design a single VSMM with separate versions for onboard and EVA applications rather than to develop two separate systems. For instance, the space-hardened version of VSMM could be used as the manipulator component of ROSS.

The main argument for developing a VSMM is that it would be less costly than developing and space-qualifying a number of specialized manipulators. Moreover, VSMM can be applied to a wide variety of space industrial and laboratory tasks much as the PUMA is on Earth. PUMA designers knew they could not foresee every future application of that manipulator, so they made it as flexible and adaptable as possible. If such a design philosophy is adopted for space station manipulators, VSMM is the natural result.

Satellite Servicing Tasks. There are many activities related to satellite servicing that will eventually lend themselves to robot application but which will first be implemented via manned EVA and telepresence, such as satellite capture and berthing for inspection, repair, or modification. These tasks may actually be done at the satellite orbital location or back at the space station. Future satellites will have modular design to facilitate repair, and robots can be used to troubleshoot and replace defective components. Another related duty for robots is fluid servicing -- resupplying propellants, pressurized gases, and cryogenic fluids that must be periodically replenished.

Space Food Services. Really palatable food, as any culinary artist will attest, is made by mixing ingredients together just before and just after the food is cooked. But even assuming that the ingredients necessary to prepare food in space were available aboard the space station, cooking is very time-consuming. One obvious solution is to construct a versatile teleoperated or robotic chef.

The robot chef would retrieve ingredients from well-organized refrigeration and dry storage facilities, open containers and perform necessary measurements, and blend ingredients together in the appropriate way. The robot chef would be responsible for food placement and removal from the oven as well as recycling, restorage, and cleanup tasks. Great human chefs on Earth could contribute recipes to the automated space chef, whose control computer could then derive step-by-step plans for executing the recipes for the astronauts. Or terrestrial chefs could remotely operate the station kitchen facilities on a "guest chef" basis, enabling astronauts to eat better and making long tours of duty more palatable. Special care must be taken to minimize the discomforts and hazards associated with hot grease, burnt food, and obnoxious odors.

Space Health Maintenance. Onboard medical procedures performed upon people and on animal specimens could be partially automated via telepresence or robotics. Major medical procedures on humans will not be performed at the station very often since astronauts with major illness should be returned to Earth for treatment. Even if emergency astronaut surgery becomes necessary, it would presumably be a significant event warranting reassignment of other crewmembers to aid in the medical procedures. In the near- and mid-term, medical and surgical procedures are most likely to be performed on animal subjects and specimens; in the far-term, extensions of these techniques might eventually be applied in space colonies and other large habitats where medical procedures must be performed on humans.

The skills required in surgery cannot be readily automated at present. Cutting and sewing living flesh requires sophisticated manipulatory skills, the ability to react quickly to a wide variety of sensory stimuli, and the application of a large amount of medical knowledge. There are, however, other manipulatory surgery-related tasks which lend themselves to automation by current and near-term projected technology. Retractor-holding is a primary example of a manipulation skill that can be automated. Once a layer of flesh is rolled back by a surgeon, a nurse must hold back the flesh with a clamping device called a retractor. A small manipulator could also hold the clamp in place, its force sensors allowing it to react to slight changes in the position of the specimen and to hold the flesh in place without tearing. A robotic manipulator could take culture swabs from a surgeon, placing them into culture mediums which are delivered to an automated lab for analysis.

The role of the scrub nurse in surgery can also be automated with a combination of existing manipulator and voice-recognition technologies. The scrub nurse is responsible for delivering to the surgeon's hand an instrument following a one-word command such as "forceps." One-word voice-recognition is well-understood for small vocabularies. The automated scrub nurse would maintain a zero-g tray of surgical instruments and pass them to the surgeon upon request. The scrub nurse is also responsible for collecting, cleaning and reorienting instruments on the tray after the surgeon has finished with them. Sometimes retrieving the instrument will mean locating and grasping a floating instrument after the surgeon has let go of it, without physically interfering with the work in progress, which may require the flexibility of a tentacle manipulator. Additional hands are also useful in medical procedures when some device or body part must be held in position, as in setting a bone.

### 3.3.4 Generic Capabilities Required for Space Station Robots

Various capabilities would make robots most useful from the standpoint of future space station applications. One of these is mobility, so that a robot can easily transport itself from an arbitrary starting point to a desired destination, possibly by crawling or free-flying. Related features are trajectory planning and collision avoidance for the manipulator arm, particularly in a constrained environment, and automatic target tracking. Another important skill is the ability to determine the position, orientation, and identity of items in the field of view. The ideal space robot would also be able to communicate with humans by listening and speaking in a natural language with an extensive vocabulary, and would possess learning ability, self-optimization, and fault-tolerance.

According to the NBS/RIA Robotics Research Workshop in 1979, to achieve the fastest development in robotics the following recommended research areas and their corresponding percentage distributions of funding and effort should be pursued: Binary vision (14%); gray scale vision (12%); off-line programming (12%); control systems (11%); touch, force, and torque sensing (11%); end effectors (10%); integration into CAM systems (8%); mechanical systems (7%); simulation and modeling (6%); safety (4%); mobility/line tracking (4); and others (1%). In Japan, the 1980 JIRA research survey listed their primary research topics (in decreasing order by number of research projects) as: Control, locomotion, vision, tactile sensing, manipulators, end-effectors and programming tools.

Although a considerable amount of work has already been done in robot vision and related areas of pattern recognition (Barrow and Tenenbaum, 1981; Gonzalez and Safabakhsh, 1982; Gevarter, 1982a; Jarvis, 1982; Kruger and Thompson, 1981; Rosenfeld, 1981), much additional research is clearly needed. Improved 3D-perception, color-sensing, pattern recognition algorithms for image understanding, and new spatial reasoning techniques are principal areas needing immediate attention. To implement more complex real-time image processing algorithms, improved methods of image data compression are needed. Designing customized VLSI chips should also greatly increase the efficiency of sophisticated new algorithms.

Other sensory skills must be enhanced as well, involving not only physicial sensing but also sensory understanding. For instance, improved tactile sensing is an area of much current activity and promise, and the development of effective artificial skin incorporating pressure, slippage, texture, and temperature sensing will permit greater robot capabilities for transporting, manipulating, and identifying objects. As another example, reasonably unconstrained voice input/output between humans and robots will require considerable additional research in large-vocabulary continuous-speech recognition. (Isolated word recognition is a far simpler task.) Recognition must take place in a high-noise environment and must be speaker-independent. Robots will also need other improved sensing capabilites, including range and optical proximity sensors. Laser scanning techniques should be developed to assist in target location, tracking, and identification. An additional consideration is the inherent interrelatedness of components. Thus, a breakthrough in robot vision may permit larger errors in tactile sensing data without sacrificing overall performance. The integration of sensory data within and among sensor types is an extremely important aspect of the overall robot performance enhancement goal.

From a mechanical perspective, future robots will need more dexterous manipulator arms and more adroit end-effectors, in addition to the aforementioned artificial skin. Creating the computer software to control these more sophisticated devices will be a major part of the development. The use of distributed processing techniques, with individual microprocessors controlling specific mechanical subsystems such as joints, should be advantageous in enhancing robot control.

### 3.3.5 Needed Development of Space Robotics Technologies

The development of robotics for the space station will be a gradual evolutionary process that utilizes new technology as it is developed. Probably the best example of an existing system that may evolve toward a robotic implementation is the shuttle Remote Manipulator System (RMS).

Background on RMS. The RMS is a six degree-of-freedom manipulator consisting of a 50-foot arm, an end-effector, and on-board control devices. The arm has shoulder, elbow and wrist joints connected by lightweight carbon composite beams. Motion is achieved by indirect gearbox control of the joints. Electronics at each joint provide signals to and from motors, tachometers, communications scanners, and brakes in the motor module, and transmit feedback from the optical position encoders. The simple end-effector works by attaching itself to a grapple knob on a payload. If needed, power and communication interfaces through the end-effector are provided.

The RMS can be controlled in one of four modes. Manual Augmented Mode allows joystick control of the arm tip. Preprogrammed Auto Sequence Mode allows the selection of one of 20 preprogrammed trajectories for the arm. Command Auto Sequence Mode allows the user to command the arm to follow a straight-line trajectory to a predetermined point in 3-space. Finally, Joint-by-Joint Control allows the arm to be moved by specifying commands to the joints. CCTV monitors at the shuttle Displays and Controls Panel provide visual feedback to the human user. CCTV cameras are mounted at RMS elbow and wrist joints.

Some of the rated capabilities of the RMS are surprising when compared with terrestrial arms. For deployment and retrieval the RMS can manipulate a payload up to 60 feet long and 15 feet in diameter with a mass of 32,000 lbs. A typical Unimate PUMA manipulator is rated for only about 5 lbs.

Future Capabilities of RMS. Future capabilities of the RMS include more sophisticated end-effector assemblies and more advanced control systems. The current grappling end-effector is unusable except on payloads equipped with a special grapple knob. A more versatile "hand" for the RMS could be developed to enable it to grasp a wider variety of payloads. An important design consideration is compatibility with current RMS grapples, so that the wider class of payloads manipulable by the new device includes the set of

all payloads with existing grapple knobs.

The RMS "hand" could itself be a sophisticated robotics device. The RMS might be used as a cherry picker to deliver, say, a robotic device to a position near a satellite undergoing repair, or to move an astronaut riding on a special platform. For versatility the RMS can be equipped with a standard end-effector interface which allows rapid changeout of end-effectors stowed on the station or in the shuttle cargo bay. To exchange an effector, the manipulator would reach into the storage housing and perform a simple twist-and-unlock procedure to remove an effector and another twist-and-lock procedure to attach a new one. It may also be desirable to place the RMS on a track to obtain an additional degree of freedom by increasing the reach envelope, highly useful during large-scale construction tasks.

There are some current constraints on RMS use. For example, there is a volume in the aft cargo bay unreachable by the RMS arm -- payloads to be deployed or retrieved cannot be placed there. Another small volume inside the cargo bay near the base of the arm cannot be reached when the end-effector is vertical with respect to the cargo bay, making retrieval and deployment difficult. The contours of the orbiter restrict the reach envelope of the RMS, making it difficult to reach, say, underneath the orbiter. Yet another constraint on manual RMS control is that the reach envelope exceeds the field of view of the typical operator, who watches the arm through a window or on one of the CCTVs (which have been known to quit unexpectedly).

In this area of control, adding spatial reasoning capabilities to the RMS would enable automatic planning of collision-free manipulator arm trajectories. One justification for introducing spatial reasoning capabilities into the RMS is that the reach envelope of the arm subsumes part of the volume occupied by the shuttle itself. Arm movements are physically constrained by the shape of the orbiter, but within the reach envelope are windows, thermal protection tiles, and instrumentation and payloads in the cargo bay. A spatial reasoning system with prediction capabilities would be useful even if it did no more than act as a backup warning and alarm system, stopping arm motion when the manipulator was in danger of collision.

The introduction of spatial reasoning and planning into the RMS system has three principal benefits. First, it allows more effective use of the operator's time since only goals need be specified, not low-level commands. Second, it increases safety by adding a backup warning system, since a spatial reasoner can predict collisions derived from current trajectories. Finally, spatial reasoning would increase RMS versatility, allowing motion along trajectories outside the operator's field-of-view.

In addition to the above RMS enhancements there are a number of other important research areas specific to robotics for space applications. These include (1) zero gravity manipulator mechanics, (2) locomotion for mobile robots in space, (3) manipulator designs for space, (4) sensors for robots in zero gravity, and (5) spatial reasoning for zero gravity.

Zero-Gravity Manipulator Mechanics. Gravitational terms drop out of zero-g dynamics equations. This implies smaller forces can be delivered at the end-effectors and smaller forces are needed to move the manipulator itself, hence smaller torque requirements at rotary joints and lighter-weight mechanisms to effect robot motion. The mechanics of pushing, grasping and placing in space is significantly different than for terrestrial manipulators. This, in conjunction with the fact that links of space-based arms can be made of lightweight composite materials, implies that station manipulator mass can be far less than that of an equivalent terrestrial manipulator.

Force and torque requirements for space-based manipulators cannot yet be precisely determined. To solve this problem one must know the maximum mass to be moved by the manipulator and the maximum velocity and acceleration desired. But since a large mass can be moved with a small acceleration in any direction in zero-g, the amount of force required at the end-effector can be made quite small. It may be found that the maximum force requirements are derived not from the size and acceleration of the largest mass moved, but by frictional force requirements that arise in assembly such as peg-in-hole tasks. Once force requirements are known, inverse dynamics equations may be applied (Brady et al., 1982) to solve for torque requirements.

The grasping, pushing, and placing problem in zero-g differs from its terrestrial counterpart because frictional forces play a lesser role, and gravitational forces do not come into play at all. For example, a pushed object continues in straight-line motion with constant velocity until it strikes another object. Such a constraint makes easier, say, the task of building a manipulator to catch a ball -- the ball can be made to travel very slowly in a highly predictable trajectory. On the other hand, manufacturing tasks requiring giving an object "a little shove" become more difficult.

Astronauts also have found that there is no such thing as "placing" an object in zero-g. Unless an object is physically attached to a surface, it tends to float away. (This has obvious implications for assembly operations in space.) Grabbing an object in zero-g requires the ability to grasp it from any arbitrary orientation. Grasping from any orientation means either that manipulators must be designed to reach objects in all configurations or that objects must be graspable in arbitrary orientations without damage.

Manipulator mechanics (statics and dynamics) is an active area of industrial and academic research at present. The problem of zero-gravity manipulator mechanics is quite unique. While we can expect much research outside NASA to focus on terrestrial manipulator mechanics, NASA is the only organization likely to sponsor research in zero-g manipulator mechanics. NASA should sponsor this research, focusing on problems of inverse dynamics for manipulator design and on pushing, placing, and grasping operations in zero-g.

Locomotion for Mobile Robots in Space. Various kinds of locomotion for mobile robots in space, including crawling, flying and rail-following, are possible but differ substantially from their terrestrial counterparts. The difference is due primarily to the absence of gravity.

Crawling in zero-g is possible only if the robot's feet have some means of attaching themselves to a surface. Open problems include the best choice of attachment system for various applica-

tions and the optimum number of legs to insure that the mobile robot does not easily become detached from a surface. Flying mobile robots are possible in space (even in the interior of a space station) but they will differ as much as do airplanes and spacecraft. Stability and control is expected to be as difficult a problem as controlling spacecraft in zero-g. Rail-following space robots must use rails to hold the mobile robot to the tracks, whereas similar terrestrial robots rely on gravity to hold them down.

Various research labs are intensively investigating mobile robots for civil and military applications. Little has been done on mobile robots in zero-g. Work on planetary surface rovers is largely inapplicable to a space station. NASA research on mobile robots should focus on the problems of zero-g crawling, flying, and rail-following.

Manipulator Designs for Space. An analysis to find optimal manipulator designs for space should consider the various terrestrial mechanical configurations of manipulators to determine which is most appropriate for given applications. For instance, noncontact manipulators relying on magnetism, charge, or fluid streams to move objects may find many applications in space. Since gravitational forces are largely absent, it might be interesting to attempt to position and suspend objects in zero-g with noncontact manipulators. Magnetic frictionless bearings have been studied by NASA for a variety of applications (such as energy-storage flywheels) and should be further examined for use in joints of space-based manipulators. Special lubrication problems arise because fluids behave differently in space (e.g., convection and dripping are not possible), heavy hydraulic gear cannot be orbited economically, and fluid lubricants may be exposed to temperature variations far greater than on Earth.

The mechanical design of manipulators is highly gravity- and application-dependent. Terrestrial mechanical constraints such as large mass requirements do not arise in space. NASA should study the problems of building manipulators for zero-g applications, taking into account mechanical design configuration options, lubrication and drive system options, and other factors affecting mechanical design of manipulators in space.

Sensors for Robots in Zero-G. Vision for arbitrary orientations encountered in zero-g situations may not be developed in connection with terrestrial applications. The emphasis in industrial vision is recognition of objects in well-ordered environments. Finding and tracking objects floating around a space station will require reference-frame-independent object recognition and motion-detection capabilities. Part location and recognition in arbitrary orientations will also be a challenge. One possibility is to use color to denote orientation -- the orientation of a floating cube marked with a different color on each face can be unambiguously determined if any two surfaces of the cube are visible. Using bar codes with multiple scanners is another possibility -- properly positioned, the scanners could observe a bar code from many possible orientations of the object. Recognition of objects in arbitrary configurations may apply to other sensors (e.g. ultrasonics and proximity sensors) as well as to zero-g world-models for multisensor integration. Position and orientation sensors already developed for space navigation may be applicable to robots.

Robot sensors will continue to be an active area of research for terrestrial applications. NASA's research should emphasize the special problems of robot sensors in space. Since NASA has great experience in other kinds of space sensors, an effort should be made to transfer senior technology to robotics applications.

Spatial Reasoning for Zero-G. Spatial reasoning refers to the broad class of artificial intelligence skills needed to reason about objects in three-dimensional space. Examples include reasoning with models of visualizable objects ("mental imagery"), planning collision-free trajectories for robots through cluttered environments, reasoning with "commonsense physics," and understanding translation and rotation of objects in zero-g. The commonsense physics of terrestrial mechanics is an open research question in artificial intelligence and cognitive psychology (Forbus, 1981), but progress is being made and an attempt to study the applications to commonsense physical reasoning in zero-g is warranted.

Intensive research into spatial reasoning problems is underway in AI laboratories today. NASA has sponsored some work on terrestrial spatial reasoning at the Intelligent Systems Research Lab at Langley (Wallace, 1983a,b) and at JPL, but little has been done to specifically address zero-g problems. NASA's support in this AI subdiscipline should emphasize the application of spatial reasoning and commonsense physics to zero-g situations.

### 3.3.6 Spinoffs from Advanced Robotics Development

Advances in robot technology fostered by NASA-sponsored research efforts will have many important applications in other fields. In the medical area alone, x-ray analysis will be assisted by research in robot vision; vision research may lead to artificial sight for the blind in which objects are located, identified, and the information communicated via speech synthesis. Similarly for the deaf, speech recognition systems to be used by robots could be adapted to understand and display words and sentences on a CRT, a set of LEDs, or by tactile stimulation. Robotics research is clearly linked to the development of artificial limbs and other aids for the injured and handicapped. Expert systems used to assist in robot sensory integration will accelerate the development of improved medical diagnosis programs.

Robotics research supported by the space program ultimately may benefit industry and commerce. Advanced robots could serve as miners, traffic officers, security guards, firemen, rescue and assembly-line workers, and domestic laborers. Other robot tasks of the future will probably include garbage collection, bus driving, and supermarket/retail clerking. When robots can perform significant tasks in space, this technology will be applied on Earth to tasks too dangerous or monotonous for humans to perform. Hazardous tasks might include military assignments, nuclear materials manipulation, deep marine research and exploration, and handling ordinance such as bombs and explosives. Development of robot-related expert

systems will contribute to the economy by providing tools for predicting and planning economic growth, and by assisting in agricultural planning, mineral exploration, energy utilization, and weather forecasting.

Advanced robots will replace some human jobs in the future, but most applications will involve jobs that are boring or dangerous. Robotics will permit the world's resources to be utilized more efficiently and therefore provide more total wealth to be shared by mankind. Robots will enhance, not pre-empt, human progress.

### 3.3.7 Summary and Recommendations

As related technology continues to evolve, robots will play an increasingly significant role in the space station and other space applications. However, significant supervisory control, telepresence, and manned EVA will remain necessary for the foreseeable future. The development of task allocation methodologies is of prime importance.

Much research manpower and funding is needed to give robots the sophisticated skills necessary for widespread space utilization. Surely this goal will be achieved, with enhanced robots serving major roles in future space station activities.

However, it would seem that autonomous space robots cannot realistically be applied to such tasks as satellite servicing until the year 2000, although some less-challenging space manufacturing applications are foreseen for the 1990s. This conclusion is based not only on the required technological developments, but also on the anticipated time required to attain space qualified status for new devices and systems as they evolve. It is difficult to predict very far into the future when high technology and government policy are involved, and some are more optimistic about the schedule of robot implementation for space tasks (Gevarter, 1982b; Freitas and Gilbreath, 1982).

NASA and the space program will benefit from robotics research that will undoubtedly be supported by other government agencies and by private industry. Improved robot vision and tactile sensing are currently the two principal thrusts in this category. But NASA itself has only limited resources available for robotics research and development, so expenditures should emphasize (1) transfer of robotics technology developed by other organizations for other applications into NASA for space applications, and (2) special robotics problems arising in connection with applications of robots in space.

Robotics research directly supported by NASA and others will produce beneficial technological spinoffs in many fields including medicine, economics, and agriculture. It will help relieve humans of dangerous and uninteresting work. Advanced robots may permit mankind to utilize its resources, extend its control, and advance its knowledge to a degree that until recently might have been considered fantasy.

## 3.4 Human-Machine Symbiosis

People and machines interact in many dimensions. Automating the space station necessitates a careful consideration of several important aspects of human-machine relationships -- especially function allocation, tool-using, and the element of human-machine mutual trust. The decision to use a machine or tool also depends on numerous factors such as availability and appropriateness, initial costs, compatibility with existing systems, and other context-dependent factors. Few makeshift tools or environmental resources will be available during space emergencies or under severe conditions, so great selectivity must be exercised.

But the concept of symbiosis goes beyond mere tool-use. Symbiosis generally refers to a mutually beneficial union or association of two dissimilar organisms or entities. Past space missions have often been termed "manned" or "unmanned," but the apparent dichotomy is illusory. The space effort has involved an ever-deepening symbiosis between people and machines. "Unmanned" missions have been manned by ground personnel -- if only in the teleoperated mode -- and "manned" programs such as Apollo and Skylab could not have succeeded without heavy reliance on automated systems. In the context of the space station, symbiosis implies an even more sophisticated and comprehensive marriage of unique human and machine talents, with each regarded as integral components of a single symbiotic system from the very first stages of conceptualization and design. Decision rules must be formulated to determine how human-machine functions can best be structured to optimize station effectiveness. And just as humans must determine when and to what degree they should trust a machine, whether and when an automated monitoring and control system should "trust" a person may also be of practical importance.

### 3.4.1 Function Allocation

Consideration of the decision to automate certain aspects of space station operations leads to an important phase in system design. This is the allocation of functions to humans and machines. At the present time there is no recognized systematic methodology available for the allocation of functions to human operators and machines (see Chapter 6), let alone between astronauts and automated systems (Montemerlo and Cron, 1982). Von Tiesenhausen (1982) provides a rational guide by which human-machine functions may be allocated in space applications. Advantages of human operators over machines include:

- ability to detect certain forms of energy;
- sensitivity to a wide variety of stimuli;
- ability to perceive patterns and generalize about them;
- ability to detect signals in a high noise environment;
- ability to store large amounts of information for long periods of time and to remember relevant facts at the appropriate time;
- ability to use judgment;
- ability to improvise and adopt flexible procedures;
- ability to handle the low probability alternative;

- ability to arrive at new and completely different solutions to problems;
- ability to profit from experience;
- ability to perform when overloaded; and
- ability to reason inductively.

The advantages of machines over human operators include:

- monitoring is usually done best by machine when possible;
- performance of routine, repetitive, and precise tasks;
- storing and recalling large amounts of precise data for short periods of time;
- computing ability;
- quick response to control signals;
- sensitivity to some stimuli within certain ranges;
- handling highly complex operations (i.e., doing many different things at the same time);
- deductive reasoning ability;
- insensitivity to extraneous factors; and
- cost reduction in many cases.

Undoubtedly, computers will be employed to a much greater degree on the space station than in the past on Skylab and the shuttle. For example, Price and Pulliam (1982) indicate that in terms of allocation of functions between human operators and computers, computers cannot set objectives and are poor substitutes for human operators in pattern recognition and fault diagnosis tasks. Computers also are unable to deal with unexpected events or to construct innovative responses to emergency situations. On the other hand, in an automated system computers can unburden the human operator and can deal with complex computations, organize information to be displayed, and act with incredible speed and reliability.

Wiener and Curry (1980) have described broad design guidelines for function allocation in automated systems which have considerable merit for the space station. "Control task guidelines" include:

- System operation should be easily understood by the operator in order to facilitate detection of improper operation and to facilitate the diagnosis of malfunctions.
- The automatic system should be designed to perform the task the way the operator wants it done.
- The automatic system should be designed so as to prevent peak levels of task demand from becoming excessive.
- The operator should be trained, motivated, and evaluated to monitor systems effectively.
- If automation reduces task demands to a low level, then meaningful tasks may need to be added to maintain operator involvement and resistance to distraction.
- Desires and needs for automation will vary from operator to operator. Thus, there is a need to allow for the expression of different operator styles.
- Ensure that overall system performance will be insensitive to different options or styles of operation.
- Provide a means for checking the setup and information input to automatic systems.
- Extensive training is required for operators working with automated equipment, not only to ensure proper operation and setup, but also to impart a knowledge of correct operation and malfunction procedures.

Among Wiener and Curry's "monitoring task guidelines" are:

- Keep false alarm rates within acceptable limits.
- Alarms with more than one mode or condition that can trigger the alarm for a mode must clearly indicate which condition is responsible for the alarm display.
- When response time is not critical, most operators will attempt to check the validity of an alarm. The information needed for such a check should be provided so that its validity can be determined quickly and accurately and not become a source of distraction.
- The format of the alarm should indicate the degree of emergency. Multiple levels of urgency of the same condition may be useful.
- Designers should devise training techniques and hardware to ensure (a) that operators are exposed to all forms of alerts and to many of the possible combinations of alerts, and (a) that operators understand how to deal with them.

In their extensive analysis of automated flight-deck operations, Wiener and Curry reiterate two virtually mandatory statements that can be and usually are made with regard to automation. First, automatic devices are very good at real-time control while human operators demonstrate flexibility as supervisors and standby controllers. Thus, in an automated system, monitoring and decisionmaking are usually regarded as the appropriate human role. Second, human operators, despite their flexibility, are held to be poor monitors, likely to miss critical signals and occasionally to make a false detection.

Wiener and Curry question the assumption that automation can eliminate all human error, claiming that it is no longer a question of whether a function can be automated but whether it should be. Although they direct their attention to the automation of aircraft systems, their guidelines for the automation of control and monitoring tasks may apply equally well to space station systems in addition to the usual human factor considerations.

Another approach to function allocation which applies to both the crew of the space station and the ground support crew, and which may be particularly applicable in the early stages of space station development and automation, is the technique of task analysis (Van Cott and Kinkade, 1972; McCormick, 1979; Woodson, 1982). Briefly, a task analysis consists of a variety of methods which define for each task the inputs needed and the outputs to be accomplished. The analysis can be used to determine task information and control requirements prior to the selection of equipment to be operated by people. Task analysis is also employed to determine skill and knowledge requirements, to estimate errors, to predict workload and scheduling, to provide timeline information, and to determine what tasks require decisions (and what kinds of decisions) and what tasks do not. Those functions or tasks not requiring decisions or only very simple ones can be allocated to machines for automation, and those requiring more complex decisions are allocated to human operators.

The decision of whether or not to automate determines to some extent the allocation of functions in a system, and will have a direct impact on the human-machine display and control interfaces associated with the space station (see Chapter 4).

### 3.4.2 Choosing Tools

The decision to use a machine or, more broadly, a tool, will depend on several factors -- availability, appropriateness for the job, simplification or enablement of task performance, ease of training, and utility. It is not necessary to have proof that a job is made easier or less costly in order to actually use a tool; nor are predictions about the usefulness of a tool necessarily accurate, since new uses for tools are discovered as experience with them grows. For instance, the superiority of a word processor to paper and pencil or a small typewriter depends on the values of and tasks confronting an individual user -- time involved, cost of equipment, continuing costs, the tasks to be accomplished, and the availability of compatible electronic equipment at the office or at a publishing firm together with the costs of interface arrangements. Analogous factors apply to the use of machines in space settings.

Sometimes people attempt tasks to justify the cost of acquired tools; conversely, people sometimes acquire an unusual tool because it seems intriguing or esthetically satisfying, and later discover it is useful for other tasks not originally foreseen or suggested by the form or function of the tool. Mere possession of a tool can be a strong determiner of future choices, rather than just a means for task performance. It would seem that the kinds of tasks undertaken in space may depend on the facilities there, as much as the facilities themselves depend on the existence of worthwhile tasks independently chosen.

The decision of exactly which machines to use in space activities has some similarity to the decision of what tools to take along on a trip. A person embarking upon an automobile journey leaves behind many possibly useful tools, assuming that if a need arises a tool can be bought or borrowed, the need deferred, or a professional tool user -- a mechanic -- called in. The situation in space (at least until the establishment of orbital repair shops) is more analogous to that of a wilderness hiker, who needs some simple gear with severe weight limitations, and who cannot buy or rent tools during his trek. The hiker must choose tools carefully for probable utility in the range of normal situations expected, for possible emergencies, and for weight, durability and strength, but also may rely on resources and makeshift tools likely to be available in the wilderness environment. If the backpacker is doing work such as geological exploration, additional specialized tools must be taken along.

However, the space station dweller has little in the way of pre-existing makeshift tools or resources in the "orbital wilderness," so even greater selectivity must be exercised, with the added consideration that some space devices must be able to withstand severe environmental extremes. This ecological difference is fundamental -- the resident space worker lives in a mechanized, automated habitat. At least a small stock of unfinished material and small components from which larger, useful things could be constructed should be planned for the station.

The non-repairing nature of current space habitation ecologies suggests an important role for humans. Maintenance and repair will be needed from time to time, some of it routine and easily done, some readily mechanizable. But most will require the kind of diagnosis and flexibility that only humans can provide. At least one person with superior mechanical and electronic repair skills, along with a good understanding of what is needed in scientific and technical development processes, probably should be assigned to the station at all times regardless of the composition of the habitat's more temporary mission-oriented population.

### 3.4.3 Humans and Machines: The Element of Trust

A true symbiosis requires mutual trust. When should a human trust a machine, and should the trust ever be complete? There is no general answer to this question. Clearly some machines (tools, devices) should not be trusted if they are dangerous, defective or prone to failure, or are not well-explored. Trusting others with probable or demonstrated reliability is certainly reasonable, since distrust may slow action. But the trust of machines, as with the trust of humans, is always measured relative to who or what is being trusted, and the kind of activity or situation the trust concerns.

Prejudicial trust, either blindly positive or blindly negative, is hardly reasonable, though both are sometimes encountered when discussing the use of machines in space. Unwarranted trust can lead to lax monitoring and poor corrective action, or to risky or costly situations without adequate support. Distrust can lead to underuse, to needless compensatory actions, and to a failure to explore possibilities for using machines in new activities. The whole business of testing devices in reliability engineering is a matter of specifying and justifying trust. Unfortunately it is seldom easy, nor even recognized as necessary, to provide "ecologically valid" (Brunswik, 1955) tests of devices in their normal use-environment. Usually it is even more complex to consider testing them in the context of human work arrangements and in the extended organizations which they will impact.

If people must gain trust incrementally, or through reputation, with the large range of devices they may encounter, this trust will be gained: (1) If they are generally disposed to the value of using machines (this trust may be qualified by cues from specific machines, or knowledge suggesting that some kinds are more "trustworthy" than others); (2) if initial experiences with the machine are safe, pleasant, and seem to accomplish what was intended from its use in an acceptable way; (3) if people are clearly gaining benefits from its use; (4) to the extent that the machine, though occasionally unreliable or quirky, permits easy recovery from losses, hangups, and errors; (5) if people understand how the machine works; and (6) if the machine is responsive in giving indication of internal or remote states, and these indicators are generally valid.

The question of machine "trust" of humans also enters the design of critical systems, a good example of an engineering problem with a clear ethical issue -- the potential effects on other people of undeserved trust of human action by a machine. In the past, people have placed faith in stable structures and even somewhat risky ones such as high-spirited horses, rope bridges, and re-entry vehicles. As a boundary proposition, it is probably true that no machine system that could impact human, animal, or ecological well-being in a significant way should be wholly inaccessible for adjustment or override. To preclude all overrides assumes system designers foresaw all possible eventualities, which is unlikely.

A system's potential for damage, as best as this can be assessed in advance of actual harm, is a factor too. The goal of a space station homeostatic system is to support fleet stability, life conditions, and so on, but it may err. A system designed to make new structures, or to move things, has more potential for harm and need for monitoring because of its less predictable uses and greater chance of causing physical damage. Another case is systems specially designed to do harm or to provide credible threats of harm, notably weapons systems. Harm-bearing systems should be difficult to actuate and defeatable by human means to the last possible moment. These matters bear on the real basis of trust -- potential harm vs. potential benefit.

We already design a kind of "system trust" into our computer networks -- a machine trusts only those persons with correct identification and password, without which interaction ceases and alarms may even be sounded. Levels of machine trust of humans are also reflected in access to sensitive areas of confidential information and internal systems codes for privileged users. If machines are to make judgments about how well to trust individual people, as contrasted with mere design biases, then those who interact with the machines must be identifiable individually, and either external information on their expertise fed in ("supplied trust") or some kind of usage statistics accumulated ("achieved trust").

Future work on distributed systems in space locales should provide good experience with the technology of trustable machines; as well as the linkage of distributed machine systems with human organizations.

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# CHAPTER 4

# MONITORING AND CONTROL

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The American space station will need a control system unlike any that has flown before. The station also requires sophisticated monitoring to assess its performance, to detect and diagnose abnormal conditions, and to help manipulate its system states knowledgeably under automatic control. A larger number of subsystems are planned than for any previous spacecraft.

The space station is analogous to an intelligent organism, having organs and effectors such as the Environmental Control and Life Support System (ECLSS) and the Power System. Much of the normal operation of these systems can be monitored and controlled by low-level devices ranging from simple feedback loops to dedicated microprocessors. These low-level monitoring and control systems are something like the peripheral nervous system in animals. Intelligence lies at a higher level, an analog of the human central nervous system with intellect divided among people and computers. Humans set the goals of space station activity. Machines help by generating and evaluating alternate choices to be presented to people for final decision, and by diagnosing system malfunctions and recommending or effecting repairs with varying degrees of autonomy. The space station organism thus may be a true human-machine symbiont.

Station monitoring and control intelligence may be visualized as a computational hierarchy. At the lowest levels are various sensors, effectors and subsystems which mediate the bulk of station activity. Primitive monitoring and control systems reside at the next higher level, with advances in computer architecture and microprocessors greatly expanding the processing power available. Above these are the higher-level control and diagnostic systems, and at the topmost level are people accompanied by their intelligent planning tools. The highest levels require adaptive control, real-time simulation and the use of artificial intelligence technologies such as expert systems, intelligent human-machine interfaces with natural language and (possibly) learning, and supervisory control systems. In the 1990-2000 time frame, humans will remain at the top of the station computational/control hierarchy, because AI-based high-level supervisory or executive systems will not yet be ready for implementation in manned space systems. In the longer-term view, however, the station may well be an increasingly autonomous adaptive learning system. Implantation of significant artificial intelligence should be a continual process.

The discussion of station monitoring and control in this chapter parallels the three-dimensional conception of autonomy outlined in Chapter 1. The first dimension measures the locus of control for tasks -- do humans or computers exercise the controlling intelligence, and to what degree? This includes issues of space station supervisory control and problem resolution using artificial intelligence techniques such as expert systems and natural language capability. The second autonomy dimension is station task performance allocation to humans or machines. To achieve greater effectiveness in monitoring and control, advanced sensors, displays, and controls are required. A complex network of linked microcomputers and parallel data buses can implement a high order of effective station autonomy. The third autonomy dimension -- locale of control -- distinguishes between Earth-based and space-based control. Examples are provided of typical applications best controlled either from space or from the ground.

## 4.1 Supervision: Locus of Control Autonomy

The control interface between a human and machine is characterized by the questions of capability and belief. In other words, to what extent is the machine capable of controlling itself and how much belief does the human have in the machine's capability? If a complex set of operations is being performed, the human must either be able to verify that the appropriate things are being done, or the control technology must be considered virtually infallible.

Control may be achieved at many different levels of device performance. For instance, control may be direct or supervisory, depending on the degree of participation of the human decisionmaker.



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Decisions for action may be adopted by an automated problem-solving and fault diagnosis system, or by people after consulting with AI-based expert system evaluators, using a natural language system on the station to access critical databases. In some cases, computers may be better equipped to handle a problem because of their ability to resolve complexities and their inherent computational speed.

### 4.1.1 Computer-Based Supervisory Process Control

Monitoring and control activities aboard the space station (and to some extent on the ground) will likely involve the following situations: (1) environmental control and life support systems (ECLSS); (2) sources, management, and distribution of power; (3) flight control; (4) thermal control; (5) malfunction and warning reconfiguration; (6) external environmental control; (7) traffic control; (8) manipulator control; and (9) Teleoperator Maneuvering System (TMS) or Orbital Transfer Vehicle (OTV) checkout and launch. In these situations, a human operator is involved in monitoring system equipment, in process control, and in the diagnosis of system malfunctions. A computer-based supervisory process control paradigm thus appears most appropriate.

Bergman (1982) differentiates process control systems by the degree of operator participation -- that is, by the extent to which the operator is in the loop. In the simplest case, known as "continuous management," the operator is involved in both monitoring and control tasks on a more or less continuous basis. More complicated is "management by exception (or alarm)," in which the operator remains an essential element of the loop but the routine monitoring of the process status is performed automatically by the system. Deviations from actual and desired states are signaled by an alerting device, and the operator is responsible for responding to warnings (provided by annunciators) by activating various controls.

A third mode of operation which appears most relevant to space station systems operation is "management by trouble". In this mode, computers monitor system status and take corrective action to the extent they are able. If a problem persists beyond their ability to take appropriate action, the computers then call upon the human operator. Thus the system may be capable of a number of rather sophisticated responses, such as correcting deviations from the desired state autonomously, indicating what has to be done to a human operator (e.g., replace a defective module), or requesting and assisting the operator to make a decision on the best course of action. Operators should be trained to retrieve appropriate information and to use expert system advisors (section 4.1.2), and all information should be displayed in a format which meets the operator's expectancies. Future management by trouble systems could be adaptive, learning correct actions after some experience. The level of automation required on the space station would seem to be that of "management by trouble" (Bergman, 1982) or "Levels I to V" as proposed by Mertes and Jenny (1974) and described by von Tiesenhausen (1982).

The primary supervisory computer controls the lower hierarchy of the monitor and control system and supports other functions such as station core activities, laboratory experiments and production. In addition, this computer carries an updated model of the monitor and control system and provides permanent onboard digital storage of diagnostics, schematics, instructions, present control configurations and other data necessary for maintenance, repair and emergency operation of the monitor and control system.

Some autonomy must reside in all levels of a practical system. Routine, robust, small-scale tasks should be controlled in substantially autonomous small loops with little need for human intervention. Critical, fragile, or large-scale operations require higher-level control, possibly with considerable human assistance. At the topmost level, human supervision governs the ground-space complex because, given present limited machine intelligence capabilities, only people can serve as innovators.

Monitoring for Supervision. It is not easy to determine when astronauts should be alerted, or whether the warning should occur at the space station, on the ground, or both. One way to approach this general problem is to consider the station as an intelligent unit. An analogy to the human body is useful here. There are many biological and biochemical systems which keep the body functioning without assistance from the central nervous system (CNS), but the conscious mind is never aware of their operation until a malfunction is significant enough to cause pain or otherwise raise an alert. There are also biosystems which use the CNS but over which the conscious mind normally has little control or even awareness -- such as the autonomic nervous system which regulates the cardiovascular system. The conscious mind can focus on some of these systems when necessary, but it would be very annoying to be alerted every time there was a change in heart rate, cardiac output or peripheral resistance. In the human body these systems monitor themselves, change operating levels and frequently make correction to accommodate malfunctions. In a similar manner, the space station monitor and control data stream should not be presented to the crew under normal conditions.

Considering the station as a unit with intelligence and autonomous operations, an analysis of continuously monitored systems can be carried out by considering the parameters outlined below. This analysis helps determine how the monitoring will be implemented, where control will be located, and what corrective actions should be taken.

The first step is to determine which systems should be continuously monitored. An analysis based on a breakdown of the major system into a set of subsystems provides the most accurate and informative result. In a continuously monitored system the data will probably be handled by one or more of the following methods:

- Not Stored (data not needed after immediate value evaluated);
- Stored in a database on Earth;
- Stored in a database on the space station;
- Used for an audit trail; or
- Displayed (data reviewed as soon as received).

A review of the system requirements will suggest data bus bandwidth needs and will help to evaluate the cost/benefit ratio of monitored funct-

ions. Data from the most important functions will probably be displayed and stored whereas data from less-important functions may not even be recorded once nominal values have been checked. Significant amounts of data will support an audit trail to provide a temporal history of major systems and to allow quick review of system operation in case of failures.

When a non-nominal value is detected a response is required by humans, machines, or both, and the proper locale of decision and action must be determined. The nature of the response depends on the seriousness of the abnormality. For example, a three-level response scheme might include the following: Level 1 -- values are beyond normal operating range but there is not a major threat to system operation or the well-being of crew or station; Level 2 -- values are significantly out of normal range, system operation is probably threatened, and some corrective action must be taken soon; and Level 3 -- system is no longer functioning and crew or station safety is in imminent jeopardy. The results of the response may be one or more of the following:

- Turn The Annunciator Off

- Modify The System Generating the Warning -- This would involve a slight modification in hardware or software, such as bypassing a failing component and/or switching in a redundant one.

- Switch To A Redundant System -- This usually would mean shutting down the present operating system and bringing on-line a complete new system.

- Turn The System Off -- No redundant system is provided the present system is in a failing mode and is incapable of providing any satisfactory output and may cause damage to other systems.

- Upgrade Warning Level -- A low level failure has occurred and some corrective action has been taken. If failure occurs again, the alarm will be at a higher level.

- Shut Other Systems Down -- Damage will result to these systems because of the malfunction in the system producing the warning.

- Fault Diagnosis -- The system is checked to determine if the warning is correct and/or action is taken to correct the fault. This could be done by either human or machine.

The primary interface for the supervisory process control system will be a CRT or similar device with its associated control console or keyboard. For data entry, the standard QWERTY keyboard would be employed in conjunction with other devices such as touchscreens, track balls and voice entry. English, Engelbart and Berman (1976) found both mouse and light pen superior to the joystick for data entry tasks.

Annunciators and False Alarms. Alarm or annunciator signals are usually employed in conjunction with supervisory process control systems to alert the operator to important changes in system status. These warnings typically consist of audible and visual signals and are generated by annunciator systems. An annunciator system has four subsystems -- audible signal, visual signal, acknowledgment system, and the linkage system which joins the others with the process being controlled and monitored (Kragt, 1982). Annunciators may be located locally (at the failure site), at the station control center, or on the ground at mission control. Alarms take a variety of forms including audio (horn, bell, voice), light, fascia, CRT graphics or alarm tables, and printers. The type and level of the warning will determine the location and type of annunciator, the respondent (whom the annunciator addresses) who may be either human or machine in space or on Earth, and the type of action taken.

As control tasks become more automated, issues of human-machine trust become paramount (section 3.4.3). In the past, the solution has been to deploy extensive annunicator systems so that warning signals are generated for every problem, even those of a nature easily resolved by the computer. But this approach hinders effective interaction between humans and machines, especially in the case of false alarms. Considerable care must go into the design of computer-based systems so that they can take a maximum number of routine corrective actions autonomously before an alarm must be sounded.

For instance, a recent study by Kragt (1982) reported that in a chemical process plant there were 2794 separate signals from the annunciator system over a 70 hour period. Most of these occurred at intervals of 1 minute or less and only 6% occurred at intervals of greater than 10 minutes. Kragt found that no response was made to 50% of the signals. Forty-three percent of the signals seemed to be acknowledgment of the system to some action taken by the operator. Only 7% of the signals required action of the operator.

In yet another study, Seminara et al. (1977) report that nuclear power plant operators frequently complain of a high number of nuisance alarms. Similar problems with nuisance alarms have been found to exist in aircraft cockpits, though to a lesser degree. Newer aircraft employ a number of alerting signals including some voice signals (FAA, 1977; Kantowitz and Sorkin, 1983). Greater specificity in alarms can be achieved with voice messages, but Cooper (1977) has pointed out the need for prioritization so as not to overload or confuse the pilot or operator. Cooper suggests a limit to the number of auditory signals of perhaps four or five.

False alarm problems also occur in medical monitoring systems. Meaningful alarms are critical in preserving patients' lives, but the sounding of meaningless alarms deadens the sensitivity of the nursing staff. Alarms are ignored or even disabled, and although the signals are still being transmitted a major advantage of the monitoring system has been lost. Sometimes even when a significant alarm is generated it may be ignored because of the frequent false cues.

If care is taken to avoid the problem of frequent nuisance or false alarms, a computer-based system of the type described above for the space station should achieve a higher level of reliability by adding parallel redundancy. In this arrangement the human operator checks the computer's output, and vice versa. (It is assumed that information from onboard computers will also be available to ground-based computers.) As automated monitoring and control systems are being designed for the space station, the level of human involvement must be carefully considered and a justifiable trust designed into the computers.

ECLSS: A Case Study. An example of a space station subsystem which requires advanced automatic control techniques is the environmental control and life support system (ECLSS). The brief discussion below is based on the minimal and partially closed ECLSS proposed for the space station, not on the present shuttle system which is highly dependent on ground-based supplies and replaceables such as liquid oxygen and lithium hydroxide canisters for carbon dioxide removal.

Five ECLSS design configurations (Lin and Meyer, 1983) can be described. In the open cycle, provisions arrive from Earth on a renewal-only basis. The enhanced open cycle employs regenerative subsystems for carbon dioxide removal. The minimum closed cycle closes the drinking water cycle in addition to carbon dioxide removal. The partially closed cycle closes oxygen and water cycles. Finally, the completely closed cycle, which may require biological processes, incorporates the food requirements into a design creating a system with only energy transfer across its boundary. In order to accomplish the general objective of supporting humans and other living elements on the space station, the ECLSS must be able to perform, at minimum, the following functions:

- Control pressurized environment;
- Provide emergency repressurization gases;
- Emergency repressurization cannot damage systems;
- Cabin pressure must be compatible with STS Orbiter;
- Remove objectionable odors and noxious gases;
- Monitor/control airborne trace constituents;
- Supplement atmospheric leakage of constituents;
- Limit overboard venting;
- Remove particulate matter from air and water;
- Limit air/water microbial concentrations;
- Dump atmosphere during emergency (as in case of fire or contamination); and
- Uses gases in ECLSS that are not explosive or fire hazards.

The integrated ECLSS subsystems are being designed with the need for continual and fault tolerant automatic control in mind. Though complex, the proposed partially closed cycle would be no more difficult to control than existing plants of similar characteristics such as those of the chemical industry and oil refineries (Quattrone, 1984; Schubert, 1983).

Generic digital computer based automatic controllers are being developed (Schubert, 1983) to control ECLSS subsystems. It is anticipated that these controllers will have to interact with other equivalent controllers in order to minimize the impact that interaction between subsystems could have on the stability or general performance characteristics of the ECLSS. A supervisory digital computer programmed to orchestrate the individual controllers could accomplish this objective.

### 4.1.2 Automated Problem-Solving and Fault Diagnosis

Decisions for action are usually the result of either a considered process of problem resolution or the response to an unexpected situation which appears to require immediate attention. The process of problem resolution may be done by a human with the aid of data supplied by other humans or by a variety of machines. Certain classes of computer programs may take on the major burden of problem resolution, with some input from a human collaborator. In some cases, a computer may be better equipped to handle the problem because of its resolution capabilities or inherent computational speed, or because it is better able to integrate the problem's enormous complexities. The computer can be supplied with rules of procedure drawn from a human expert and can be expected to follow these rules in much the same way that a knowledgeable human would. These software systems are sometimes called "expert," "knowledge-based," or "rule-based." In general, expert systems can best be used to address problems that are well defined, restricted in scope, and which can be procedurally solved by a human expert.

Recent advances in expert systems and knowledge engineering (Gevarter, 1982; Nau, 1983) may provide a useful tool for high-level space station planning, monitoring, interpretation, and control functions. Expert systems operate in a manner determined by human procedures, and can be verified by users to be following human-originated rules. This verification is supplied on demand and is essential to human belief in the results. Expert systems are just now evolving out of the research stage. They have been most successful in problem-solving applications such as medical diagnosis, molecular structure and spectral analysis, military threat evaluation, crisis management, electronic circuit analysis, and mineral prospecting. However, they also hold substantial promise for providing a control mechanism where interpretation is required. For example, the shuttle has five flight computers, each constantly making judgments as to whether it and the other four are operating correctly. This judgment is displayed as a 5x5 pattern of lights on the shuttle command console. Three of the computers are in use at any one time. Currently, an astronaut interprets the display to decide which computers should be used. An expert system could relieve humans of this task rather easily.

Expert systems are a promising methodology for automating much of the decision process regarding fault diagnosis and correction procedures. An even more complex concern is the ground monitoring and control of space missions. Currently, many personnel are needed -- about 400 people every shift for the shuttle. On Skylab, seven people per shift were required just to control power load balancing. This type of control could be partially handled using a mixed-initiative expert system able to respond to data on an exception basis. Most current expert systems collect data from a broad range of sources, some not particularly relevant to the solution of the problem at hand. An exception-driven, mixed-initiative expert system would respond to information passed to it of an exceptional nature, informing the crew, for example, "CABIN PRESSURE REDUCED TO 5 PSI" and then initiating requests for additional data that might be relevant.

Expert Systems: Basic Structure. Search strategies alone, even if augmented by heuristic techniques, are often inadequate to solve real world problems. The complexity of these problems is usually such that either a combinatorial explosion occurs causing unreasonable search times, or the ability to generate a suitable search space does not exist. In fact, it has become apparent that for many problems the expert domain knowledge is more important than the search strategy (or inference procedure) -- in knowledge lies the power. This realization has led to the field of "knowledge engineering" which focuses on ways to use expert knowledge in problem solving. The resulting expert systems technology, once limited to academic laboratories, is now becoming cost-effective and is entering commercial application.

An expert system consists of (1) a knowledge base of domain facts and heuristics associated with the problem; (2) an inference procedure (or control structure) for utilizing the knowledge base in the solution of the problem; and (3) a working memory for keeping track of the problem status, the input data for the particular problem being resolved, and the relevant history of what has been done so far. A (human) domain expert usually collaborates to help develop the knowledge base. Once the system has been developed, it can help human experts in developing their own expertise.

It would be desirable to have a true natural language interface (see section 4.1.3) to the expert system to facilitate its use, but this remains an unsolved problem. A few systems do have a pseudo-natural language interface. Explanation modules allowing the user to examine the system's underlying reasoning process are necessary in a fully functioning system. Indeed, it was the explanatory capability in the MYCIN (Shortliffe, 1976) project that brought user credibility to expert systems.

An expert system differs from a more conventional program in several important respects (Duda and Shortliffe, 1983). In an expert system, there is a clear separation among general knowledge about the problem (knowledge base), information about the current problem (input data), and methods for applying the general knowledge to the problem (inference engine). In a conventional program, knowledge pertinent to the problem and methods for utilizing this knowledge are intermixed so it is difficult to change the program. Ideally, in an expert system the program is only an interpreter and the system can be changed by simply adding or subtracting rules in the knowledge base.

The most popular approach to representing the domain knowledge needed for an expert system is by production rules (see section 6.2). Often a knowledge base is made up mostly of rules which are invoked by pattern matching with features of the task environment as they appear. Additional ways of representing the domain knowledge are "frames" and "semantic nets." All three representations are generally isomorphic. However, it is probably easier for a human expert who is not conversant with artificial intelligence techniques to think in terms of production rules.

The rules in a knowledge base represent the domain facts and heuristics -- rules of good judgment to determine actions to be taken when specific situations arise. The power of an expert system lies in the specific knowledge of the problem domain. All else equal, the most powerful systems are those containing the most knowledge. An expert usually has many judgmental or empirical rules for which there is incomplete support from the available evidence. In such cases, one approach is to attach numerical values, called "certainty factors," to each rule to indicate the degree of certainty associated with the use of that rule. The expert system combines these certainty values with each other and with the certainty of the problem data to arrive at a net certainty value for the final solution.

As indicated earlier, expert systems consist of a set of rules, a global data base, and a rule interpreter or inference engine (see section 6.2). The rules are activated by patterns which, depending on the direction of search (e.g., bottom-up, top-down), either match the IF or the THEN side of the rule. The application of the rule changes the system status and enables some rules while disabling others. The rule interpreter uses a control strategy for finding the enabled rules and deciding which rule to apply. The basic control strategies used may be top-down (goal-driven), bottom-up (data-driven), or a combination of the two that uses a relaxation-like convergence process to join these opposite lines of reasoning together at some intermediate point to yield a problem solution.

Expert systems can be used to diagnose, monitor, analyze, interpret, consult, plan, design, instruct, explain, or learn. Thus they are applicable to mission planning, monitoring, tracking and control; to communications; to signal analysis; to command and control; to intelligence analysis; to targeting; to construction and manufacturing (design, planning, scheduling and control); and to education (testing, instruction, and diagnosis)

Current systems are limited primarily by three characteristics. First, they have a narrow domain of expertise, largely because of the difficulty in building and maintaining a large knowledge base. Second, expert systems require laborious construction. At present, a knowledge engineer must work with a human expert to extract and structure the knowledge to be placed in the knowledge base. In general, it has been difficult to create knowledge acquisition systems to extend the knowledge by direct interaction with a human expert without the aid of a human engineer. Third, current systems reflect the viewpoint of a single expert or "knowledge czar." AI specialists in expert systems currently lack the ability to maintain consistency among overlapping data in the knowledge base. Therefore, the pooling of knowledge by several experts to extend the limits of the represented knowledge and to enhance the represented knowledge is an unresolved issue requiring further research.

System Evaluation and Fault Diagnosis. System evaluation involves the continuous assessment of spacecraft and ground support performance in achieving desired mission objectives. This includes assessment of the state-of-health of the spacecraft and its components, and its suitability for further activities. The evaluation can include modeling of system status to diagnose failures and to detect potential failures. For example, in the event of a sudden power loss, the type and cause of the problem must be diagnosed. It must be determined whether there is an actual power loss in a component, such as a solar array or laboratory module, or if there is a sensor or

software error.

To perform fault diagnosis of spacecraft components, a system will often have the ability to recognize that it has failed or will soon fail. The system will then act to make its controlling system (such as a human operator or a computer controller) aware of its degraded condition. This can occur, for example, by the sounding of a buzzer or the illumination of a red warning light. Another method of determining proper operation is to perform data checks on a system by comparing its output data to a system model and evaluating consistency and plausibility (Smith et al., 1982). Such data checks are a nonintrusive procedure which operate on normally available data. Checks can be performed by a human who would, for example, examine system output (possibly in the form of a computer printout) for inconsistencies. Checks can also be automated and conducted by computers or dedicated microprocessors. There are some tradeoffs involved in automating this function which must be considered -- humans are better than machines at detecting some types of anomalies, and vice versa.

Function tests are an intrusive fault diagnosis procedure in which commands are sent to spacecraft systems requesting that specific actions be taken. Performance is monitored and compared to expected levels to ensure all systems are nominal. As with data checks, the results of function tests can be evaluated by humans, computers, or by dedicated microprocessors. But a very important part of the operation, preceding the actual performance of these evaluations, is deciding which evaluation to conduct. This involves the formulation of hypotheses to explain the anomalous data and identification of suspected defective hardware or software.

The usual method for deciding which procedure to follow in identifying or correcting a shuttle flight failure is to reference checklists constructed in advance and containing, it is hoped, all possible failure modes, the means for identifying them, and what to do about them. Checklist development is exceedingly time consuming and expensive, and the difficulty rises exponentially with increasing spacecraft complexity. Preparation of shuttle flight checklists is nearly an unmanageable task already -- a new approach is needed for the space station. Expert systems are a promising methodology for automating much of this decision process. While expert systems are restricted to consistency verification in checklist development, their potential utility in the checkout process itself is very high. These AI systems are driven by rules much like the items in a checklist. An expert system could successfully identify any problems identifiable through the use of a checklist. And checklist procedures are often relatively unfocused and inefficient as humans try to recognize and define problems. Expert systems have the potential to quickly identify key problem areas.

Indeed, according to Smith et al. (1982), expert systems may become not only desirable but necessary in future spacecraft missions. The traditional philosophy is to anticipate all possible one-point and two-point failure modes during the design process, and to design either safeguards or recovery systems to deal with possible problems. However, as spacecraft complexity increases, the prediction of all failure modes and effects becomes combinatorially enormous. At the same time, on-orbit repair systems will become available, such as the shuttle, the Teleoperator Maneuvering System, and possibly repair teleoperators aboard the spacecraft itself.

This suggests an alternative to the total-failure-prediction criterion. It may be sufficient to load a detailed functional representation of the spacecraft (or space station), including the relationships between components (particularly the effects of component failures on other components) into the relational database of an expert system. Then the expert system can perform two services. During design it can systematically search for severe failure combinations, to be designed out of the spacecraft; after launch, it can assist in (or perform) failure diagnosis, suggest potential solutions, and verify that proposed solutions will cure the problems. The repair systems can then implement those solutions.

While expert systems can perform many lower-level component evaluations and diagnoses, in the near-term astronauts will still conduct higher-level system evaluations of performance to achieve desired mission goals. A wide variety of factors, many of which cannot be anticipated in advance, must be taken into account. People are particularly good at this.

Intelligent Assistants. Intelligent assistants represent the panoply of AI-based hardware and software systems that will provide intellectual and operational support to the space station crew. Simple computation algorithms are useful where the knowledge may be expressed in terms of equations as with spacecraft guidance systems, and basic information retrieval such as the daily schedule can be done using standard database systems technology. But these programs are generally inflexible in that the knowledge is hidden in the code itself and therefore requires a programmer to deal with updates and modifications. Artificial intelligence will impart added capability, flexibility, and a new measure of user-friendliness to onboard computer systems, contributing significantly to station autonomy and effectiveness.

For example, rather than imposing schedules on station crewmembers from the ground, an intelligent assistant can work with the crew to establish a schedule for attaining a set of goals. Use of facilities can be scheduled taking into account the nature of the requests and the specific capabilities of deployed station modules. Intelligent assistants can enhance satellite servicing or construction missions by helping to plan the required activity sequences and detecting abnormalities and modifying plans accordingly. Inventory maintenance, including acquisition of new items either by manufacturing them in space or by ordering them from the ground, can also be performed. If the space agency charges fees for using laboratory, manufacturing, computer or communications facilities and for expendables consumed, intelligent assistants can monitor usage directly and compute current charges for each customer. Other intelligent assistants might be used to monitor the station radiation environment or to maintain constant vigil against potential collisions with other space objects.

Of course, some of these functions can be performed without AI techniques -- flight control and inventory control programs can be implemented easily with off-the-shelf systems. But more sophisticated approaches and increased capabilities will require AI technology. For instance, the inventory control assistant may decide to make a re-

placement part by creating it from onboard materials; or the flight assistant may need to take into account a motion sensitive experiment in progress elsewhere in the space station complex.

Software Reliability, Credibility, and Confidence. Program verification, software engineering, and automatic programming are three major research areas in computer science that are concerned with creating reliable software. Program verification is a methodology for mathematically proving programs to be correct. Software engineers, on the other hand, develop software design techniques which are coupled with empirical program testing. Automatic programming is a software technology in which one program writes other programs to match given specifications.

The area of program verification has its roots in the development of Hoare's logic -- an accurate description of the state of a computation at each step of program execution through a set of logical predicates. Each statement in the program transforms the computational state as specified by the semantics of the statement itself (hence Hoare's logic). This is generally rigorous enough so that a program analysed in this fashion or written with these transformations in mind can be proven correct, thus providing 100% confidence that the software is correct. The theory may also be used to create automatic programming systems. If a program can be verified, and all assumptions are well-defined and complete, then there is a high degree of certainty that the software does what it is supposed to do. The problem of reliability is passed on to the hardware.

One of the reasons why this technology has not been widely accepted as standard procedure is that it relies heavily on defining the problem to be solved accurately and completely, and on completely specifying the initial set of assumptions from which the computation starts. Neither is a trivial task, and how to use the logic on itself to achieve automatic verified programming is unclear. The process is somewhat analogous to discovering a mathematical proof of a theorem. Although theorem-proving is an active research area in AI, only small, well-constrained proof domains can be accommodated at present. The only alternative is to prove the correctness of previously written code. This is more mechanical than using the logic directly to write the program, but even so, problems remain in finding invariant conditions during loop execution and in keeping track of the many predicates invariably generated.

Other difficulties with program verification technology are more intrinsic. For instance, not all programming languages have well-defined semantics. Even supposedly well-defined languages such as Pascal have ambiguities and inconsistencies. A number of languages have been developed to try to address this issue, including Modula, Clu, and Alphard. Also, it is difficult to apply Hoare's logic to programs using interrupt processing such as real-time programs -- interrupts may be serviced at any time, so it is impossible to predict the state of the computation at a given point in program execution. Unfortunately, many of the crucial time-dependent software applications for the space station fall under this category, such as monitoring life support systems where malfunctions must be addressed in real-time.

Software engineers are concerned with creating large, complex software systems. To accomplish this, a careful analysis of the problem definition is first performed by generating a complete set of specifications and test data. Then the software system is designed in a "top-down" fashion by starting with the overall problem and successively refining the design. These refinements usually involve breaking down the package into smaller modules that can be independently designed. Ultimately, submodules are created at such a simple level that routines can be written with a high degree of reliability. The major goal is to generate software systems that are easily understood, maintainable, and updatable. Through a greater understanding of the software system, it is hoped that the possibility for error is greatly reduced and that when an error does occur, its effects are limited and are easily corrected. By addressing the issue of maintainability and updatability, software engineering tries to deal with the difficulties inherent in an evolving software system -- an important factor as regards software development for the space station.

Another promising solution to the problem of software reliability is automatic programming. Although the difficulty of trying to define the problem completely (using software engineering techniques) remains, the automatic programming system can be drawn upon to actually write the code. Results from the field of program verification can be used to drive the creation of the software. Since the automatic programming system is keeping track of the predicates and is running the transformations automatically, the resulting program can almost be guaranteed to execute according to specifications. Of course, the specifications defining the end product must also be verified.

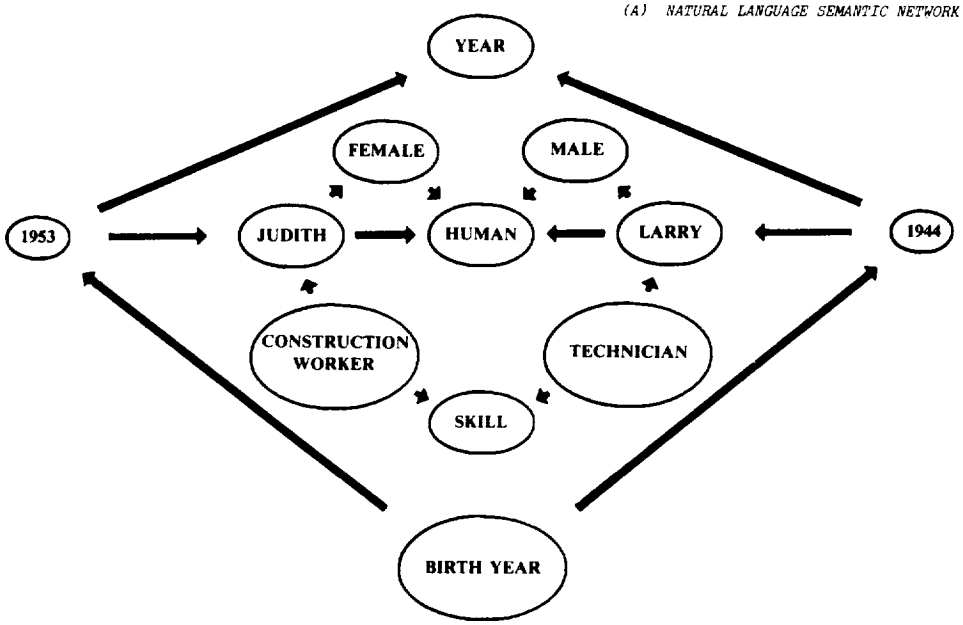
From the standpoint of generating human confidence in machines, AI offers bright promise for the future. For example, there is quite a bit of research being performed in the area of "commonsense reasoning" -- naive physics, understanding and dealing with people's beliefs, applying general knowledge about the world to specific situations, and so forth. By mimicking human commonsense reasoning, an intelligent space station system could recognize anomalies, notify the crew, and possibly deal with the situation itself. Much basic research remains to be done in connection with these systems, and it is unlikely that completely error-free software systems or machines will ever actually be built. Still, efforts should be made to produce software and hardware that works with tne highest practical degree of reliability possible. The fields of fault-tolerant computing (possibly including expert system troubleshooters), software engineering, and program verification provide the keys to software reliability.

### 4.1.3 Natural Language and Station Information Management

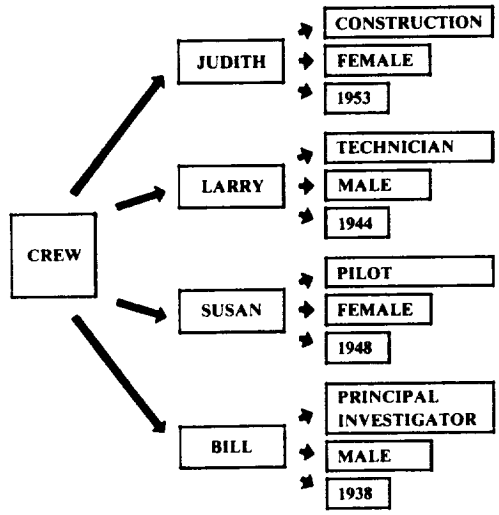
A natural language is a symbolic communication medium devised by people to communicate with other people. Although "natural language" is sometimes broadly defined as including such things as body language, usually it has the narrow technical meaning of a written or spoken language such as English. Natural languages should be distinguished from formal languages which use some elements of a natural language. Truly natural languages are flexible in terms of word order and word meaning.

**FIGURE 4.1. DATA REPRESENTATION ALTERNATIVES FOR SPACE STATION DATABASE MANAGEMENT SYSTEMS**

*(A) NATURAL LANGUAGE SEMANTIC NETWORK*




*(B) HIERARCHICAL (TREE) DATA STRUCTURE*




| NAME | SKILL | GENDER | BIRTH YEAR |
|---|---|---|---|
| Judith | Construction Worker | Female | 1953 |
| Larry | Technician | Male | 1944 |
| Susan | Pilot | Female | 1948 |
| Bill | Principal Investigator | Male | 1938 |

*(C) RELATIONAL DATA STRUCTURE*

The specific goal of an AI-based natural language system aboard the space station is to enhance human-to-machine and machine-to-human communications. The astronaut may wish to tell the machine to do something, or the machine may need to provide information to someone, both of which are best accomplished in a natural language format. It may be desirable for the machine to supply information in a natural language both in response to requests and on its own initiative. For instance, the system could respond to the spoken command "ROTATE INSTRUMENT POD NINETY DEGREES" or it could initiate the message "FIRE IN STORAGE LOCKER A12."

Natural language can be either spoken or written, and significant research has been done on both forms. Understanding spoken input is more difficult than understanding written input. This is because without a partial understanding of what is being spoken, it is difficult to separate one word from another in normal continuous speech -- which compounds the problem since some comprehension is required even before the utterance is complete. Pauses in mid-word may be larger than pauses between words. The only speech understanding systems that currently work reliably are those requiring lengthy pauses between each spoken word of a restricted vocabulary. For the most part, work has been terminated in the continuous speech understanding projects. The few remaining projects do not attempt to recognize or understand words, but only to phonetically annotate utterances. It is obvious that natural language communication with machines would have considerable utility, but it is not yet clear exactly how to do it.

Database access via natural language on the space station is also desirable. Natural language database query systems have three characteristics that aid their analysis: (1) The portion of a natural language's syntax that must be covered is a subset of the syntax of the entire language; (2) the pragmatic use of language in queries limits the semantic interpretations of a statement; and (3) the analysis can be significantly guided by the assumption that a statement is a request for data from a known database. The application closest to practical realization is that of a natural language interface to a database. An ideal natural language would be highly domain portable, requiring minimum modification to be moved from one subject or domain of discourse to another. Currently, there is a lack of significant research in domain independent natural language systems. Most natural language research is based on providing a means to describe the discourse domain so that the "world model" of the domain can be used to comprehend the natural language statement.

Abstracted forms of natural language descriptions such as semantic networks (Figure 4.1(A)) may eventually be useful as a means of accessing high-level knowledge. Using an abstracted form provides a description of a problem "world" that a problem solver can use to draw inferences and understanding of relationships. These in turn can be used in the resolution of problems that relate to that "world." However, while natural language communication techniques are close to being useful, natural language abstractions to supply knowledge remain the subjects of basic research.

Using a computer to handle natural language is a difficult and complex undertaking. Considerable effort has been spent on the problem beginning with the earliest computers. One of the compounding difficulties is that linguistic theory has proven to be incomplete and not particularly helpful with decoding natural language on a computer. It is not known if the complexities of the problem are finitely bounded, because natural language is highly expressive, ambiguous, and semantically very context-dependent. However, identifying the particular word role (e.g., verb, noun, adjective) and phrase boundary recognition may or may not be context sensitive (Gazdar, 1983). Word meaning may be either narrowly precise or relatively imprecise. For example, the term "hot" may be used in a two-valued mode (e.g., hot or cold) or be used relatively and fuzzily (e.g., "hot food"). Meaning resolution is difficult even when not dealing with multi-valued or fuzzily-defined terms. For example, in the statement "John tickled the girl with the feather," is John using a feather to do the tickling, or is he tickling (method undisclosed) a girl who has a feather?

Natural Language Systems: Background and Brief Tutorial. In the late 1950s, significant efforts (Bar-Hillel, 1960) were expended in an attempt to perfect machine translation from one human language to another. Because of an inadequate awareness of the need for semantic analysis and an insufficient theoretical basis from linguistics for syntactic analysis, these efforts failed to produce effective machine translation systems. The most significant contribution from these projects was an awareness of the syntactic and semantic sophistication required for natural language processing. The exact roles that syntax and semantics play in natural language processing are not yet clear, but current natural language systems can be classified by the kind and the amount of each type of analysis used in the system.

Syntactic analysis is concerned with the grammatical structure of natural language statements. Several different syntactic models have been used, including context-free grammars (Earley, 1970), transformational grammars (Woods, 1970), and case grammars (Simmons, 1973). Case grammars are verb-centered grammars that attach to the verbs in a sentence those cases that are needed by each verb. The cases used vary from grammar to grammar. Typically the cases define the subject and object of the verb. Context-free transformational grammars are designed to provide a basis for representing the meaning of statements. Context-free grammars are common in database query systems and case grammars are most frequently used in natural language understanding systems.

Semantic analysis is concerned with the "meaning" of a statement. The nature of the semantic component of a natural language system is often dependent on the syntactic analysis method with which it is used. The most common semantic methods are syntax-directed. These assign semantic interpretations to syntactic structures, an approach similar to that used in modern compiler design (Aho and Ullman, 1977). Other semantic methods give syntax a smaller role to play in identification of a statement or text meaning. These types of analysis are aimed more at development of the underlying "deep structure" of the statements. Schank (1975) uses a world model and an inference-making mechanism to discern the semantic meaning of a statement. Some systems (Winograd, 1973) use a hybrid approach to semantic analysis including both syntactic analysis and a world model in the semantic component of the natural language processor.

In addition to these basic syntactic and semantic analysis techniques, a number of alternate semantic or internal representations have been developed. These representations are the target of the syntactic and semantic analysis methods and represent the semantic meaning of the original natural language statement in a format more amenable to further processing. Representations devised to date include semantic nets, frames, parse trees, templates, and deep structure, described briefly below.

Semantic nets (Scragg, 1976; Simmons, 1973; Mylopoulos et al., 1976) are a graphic representation of information. A semantic net consists of a set of concept nodes connected by a set of edges whose labels define the semantic relationship between the nodes. The concept nodes usually represent word sense meanings often taken from a dictionary or lexicon. The nature of the semantic relationships in a semantic net differs among different implementations of semantic nets. A type of semantic relationship commonly used is the verb argument structure of a case grammar. Semantic nets can be used for two fundamentally different purposes. First, they can be used as the internal representation into which natural language statements are translated by a natural language processing system. Second, they can be employed as a world model, in which case the concepts and semantic relationships in the net describe the activities and characteristics present in the environment being modeled.

A frame (Minsky, 1975; Goldstein and Papert, 1976) is a data structure for representing a stereotyped environment. The data structure contains information which is always true in a given environment. It also contains slots for other attributes of the environment which are not fixed. These slots will be filled in as the necessary information becomes available in a specific instance of the environment. Arbitrary restrictions may be placed on the values that are permitted to fill a given slot. A slot may have a default value assigned to it, assumed to fill the slot unless displaced by contradictory information from the environment. For example, consider the sentence "John tickled the girl with the funny nose." The frame for the verb tickle would have empty slots for the agent (the person doing the tickling), the object (the person being tickled), and the instrument (what the agent is tickling the object with). Associated with each slot in the frame is a list of items that could fill it or a description of the kind of item that may fill the slot. Whether frames should possess direct knowledge (a list) or indirect knowledge (a description) of the items that can fill a given slot is an unresolved question in frame theory.

Parse trees may be used as the internal representation in a system that uses syntax-directed translation. Under this approach, dictionary or procedural definitions of words and semantic rules with tree fragment pattern matching are used to attach semantic interpretations directly to the syntactic structures of a statement (Woods, 1970). For some grammars the parse tree for a statement may not be unique. When multiple parse trees exist for a statement the semantic analysis must select the appropriate parse. If the statement is ambiguous, then it will be impossible to select a single parse.

The template representation method is often used in natural language query systems (Waltz and Goodman, 1977). Templates are stereotyped statements that are matched against the input statement; if a statement matches a template, a semantic interpretation of the statement can be made. For example, the template: "<command word> <desired information> <quantifier> <required attributes>" matches the query "list the name and phone number of all French-speaking employees."

Deep structure is used as the target for transformational grammars (Schank, 1975; Wilks, 1977). Deep structure is intended to represent the meaning of a statement in a form that is independent of the surface or syntactic structure of a statement or even of the source language itself. Various implementations of deep structure have been suggested (Wilks, 1977). Schank (1973) claims that "any two utterances that can be said to mean the same thing...should be characterized in only one way in the conceptual (deep) structures." Implicit in this claim is the notion that any idea which can be expressed in any language can be characterized by its unique deep structure. However, the developers of the Eurotra translation system (King, 1979) have found it necessary to use a different deep structure for each language included in the translation system.

Natural Language in Database Management. It is very important that the data management system for the space station be planned in the very beginning stages of station design, and not instituted as an afterthought. According to Smith et al. (1982), NASA should consider developing a computer simulation and data management system for satellites, to be implemented end-to-end, i.e. from the original mission definition, through spacecraft design, manufacture, test, integration, launch, on-orbit checkout, nominal operations, spacecraft modifications, and fault diagnosis and handling. Such a system would enhance communication between mission supervisors and reduce documentation costs. Important objectives are that each individual should have access to all the data, and that paper should become secondary to the computer as a communication medium.

In addition, Brown and Cheeseman (1983) note that "an outstanding opportunity, perhaps a necessity, exists for the application of computer-aided engineering to the space station. The knowledge base that is now beginning to grow with the Space Station Task Force and the concept studies being conducted by the aerospace industry needs to become part of the space station knowledge base that will be used throughout its lifetime, from original concept to perpetual maintenance. As such, it must be guided not only by the essential standards for compatibility, such as standard character codes, but also by the principles of knowledge base construction that are being discovered, tested, and formulated in the course of research in artificial intelligence. Many databases that have been or are being developed for non-AI applications can be incorporated in AI systems without difficulty (parts lists, for example). However, when knowledge (e.g., decision rules) is the basis for decisions that may require explanation or modification, such knowledge must be represented in a way that will facilitate the needed explanation or modification. If this is done for databases connected with the space station, a good foundation will then have been created for other station subsystems that will utilize the original space station knowledge base and embody artificial intelligence."

Brown and Cheeseman further recommend that an "early application of artificial intelligence will guide the development of the space station databases to make them more compatible with AI techniques, as well as providing an opportunity to test and verify databases. AI should be introduced into the design of the space station on a selective basis at first, but eventually with a sufficiently broad scope to encompass the entire knowledge base. All database development for the space station, including IPAD databases, should be planned for eventual operation with AI systems. The management of the space station project, in both its development and its implementation, should be supported by an expert planning system."

In the broadest sense, data management can be used to include all of the elements involved in the processes of data collection, definition of data storage organization, storage, communication, and eventual dissemination. However, current usage in computer science has narrowed the definition to focus on the computer-based processes that store, organize, and access discrete data items.

Computer-stored data can be kept in an organized structure known as a "database." Most databases are "preformatted" in that both their logical and physical organization are defined before any data is stored within them. In larger computer installations, a single person (the database administrator) is responsible for the definition of the structures of the databases in use. Because it is difficult to foresee exactly how all the items in a database are going to be used, preformatted databases may become inefficient or unwieldy. For this reason, additional research is needed on self-organizing databases.

Databases are often imbedded within a database management system (DBMS). The general purpose of a DBMS is to provide an interface between the user's environment and the structure holding the contents of the database. Numerous DBMSs have been developed using a wide variety of different ways of relating individual data items to each other. Probably the most popular current DBMS is IBM's "IMS" which stores data in a tree-like hierarchical data structure (Figure 4.1(B)).

Current thinking among workers in the database area is that a relational or set-theoretic view of data organization (Figure 4.1(C)) is superior. Several DBMSs claimed to be relational have been developed, though not all can properly be labelled as relational. Relational DBMSs range from those requiring a large mainframe computer (e.g., R*) to those that can fit on a microcomputer (e.g., dBase II). None has yet achieved market dominance.

Access to the material stored in a database is usually achieved through a query statement programming language which acts as a bridge between the application program environment and the environment provided by the DBMS. Sometimes query languages can only be used to access or manipulate data stored in the database. In other cases the database query language can be included within a general purpose language. For example, DL/1 is the query language for IBM's IMS database management system. DL/1 can be imbedded within PL/1, COBOL, and assembler. Other DBMS query language statements cannot be included in another programming language. The advantage of including a DBMS query language within another programming language is that the query language need only assume the burden of database access and can leave all other data manipulation and reporting functions to the host language. The advantage in having a separate, special purpose query language is primarily efficiency, at the cost of decreased flexibility.

In the environment of a space station, it is inefficient to require astronauts to write their own programs to access a particular item in an onboard database. It is better to allow natural language access. To accomplish this, either the DBMS package must provide natural language capability or else a natural language interface must be provided between the human user and the programming language used to access the database. In either case, the analysis of a natural language query statement is much the same. A separate interface has the distinct advantages of (1) being more flexible by accommodating the use of a variety of different database management systems, and (2) the problems of database development and natural language understanding are kept separate and thus do not complicate each other.

There are five important advantages in using a natural language as a database access language: (1) A large number of potential computer users are unwilling or unable to learn and use formal computer languages; (2) for at least some applications, natural language provides the ideal communication medium (Grishman and Hirschman, 1978); (3) potential users already know their natural language so little training in its use as a query language is needed; (4) natural languages are powerful tools for the expression of certain non-mathematical ideas and concepts -- it is unlikely that formal languages can be developed that express these ideas as well as natural languages can; and (5) the immediacy and flexibility of information retrieval are significantly improved when end users retrieve the data themselves rather than going through an outside technical expert -- regardless of who inputs the request.

The process of converting a natural language query into a programming language statement that can be understood by a computer is essentially one of mapping an informal language, such as English, onto a more formal language, such as DL/1. A comprehensive understanding of the initial natural language statement, while perhaps desirable, may not be necessary. As an example, for the query "HOW MANY DOGS ARE BLACK?" it is not important for the computer to understand the basic nature of dogs.

Whether or not natural language understanding of database queries is necessary to the process of query resolution is a matter of current research. Some investigators (Mazlack and Feinauer, 1982) are concerned with minimal semantic techniques while others (Schank, 1976, 1981; Schank and Burstein, 1982) believe that a rich world model is necessary. Minimal semantic techniques, sometimes called "surface structure methods," attempt to accomplish query resolution without developing human-like cognitive understanding of the query. Deep-structure methods, on the other hand, utilize rich world models and attempt to accomplish query resolution by developing human-like understanding of the query. Surface methods hold the promise of easier implementation and domain portability. Deep-structure adherents admit higher development costs and domain inflexibility with their approach, but maintain that the problem cannot be resolved otherwise. The proper form of the knowledge representation remains an open question in deep structure theory, the dominant approach in the United States. Work is proceeding on both approaches in Europe.

## 4.2 Technology Systems: Task Performance Autonomy

Aside from the locus of monitoring and control intelligence, another monitor/control autonomy issue is the allocation of physical tasks among humans and machines. The most basic such task is environmental sensing (section 4.2.1), a function best left largely to machines. However, the interpretation and utilization of sensed information is a principal research area restricting space station machine autonomy and requiring significant human participation.

The human-machine interface is another major technology area critical to the implementation of effective monitoring and control in space station automation (Montemerlo and Cron, 1982). Much information is already available and the development of good interfaces will involve the application of existing human factors data. Displays (section 4.2.2) and controls (section 4.2.3) are the primary human-machine interfaces which will be employed on the space station.

A complex network of linked microcomputers and parallel data buses supports and sustains space station monitor/control autonomy (section 4.2.4). Station controllers -- microprocessor-based digital computers -- are responsible for maintaining the environment within a stringent set of tolerances, distributing power to devices based on equipment need and power system potential, monitoring adjacent space, and maintaining a fleet of manned and unmanned platforms. Network buses allow access to data by any controlling computer, making possible automatic self-correction by individual failed controllers. A multi-computer-based network with multi-accessible channels and modules for distributed controls, interactive supervisor consoles, and automatic ground communications, provides a "nervous system" for the intelligent space station.

### 4.2.1 Sensor Technologies for Space Operations

Systems gain information about their environment via sensing. Human beings typically rely upon vision, hearing, touch, taste, and smell. These senses provide us with information necessary for the mechanical control of our surroundings. The capacities and limitations of man's senses are compiled in von Tiesenhausen (1982). Mechanical sensing amplifies and augments human senses and enhances machine capabilities. The design of appropriate sensors is thus a key part of space robotics and telepresence system development.

Sensors respond to physical stimulus and transmit a signal containing information about the stimulus to a controller or operator. The most direct approach is to implement the five human senses, in hardware. There are two aspects to this problem -- (1) detection and (2) intelligent integration and interpretation.

For detection, current technology already exceeds human capabilities in vision and hearing. Force and torque sensors are currently available, and progress has been made on tactile sensors (to measure slip and pressure distribution) although these are not yet commercially available. No true olfactory sensors exist, although some sensors can detect the presence of certain gases. Odor detection has potential for early warning of leaking gases or liquids on the space station, but, in general, smell is not as important as vision, hearing, and touch for overall effectiveness. Taste sensing has little relevance to currently projected activities. Thus, the machine implementation of the five human senses is not a central problem. Rather, the interpretation and utilization of sensed information is the principal research area restricting space station task performance autonomy.

Additionally, in robotics and telepresence system design many "senses" not known to be possessed by humans are available, such as particle radiation detection, infrared wavelength imaging, relative motion/ranging, and electric/magnetic field sensing. Robots and teleoperators can potentially surpass the human capability to sense the physical parameters of the world around them. Sensor technology allows tasks (normally requiring the presence of humans in space) either to be performed from the ground or to be fully automated. Sensing plus appropriate interpretation permits the extension of human capabilities to the performance of tasks that would otherwise not be possible.

For example, radar uses millimeter wavelength electromagnetic radiation to find and identify cooperative (capable of emitting or amplifying a signal) and non-cooperative targets. The angular resolution of radar becomes very poor within 200 meters of a target. Accurate long-range docking information can be obtained using radar similar to the shuttle Ku-band system. Technologies developed by the FAA for air-to-air collision avoidance might prove useful on the space station to warn of impending impacts with large nearby objects or local debris. Unfortunately, state-of-the-art radar systems remain highly classified because of their military applications.

Proximity sensors are short-range devices to determine nearness to a designated target. A proximity sensor for the shuttle Remote Maneuvering System (RMS) grapple has been developed and tested (Albus, 1979; Bejczy, 1980). The information returned by such a sensor is useful in telepresence and robotics applications, especially in obscured-vision environments.

Laser radar (lidar) employs a laser to determine the position, velocity, orientation and identification of passive cooperative targets. Such targets do not actively respond to the laser radiation, but have retroreflectors at strategic locations to reflect radiation back to a detector near the laser source. Laser ranging offers accuracies beyond the capability of any other technology. Systems have been developed to align large space structures and the technology is potentially useful for automated docking systems.

Spacecraft orbital position and velocity are determined by onboard navigation systems, ground tracking, and other external reference systems such as the NAVSTAR Global Positioning System (GPS). GPS is a passive navigation satellite system proposed for operation after 1985 using highly accurate atomic frequency standards to determine three-dimensional position, velocity, and time on a continuous worldwide basis. NAVSTAR will be useful in collision-avoidance, rendezvous and docking, navigation, survey and mapping, aircraft landing, and many other applications. For instance, the system offers 10-meter absolute position accuracy and 2-meter relative position error between two receivers employed for collision avoidance (Logsdon, 1982; Fell, 1980).

Laser optical scanners are commonly used in grocery stores to read identification codes on

products at the checkout register. A similar system could allow easy identification of space station components to facilitate inventory management or automated parts recognition, and would be inexpensive and easy to implement. Recognition codes should be provided on all spacecraft and space station parts and supplies to enable future implementation of this technology. Even if a decision is made not to use optical scanners in the near-term, there is little harm or cost in requiring unused recognition codes on all equipment.

Force and torque sensing permit the control of physical loads applied to objects. This information can be passed directly to a telepresence operator or used by autonomous control systems to ensure accurate force application so that structural and operational limits are not exceeded. Force and torque sensing is a mature technology requiring little further development. Force levels can be measured by strain gauges or by electrical current in the actuator motor applying the force. Torque sensors incorporate geometrically-aligned strain gauges. For space use, fiberoptic strain and current sensors are less sensitive to thermal distortion and electromagnetic interference (Thiel and Kurtzman, 1983).

Tactile sensors provide texture information. Two basic types of tactile sensors, touch sensors and slip sensors, have been developed (Bejczy, 1980). Touch sensors are multipoint proportional detectors with a pressure-conductive plastic grid pattern to sense force distribution. Slip sensors use a rolling sphere to measure omni-directional slippage and its direction and rate. Slip information is useful in teleoperation and robotics applications where end-effectors may lose traction with manipulated objects. Present touch and slip sensor systems are in breadboard form only, with data displayed on TV monitors. No method has yet been devised to permit direct tactile communication with human operators.

Optical imaging sensors such as video cameras are critical for operations in space. Small black-and-white cameras have been developed and space-qualified for use on pressure-suit helmets during EVA. A color video system could provide valuable cues for remote viewers to aid in scene recognition and understanding (Thiel and Kurtzman, 1983), and small lightweight CCD color cameras are under development. Images from two video cameras can be coordinated to give stereo capability, and wide-angle and zoom cameras would also be beneficial. Optical sensors will exceed human visual resolution and field of view, and future sensor requirements will be driven more by machine than by human vision needs (Thiel and Kurtzman, 1983).

Infrared imaging sensors utilize thermography to obtain thermal profiles of a structure to evaluate its thermal behavior. Thermography has been used to study the space shuttle upon reentry, and a temperature profile accurate to within 10-20 $^{o}$K was obtained (O'Lone, 1982). In one existing system, an infrared scanner signal is processed and supplied to a standard black-and-white TV monitor in an aircraft cockpit where a real-time high-resolution image is displayed. Such a system can be used for search and rescue, security surveillance, power line and substation inspection, forest fire control, pipeline control, and in various agricultural applications (Scott, 1982). Thermal imaging may also be useful to evaluate structural characteristics in stress contour and crack development studies (Mountain and Webber, 1978).

Acoustic sensors measure sound frequency and intensity. These can be used inside the space station to monitor crew activity and as an input channel for a voice-activated control system. For example, acoustic sensors placed in a module could sense a human presence and adjust the lighting conditions automatically. These sensors are also useful in testing for structural failure. Acoustic signals are passed through a structure and the response is recorded. Any large deviations from normal response may indicate flaws or failures in the structure.

### 4.2.2 Space Station Displays

The primary purpose of a display is to communicate or to convey information. Planners must make an informed selection of displays (and controls) likely to be involved in space station activities such as EVA, supervisory control of ECLSS, or telepresence. Many existing displays are not operator-optimal, but may be improved by (1) knowing what information is needed, (2) ensuring quality and appropriate coding of information presented, and (3) providing an appropriate spatial and temporal configuration of the information within the display (Montemerlo and Cron, 1982).

Two basic principles should be kept in mind in the development of space station displays. First, displays should be standardized as to how and where information is to be presented. Second, proper displays require stimulus-response compatibility, also known as display-control compatibility, display control movement expectancies, or population stereotypes. This refers to the expected relationships between display movement and the movement of a control (Brainerd _et al._, 1962; Fitts and Seeger, 1953; Greenwald, 1970; Kantowitz and Sorkin, 1983; Woodson, 1981; McCormick and Sanders, 1982; Chapanis, 1972). There should also be compatibility between two displays which present the same information. The observance of these principles in the design and implementation of display (and control) systems greatly reduces operator error. Indeed, the current military human-engineering standard (DOD, 1981) regards them as general requirements.

_Selection of Sensory Mode._ One of the first steps in deciding how to display information is to determine the appropriate sensory channel, whether visual, auditory, or tactile. Visual systems are good at imparting spatial information -- it is very easy to locate an object in space using vision, and large arrays can be presented to the operator and assimilated as long as instruments are positioned together (as in an airplane cockpit or a workstation). The auditory system does not convey spatial information as well. Visual maps are easier to use than verbal directions, and it is more difficult to localize objects in space acoustically. However, the human auditory system provides a better temporal sense than vision -- the ear can discriminate audio events separated by only 3 milliseconds, compared to 30 milliseconds for the eye. The tactile system, though little used as a channel of communication except in special circumstances, lies somewhere between visual and auditory systems in both spatial and temporal information processing. For example, the tactile system, while not as good as vision in processing spatial information, is generally better than the auditory system (Geldard, 1968), and the minimum

dermal response time is about 10 milliseconds. There exists a wealth of tabular information on the capabilities and limitations of human sensory systems (Van Cott and Kinkade, 1972; Huchingson, 1981; von Tiesenhausen, 1982).

Each sensory system has certain advantages. For instance, if an operator is required to move around a control room, a space station, or a ground station in order to monitor several control panels, the auditory system has some advantages over the visual -- a flashing light might go unobserved but a bell or synthesized speech signal would be likely to alert the operator to a potentially hazardous situation. Both the task and the conditions under which the human is operating must be examined with care before a sensory channel for display can be selected. In the space station environment, visual and auditory displays are preferable.

Speed and Load in Displays. Speed refers to the rate at which displayed information is changing. As the rate of information presentation rises, operator speed stress increases (McCormick and Sanders, 1982; Reason, 1974). Load refers to the number of channels of information the operator must monitor. The greater the load, the greater the load stress. Several steps may be taken to reduce the effects of speed and load stress on station operators. One example is a supervisory control system to reduce operator workload. This would monitor the state of a particular system, take corrective actions, and call on the operator only when the supervisory system had exhausted its repertoire of corrective actions for a particular problem. Prioritization of speech signals is another way to reduce speed and load stresses, particularly in the auditory channel.

The major roles of space station operators will be monitoring, decisionmaking, and management (Montemerlo and Cron, 1982). Thus the design of the human-machine interface is crucial to station effectiveness and success (Brown et al., 1983; Card, Moran, and Newell, 1983; UCSD, 1983; Smith and Aucella, 1983). Guidelines governing productive, non-stressful, and user-friendly human-computer interactions need to be identified and applied in the early phases of space station design.

A related consideration is the problem of mental workload (Chiles and Alluisi, 1979; Moray, 1979; Ogden et al., 1979; Williges and Wierwille, 1979; Wierwille, 1979). There is no universally accepted definition or metric of workload, a theoretical concept closely related to operator stress and effort. Chiles and Alluisi (1979) use the term to refer to the combination of occupational demands for action imposed on the human operator.

However, operational definitions based on workload measurement are more common. Quantification of workload has been based on behavioral (Williges and Wierwille, 1979) and physiological (Wierwille, 1979) measures. Behavioral measures typically include subjective opinions (rating scales, interviews, questionnaires), spare mental capacity (the secondary task technique), and primary task considerations (single measures of primary task performance). Wierwille (1979) reviews a large number of physiological measures of workload, among which the most promising are pupil dilation, evoked cortical potentials (event related potentials), and body fluid analysis. Considerable work remains to be done in order to find an acceptable definition of workload and a metric or set of measures that adequately reflect mental workload. Further research is needed to accurately determine crew workload in zero-g and to establish criteria for acceptable workloads as a function of time and stress. The benefits of such research include improved crew performance and avoiding loss of flight objectives.

Visual Displays. There are four basic types of visual displays: (1) Numerical or quantitative information displays; (2) qualitative or status-reading displays; (3) setting or feedback displays (a value is entered via a control which then appears on the display); and (4) tracking displays, which present directional or command information. Tracking displays, the most versatile of these, require users to keep two indicators aligned (Adams, 1967).

Tracking displays may be pursuit or compensatory. Pursuit tracking displays usually have two indicators which must be kept aligned -- the input or "target," and the output or "follower." The operator's task is to align follower and target. Compensatory tracking displays use a fixed reference marker plus an error marker which displays the error or difference between target and follower.

Pursuit displays provide knowledge-of-results (KR) (i.e., when the operator manipulates a control, the effects on the follower are immediately observed) and facilitate prediction of target movements. Compensatory systems indicate magnitude of deviation, not which marker has moved, so KR and predictability are lost under most conditions. However, compensatory displays are physically more compact and easily fit into an aircraft cockpit instrument panel, whereas a good pursuit display may not. It is expected that instrument panel space will be at a premimum on the space station. While a pursuit display almost always allows better tracking task performance than a compensatory display, compensatory systems do as well for slow (up to 2 Hz) and predictable (e.g., sinusoidal) target motions. Johnson and Roscoe (1972), following the work of Senders and Cruzen (1952), show that hybrid pursuit and compensatory displays combine the advantages of both -- for instance, by allowing the fixed reference marker a small amount of movement.

Symbolic and Pictorial Displays. Displays which provide continuously changing information (e.g., velocity or orientation) and those which present discrete information (e.g., warning signals) can be divided into symbolic and pictorial systems.

Symbolic displays provide abstract information, usually alphanumeric, and are the standard instruments found in aircraft, automobiles, and nuclear power plants. There are three main types of symbolic displays: Counters, providing a fast accurate reading of basically slow-changing information; and circular and linear displays, with fixed scales and moving pointers or fixed pointers and moving scales, used to indicate temperature, pressure, power, or other variables which require a numerical value and some indication of the direction of change. Circular and linear displays present both quantitative and qualitative information, and operators have certain expectancies. For example, a variable such as altitude or cabin

pressure usually increases when the pointer moves in the clockwise direction, but the relationship is reversed for the fixed-pointer/moving-scale arrangement. Space station symbolic displays should include counters along with fixed-scale/moving-pointer displays when non-pictorial information is required.

Pictorial displays are a more recent development. These take advantage of past perceptual learning to present a pictorial model, analog, or representation of the real world, while at the same time integrating several display functions or data types into one consolidated system. Pictorial displays have been used in aircraft and in submarines, and fall into one of three classes: (1) Horizontal, situational, or downward-looking; (2) vertical or forward-looking; and (3) sideways-looking.

Horizontal displays create a pictorial representation of the physical position of a vehicle operating in three dimensions, projected onto a horizontal plane beneath it (e.g., a "downward" view). A good example is the map-type display, which integrates in a single exhibit information from the magnetic compass, the course selector dial and the directional gyro. This system has been used for flight navigation and successfully reduces navigational errors near air terminals (Roscoe, 1968).

Vertical pictorial displays are used in flight control to monitor forward translation and attitude of aircraft and spacecraft. A good example is the computer-aided contact analog display, which depends upon past perceptual learning and attempts to present a model or analog of the real world. The contact analog displays either command information telling the operator how to move a control or what to do, or error information showing deviation from a prescribed path.

Sideways-looking displays involve a projection onto a vertical plane parallel to a vehicle's position or flight path, often with the basic dimensions of elevation or altitude vs. range or speed. Pictorial integrated displays could be useful on the space station for monitoring orbital position, representing the station relative to a fleet of space platforms, for fleet management, for monitoring the position of the station relative to Earth, and in telepresence operations.

Head-Up, Historical and Predictive Displays. The head-up display (HUD) was originally developed for low-altitude high-speed flight or nap-of-the-earth flying. It usually consists of a partially silvered mirror placed between the observer and objects in the field of view. Information is presented by reflection from a CRT or fiberoptic bundle source using collimated light. By employing collimated light, the observer, when focusing on the information, is essentially focusing at infinity, thereby allowing a more relaxed visual accommodation. The observer can read or resolve and process the information presented on the HUD, but also can focus on targets well out in front without having to shift fixation and accommodation. A helmet-mounted head-up display could present data on pressure suit visors, permitting information to be transmitted to space station astronauts during EVA.

Historical displays provide a chronology or audit trail of past conditions or values of a particular variable over time. A strip chart recorder is one example (Kantowitz and Sorkin, 1983). A more useful historical display for the space station is a CRT showing data stored in the computer concerning the past behavior of a control variable -- especially helpful in implementing adaptive features in a computer-controlled system.

Predictive displays, usually associated with control, are useful in telepresence operations (Thiel and Kurtzman, 1983). One form of predictor display extrapolates the condition of a particular variable into the future, given that no further control movements are made or that the control is returned to a neutral position. Recent advances in computer-aided modeling show that predictive displays are potentially useful in eliminating many telepresence limitations imposed by time delays.

Location and Patterning of Displays. The location, arrangement and patterning of displays also is significant. Displays are best positioned according to the sequence of their use in performing a certain function. Link analysis (Woodson, 1981) can determine optimal display arrangements. Link analysis is a human factors technique used to assist in redesigning displays, their layout, and the layout of controls and other equipment. Numerical values are assigned to links between devices based on relative frequency of binary interaction, frequency of intercommuniciation, and the relative importance of inter-element links. Displays can also be grouped by function so that within-function tasks can be handled more easily. Another arrangement is simply to locate the more important displays in the center of the visual field and the less important ones peripherally. When the importance of a display is not relevant, the frequency of use becomes the primary criterion for a central location within the field of view (Kantowitz and Sorkin, 1983).

When a large number of displays must be monitored simultaneously for nominal check reading, the dials may be patterned to facilitate the detection of an abnormal reading (McCormick and Sanders, 1982). For example, pointer positions can be oriented to form symmetrical patterns, or the pointers on dials could be oriented in the same direction to indicate normal status. Human operators aboard the space station may have to monitor many different systems such as the ECLSS, so display patterning for check reading is advisable.

Display Technology for the Space Station. The primary human-machine interface on the space station will most likely be a high-resolution CRT or flat-panel videoscreen capable of displaying alphanumeric and graphic information. This interface must also be able to present a computer graphic display of gauges for monitoring, have addressable pages for process control systems, and use map- and tracking-type displays for navigation and fleet management (assuming there are free-flying platforms near the station). Television displays could be used to augment station-to-ground and EVA communications. For teleoperator manipulation, a television-type display with the capability of superimposing computer graphics could be used to aid satellite servicing and other tasks. In all cases, and particularly where form perception, depth discrimination, and coding is important, videoscreen color should be employed. Displays and controls should be augmented with predictor and quickening (display augmentation using control

signal feedback) attributes. The general integration of display information is compatible with the implementation both of supervisory control of telepresence and of supervisory process control.

A second application for display technology is the use of auditory (Van Cott and Kinkade, 1972) and visual alarms and warning signals associated with various monitoring tasks in space station operations. Alarms or annuciator systems will also be employed in conjunction with supervisory process control to alert operators to important changes in system status. Annunciators may include horns, graphic fascia and panels, position switches, CRT graphics and alarm tables, and alarm printers (Kragt, 1982). The most common and simplest of auditory displays are alarms with an attention-getting quality and that provide a brief and concise message while alerting the operator regardless of his exact location. Detection by human operators is maximized using combined auditory and visual signals (Colquhoun, 1975), and also by forcing the operator to take action to terminate the warning (one function of acknowledgment in annunciator systems).

The selection of auditory signals should conform to prior learning and conventions. The principle of compatibility also applies to the encoding of auditory signals (McCormick, 1976; Huchingson, 1981). For instance, wailing sirens are associated with emergencies and thus should not be used to signal non-emergency events. Other principles of auditory display selection are relevant to the development and operation of an annunciator system for space station supervisory process control, including: (1) Approximation (using one signal to alert the operator to more specific information to follow); (2) dissociability (using auditory signals easily distinguished from background sounds); (3) parsimony (minimizing the number of distinct auditory signals); and (4) invariance (standardized signal meanings). Nuclear power plants are replete with nuisance alarms, and newer aircraft employ an excessive number of alerting and voice signals. Greater specificity in alarms is needed on the space station, and this might be achieved by the use of speech or voice signals if these are limited and prioritized so as not to overload or confuse the operator (Cooper, 1977).

Speech synthesis provides an additional and powerful means of displaying information, and allows differentiation of vocal signals by changing speech characteristics such as frequency and by the use of male and female voices. Speech synthesizers have only recently overcome serious limitations in reliability, cost, and voice quality. Their use is increasing rapidly -- typical consumer and commercial systems now available include Chrysler's Electronic Voice Alert, the Speak-and-Spell educational toy from Texas Instruments, and aircraft cockpit voice warning systems mandated by the FAA. Most speech synthesizers model the excitation and resonance characteristics of human vocal tract physiology (Michaelis and Wiggins, 1981, 1982). There are several techniques for producing synthetic speech, each with its own advantages and limitations. Two of the most commonly used methods are linear predictive coding (LPC) and phoneme speech synthesis (PSS). The LPC synthesizer uses an analysis/synthesis format and provides a good quality of synthetic speech but is limited in vocabulary, whereas the PSS synthesizer uses a synthesis-by-rule format and has an unlimited vocabulary but poorer voice quality. Speech warning signals in which intelligibility is paramount, as in a noisy space station environment (Chambers, 1983), should probably be produced by an LPC synthesizer. Intelligibility can be estimated using short-cut techniques such as the articulation index (Chapanis, 1959; McCormick and Sanders, 1983). PSS is better for prolonged interactions with a computer where a large vocabulary is necessary.

What are the relevant decision rules for using visual or auditory displays? Michaelis and Wiggins (1982) suggest a number of guidelines directly applicable in space station planning. Specifically, visual output should be employed when the message: (1) is complex, contains technical or scientific terms, or uses terms with which the user might not be familiar; (2) is long; (3) needs to be referred to later; (4) deals with spatial orientation or the location of points in space; (5) lacks urgency; and also when (6) the auditory channels are overloaded with messages, signals, or sounds to which the user must pay attention; (7) the auditory environment is too noisy; (8) the user may remain in the same position to view displayed messages; and (9) system output consists of many different kinds of information which must be displayed simultaneously, monitored, and acted upon by the operator. Michaelis and Wiggins recommend synthesized speech when the message: (1) is simple; (2) is short; (3) does not have to be referred to at a later time; (4) deals with events in time; (5) requires an immediate response (e.g., a warning signal); and when (6) the visual channel of communciation is overloaded; (7) the environment is unsuitable for the transmission of visual information; (8) the operator must be free to move around; or (9) the operator may be subject to high G-forces or anoxia which can affect the visual reception of information before it affects the auditory system.

### 4.2.3 Space Station Controls

Controls facilitate communication between people and machines and enable execution of human commands and goals. Controls are of two main classes -- discrete controls (on-off controls such as push buttons or toggles, and position controls such as TV channel selector dials); and continuous controls (such as the volume knob on an FM tuner). Kantowitz and Sorkin (1983) suggest that discrete controls are preferred to continuous controls when: (1) there is a limited number (say, less than 25) of control states; (2) numerical, alphabetical, on-off or yes-no information is needed; or (3) only small mechanical forces are required or available. Continuous controls are recommended whenever: (1) there is a large number of control states; (2) the operator must exert substantial force; or (3) speed of operation is more important than accuracy of control setting.

Controls can also be classified as linear or rotary. Linear controls move in a straight line (e.g., pushbutton, toggle switches, and slides) while rotary controls move in an arc (e.g., telephone dials, volume and tuner controls, and door knobs). There is no well-established basis for choosing between linear and rotary controls.

<u>Design Considerations for Controls.</u> Human factors design considerations applicable to standard controls must be taken into account in the development of any complex human-machine system such as a manned space station. These considerations

should aid in the reduction of operator error. For instance, in each case the appropriate control/display (C/D) ratio must be selected -- the amount of control displacement relative to the amount of display movement. A high ratio means that a large control motion produces a relatively small movement of the display element. High C/D ratios are good for fine adjustments while low C/D ratios give short travel times. Jenkins and Conner (1949) found that there is an optimum C/D ratio for each control-display combination which usually must be determined empirically for each combination of display and control. However, Buck (1980) shows that movement time also depends on target size when C/D ratio is held constant. Human factors evaluation is recommended for determining important space station control-display relationships.

To reduce operator error, especially reversal errors, control-display compatibility or expectancies must be observed. Reversal errors occur when a control is moved in the opposite direction from what is intended. (E.g., one would expect a control lever to be moved down to lower aircraft landing gear and moved up to retract it.) Movements of the part and the function of the part being controlled must taken into consideration from the point of view of the operator's expectancies.

For example, Huchingson (1981) reports that the control for sweeping back the wings of the F-111 (to provide a high-speed flight configuration) did not initially meet pilots' expectancies. The control was designed so that its forward movement resulted in a swept back configuration leading to higher vehicle speed; pulling back on the control led to a more swept forward wing configuration and a slower airspeed. However, the pilot expectancy was that moving the control backwards would sweep the wings back, and vice versa. The control was changed to conform to the pilot's expectancies of the movement of the part rather than to the nature of its function.

Controls should be spaced far enough apart to prevent, or at least severely limit, the possibility of accidental activation of another control. Adherence to the principles of anthropometric design in the work station (i.e., those factors which take into account static and dynamic measurements of the dimensions of the body) should reduce this possibility.

Substitution errors can also result in the manipulation of the incorrect control. These errors can be reduced by proper coding. For instance, the shape of a control can be coded, often in the form of its actual purpose. If the operator reaches out blindly or quickly, the correct one will be located by touch. Other methods of coding include color, texture, size, placement, and labeling.

There will be controls on the space station which are to be used only under emergency conditions or whose accidental activation might lead to damage, injury, or to the degradation of station functions. To prevent this, some controls may be recessed, provided with a cover, guard, or interlock device, resist movement, or require a lock to prevent the control from passing through a critical position without a time delay. As with displays, controls intended to be activated in sequence or which operate together should be grouped together. The most important and frequently used controls should have the favored positions (e.g., the joystick on an aircraft).

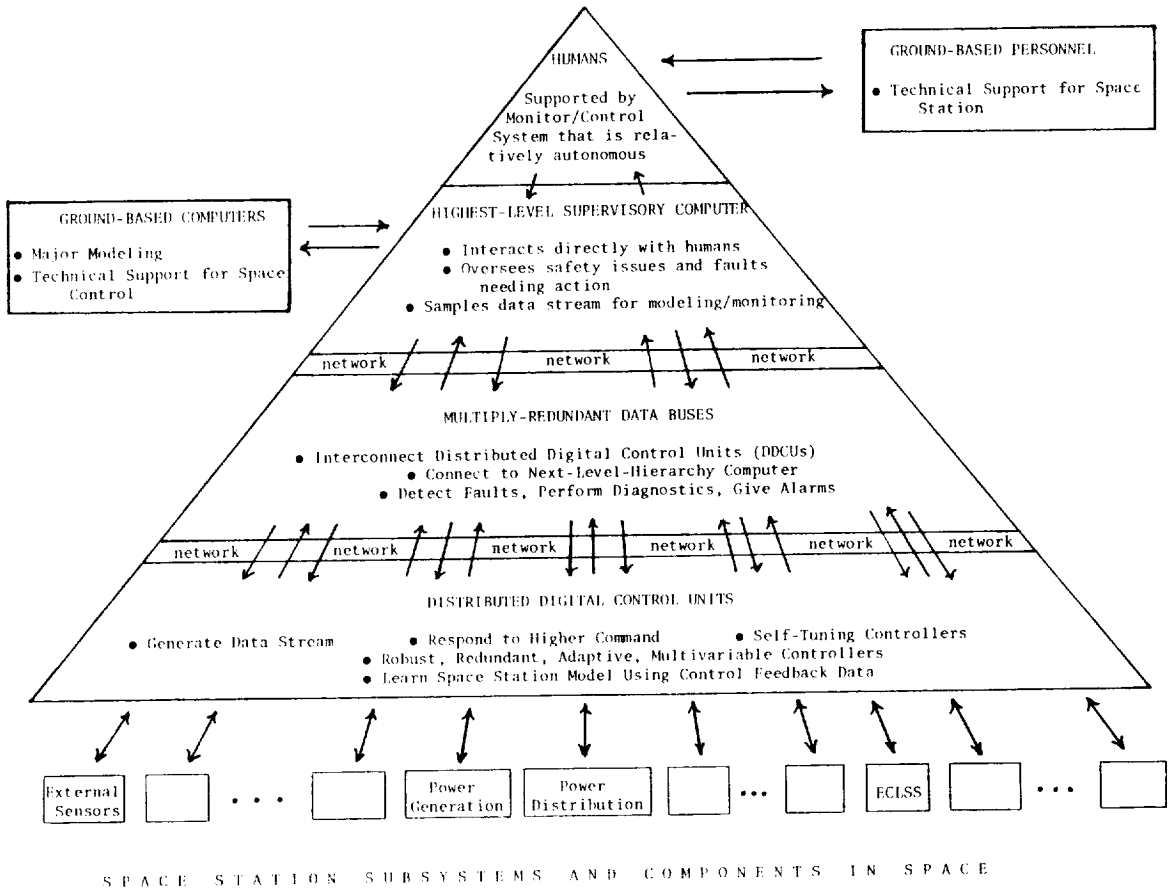
Control Technology for the Space Station. The principal interface between human operators and the space station will most likely be a videoscreen, and the primary channels for data entry will be touchscreens, QWERTY keyboards (Kantowitz and Sorkin, 1983; NRC, 1983) and joystick/mouse pointers, in the near-term. Track ball positioning devices embedded in workstation desktops may be advantageous in a zero-g environment, and data tablets are handy for manipulating graphics displays. The use of a menu select system could help reduce the number of discrete controls (and displays) on the space station (Montemerlo and Cron, 1982), but a high degree of robustness is essential to maintain user confidence.

An unusual but promising future control technology is biocybernetics, the use of electrical potentials from the human brain. This technique is still in the initial stages of development and much work remains to be done before direct brain control of machines becomes a viable alternative (Vidal et al., 1976; Hickman, 1977; Thompson and Teyler, 1972). Considerable research has been conducted by Wickens and Donchin and their associates at the University of Illinois on ERP -- Event-Related Potentials (Donchin, 1975; Donchin et al., 1978; Donchin, 1979; Isreal et al., 1979; Wickens et al., 1980; Wickens, 1980). The ERP is the brain's neural response to discrete environmental and cognitive events, consisting of a transient series of positive and negative-going voltages. It has been suggested that direct brain control of devices might take place by having a person look at one of a number of flashing light patterns which would then produce characteristic ERP brain waves and lead to the operation or activation of a particular device (Becker, 1983).

Speech recognition or voice entry is another way to enter data and to control such devices as the MMU (Manned Manuevering Unit). Speech systems recognize acoustical wave patterns as specific words in a language (Huchingson, 1981; Seifert and Bubb, 1982; Ford and Shirk, 1981; Welch, 1977; Davies and Peckham, 1980). Voice recognition can be combined with speech synthesis to interrogate a computer and receive feedback (Slivinski and Givens, 1983).

There are two major speech recognition systems -- isolated (discrete) and continuous (connected) speech recognition. Isolated systems require a short pause before and after an utterance, whereas continuous systems recognize words or phrases run together as in natural speech. Both are affected by background noise which may hinder use on the space station, and both employ template matching to recognize speech. Continuous recognition is more expensive because more data comparison is required to know where words begin and end, and because of greater acoustic variation in connected as compared to isolated speech (Petry, 1983). For purposes such as controlling the MMU, teleoperators, or space station computers, an isolated recognition system is more feasible and cost-effective. While existing systems sometimes have difficulty recognizing voice-entry commands given during high-acceleration aircraft maneuvers (Montague, 1977; Curran, 1970; VanBronkhorst and Abraczinskas, 1982), this should not be a problem on the space station unless there are unforeseen changes in vocal patterns during long stays in orbit. Other problems with voice entry include slow input rate (particularly when using isolated speech systems), erroneous recognition, and the potential for inadvertent activation.

**FIGURE 4.2. SPACE STATION MONITORING AND CONTROL ARCHITECTURE: HIERARCHY OF INTELLIGENT MONITOR AND CONTROL SYSTEMS**




Wickens et al. (1983) finds that the best performance and the least interference with a simulated flight task are obtained when a spatial task (target acquisition) is displayed visually and responded to manually and when the verbal task (memory) is displayed auditorily and responded to with speech. Based on these results, Wickens suggests that stimulus-response compatibility is greatest when visual tasks are attended manually and verbal tasks answered with speech. These results should be kept in mind when assigning or developing displays and controls to be used on the space station. For example, the best response to some auditory signals from the computer such as alarm speech signals might be voice entry, while in other situations involving visual input of a spatial nature (e.g., location of a fault in a process control system) a manual keyboard or touch panel response might yield better results.

The MMU represents another opportunity to apply human factors to space station control systems. The MMU may play an important role in EVA assembly (Howard, et al., 1982), but control design appears suboptimal. Rotation is controlled by the right hand, translation by the left hand. Carrying a hardware item or a structural component is awkward with both hands thus occupied. A single-handed joystick could control rotation, with voice entry controlling MMU translation, freeing one arm and perhaps even allowing the removal of one of the MMU arm extensions thus reducing the possibility of unintentional activations and collisions. The operator would receive feedback in the form of buzzers or tones during engine operation and voice signals in certain emergency situations (e.g., fuel depletion imminent).

### 4.2.4 Space Station Computer/Controller Network

Substantial computer capability is required to monitor and control a complex space station. To ensure that the computer package chosen by NASA will remain contemporary and adequately supported with the passage of time, station supervisory computers and microprocessor systems should be chosen on the basis of widespread industrial, government and educational installation in addition to their performance characteristics. Commonly available software languages should be employed. NASA alone has insufficient funds to assure prolonged support for specialized computers and languages, thus should not develop new computers or software languages solely for space station applications.

All onboard computers must satisfy reasonable space rating criteria, but aside from the initial

shuttle launch the station environment is reasonably tolerant. To allow for continued station evolution and future advances in computer technology, all installed equipment should be upward compatible and plug interchangeable. The memory capacity of the computer system should be vastly larger than normal initial operational requirements demand.

Evolution in station automation should provide for the possible development of a near-autonomous unit. A multi-computer-based network with multi-accessible channels and modules for distributed controls, interactive supervisor consoles, and automatic ground communications will form the fundamental nervous system for the intelligent space station, using, quite possibly, an existing commercial configuration. The many small computers acting as system controllers or monitors must be able to share data and system conditions with other controllers and be able to gain information about system states and performance levels. This information transfer requires interprocessor communication devices such as buses. There are numerous bus configurations available, each with some desirable attributes. Additional configurations can be formulated from computer science, artificial intelligence research, and software engineering experiences (Appendix 4A).

Computation. System identification and adaptive control techniques will be widely employed in onboard space station systems. These techniques, some of which are common in industry, develop models and manipulate system variables to optimize performance criteria. Methods at the threshold of true learning systems, such as adaptive or self-organizing control, will be commonly employed in conjunction with space station artificial intelligence. Expert systems should be utilized even in the initial operating station, but more advanced AI technologies are required to further elevate station autonomy and effectiveness. Probably the single greatest use of space station computational facilities will be to provide data management -- the process of acquiring, storing, and retrieving specific data items with the aid of a database management system (DBMS). It is expected that little programming will actually be done by people in space.

For ease of both future modification and initial program development, software should be developed and maintained in a high-level programming language exhibiting state-of-the-art software engineering techniques. High-level languages rise above the inner workings of the computer, more closely resemble human thought processes, and are transportable from computer to computer. Current high-level languages that exhibit excellent software engineering principles are Pascal and Ada, and, to a slightly lesser extent, PL/1 and ALGOL. There are other very powerful special-purpose languages such as LISP and APL which may be useful for certain tasks. Of greatest interest are the object-orientated languages LISP, PROLOG and FORTH. However, these languages may yield programs difficult to verify or modify so they should be employed with restraint.

A general question is whether the station should have one large computer or several small computers. Large computers are usually faster, but a group of small computers (of equivalent computational power) is more flexible, more fault tolerant, and more amenable to incremental expansion and evolution. Major concept alterations, such as a change in fundamental design to a non-von-Neumann architecture (Appendix 4A), are more easily accommodated if the computational support can be incrementally modified. Standard commercial software and hardware should be used because of its robustness, shared development cost, trained manpower pool, and available evolutionary "migration paths." Migration paths which allow changes in hardware/software configurations due to improvements in technology or changes in need are commonly supplied by commercial vendors to allow customers to modify their equipment and software without undue hardship.

Station Network Configuration. A system of many small computers/controllers distributed throughout the space station should be superior in speed, cost, and reliability to a system of fewer but larger computers. Larger machines are designed to be faster, but this advantage is eliminated when compared to the capability of many small computers operating in a nearly parallel environment. Further, deploying many small machines may yield a less-expensive total system configuration. Larger machines require more sophisticated internal architecture which multiplies hardware and, eventually, software costs. The use of multiple less-expensive machines is a design philosophy increasingly popular in industry because of the significant cost benefits. Finally, system reliability with many small machines is increased since less-complex and already-proven computers can be employed. Computer chips such as the Intel 432 are small microprocessors with the desired fault-tolerant attributes.

Controllers are envisioned to be microprocessor-based digital computers, more than a hundred of them on the manned platform alone. These will be responsible for sustaining the environment within a stringent set of tolerances, distributing power to devices based on equipment need and power system potential, monitoring adjacent space, and maintaining a fleet of manned and unmanned platforms. Controllers must be robust, adaptive and multivariable, with redundancy, adaptability, reliability and maintainability. The design approach should be to employ equivalent machines in each subsystem application. With uniform computing hardware the specific characteristics of controllers become software-based. Hardware is easily exchanged from less critical to more critical systems in times of need. Controllers should be designed for easy replacement, especially to permit long-term evolutionary development of the station control system.

An individual control unit may be primarily responsible for a single subsystem, a fraction of a subsystem, or multiple subsystems. Subsystem/controller allocation is influenced by controller capability and speed, complexity, controller algorithms, and the magnitude of front-end requirements. Controllers are digital microprocessors with control algorithms, fault-detection and data manipulation software. The software implementation aids in making these controllers replicable modules. For instance, under situations of complete hard module failure, a replacement module could be automatically programmed through downloaded coding via the network bus.

The controlling computers are interfaced to the process/subsystem through network buses, possibly fiberoptic-based (Swingle, 1983). Computer

network buses will permit common access to data by any controller or other device directly or indirectly connected to the network, with the added benefit that individual failure of controllers might be automatically corrected or compensated. A highly integrated fault-tolerant system can be created using multiple sensors, redundant sensor paths and redundant front-end hardware in addition to robust, adaptable controllers or computers. Multiple buses can add fault protection, and should be used. Systems with common speed or data requirements may be connected to a mutual bus. Then, through additional bus controllers, these mutual buses can be networked together. On each bus will be not only the process controller and bus controller, but also those computers whose objective is to supervise the controller's operations. These could test for integrity and faults, service out-of-bounds conditions or alarms, download operation software to backup units, and communicate over the network to functionally higher-level machines.

In the system envisioned here (Figure 4.2), a distributed set of robust controllers governs one or more automatic control loops. Each controller carries a dedicated microprocessor and has at least one backup. Sensory data from throughout the station such as temperature, pressure, fluid flow, electrical current or voltage are used to control elements of the process such as resistance, flow valves, or on/off switches. In addition, some portion of the input is passed to higher levels of the control hierarchy, to viewing consoles, to the supervisory computer for relay to the ground or other members of the space system, and to other controllers as required.

The actual functions, the nature of the elements controlled, and the state of the subsystem determine how high up the hierarchy the sensory data should be relayed. If the operation is between safe limits there is no need for this information to appear at higher levels, but failure in a critical system as the oxygen supply line requires immediate high-level attention. Routine subsystem operation should remain as autonomous as possible, with data remaining at the lowest possible levels of the hierarchy. A monitor/control system which may have application to the space station might be found among the many successful commercial systems in widespread use, particularly in the chemical processing and power industries (Martinovic, 1983).

Desirable characteristics of human-supervised monitor/control systems that are considered state-of-the-art include:

- Multivariable;
- Capable of self-repair;
- Can optimize;
- Self-diagnostic;
- Automatic start-up and shut-down;
- Safety interlocks;
- Emergency manual operation;
- Appropriate human-machine interface; and
- Appropriate alarm protocols.

Robust, adaptive, fault-tolerant feedback control technology is presently available. Self-learning is a feature of autonomous operational systems which must be reserved for the future.

Figure 4.2 illustrates the hierarchical nature of the intelligent monitor and control system with humans at the pinnacle. The data streaming toward higher levels is greatest at the lowest level of the hierarchy. At the topmost level the stream is very narrow and the detailed workings of the lower levels is normally unknown, but knowable if needed. Commands and feedback from higher levels produce an information stream enlarging toward the lower levels. Since the monitor and control system is meant to support humans and not to attract their attention away from their primary duties, its actions will normally lie below human awareness, with station systems functioning "subconsciously" during healthy nominal operation.

Subsystems which are very different by their nature may require separate data highways. For example, flow control information is generated at a very low rate compared to radar information and separate buses may be required for each. Optical fibers are now in widespread use and allow very large data transfer rates. The use of optical fibers in the space station is highly recommended, and is virtually inevitable in future advanced space systems. (Even if not required in the near-term, provision should be made for the eventual installation of optical fibers in the space station at a later time when it becomes necessary.) Signals returned to the controllers from the supervisory computer and from the ground can be used to reconfigure the monitor and control system -- for example, by altering set points or tolerance limits or by adopting new operation points for a replaced item. For station data communication, commercially available hardware and software protocols should be used to create an expandable bus network. NASA should not design its own protocols but should use technology already available in the marketplace.

The decision on precisely which network structures to employ on the space station must be based on the evaluation of many factors. Besides interactive subsystem control, such as the chemical process control plant of the ECLSS, there are subsystem components responsible for fault-detection, diagnosis, and human interfacing. With few exceptions (e.g., space ratings and physical space requirements), most required design features are probably available today in commercial systems. It is anticipated that the digital process control industry may already have all of the most important factors integrated into packages and could offer hardware (not just design philosophy) and viable software ready for space station implementation.

### 4.3 Ground vs. Space: Locale of Control Autonomy

Regarding the locale of control, there are three possibilities. First, control computers could be located primarily in space. This increases locale autonomy of the space station system, but it may also dramatically decrease maintainability. Second, control computers could be located on the ground, which would alleviate the maintainability problem but create a new problem with communication -- any failure in communications could be catastrophic, and the delay time is problematical. Third is a balance between space and ground

-- to select the benefits of both ground and space distributions of monitoring and control systems and tasks.

A summary of representative systems which require monitor and control tasks, along with an interpretation of the nature of the monitor and control normally required, the character of the human-machine interface, and the anticipated control location, are given in Table 4.1. "Continuous" is defined as substantially continuous without any human intervention, while "periodic" may range from seconds to many hours. "Intermittent" indicates non-continuous and non-periodic. It is quite evident that the nature of the required monitoring and control, the character of the human-machine interface, and the control location are quite varied, indicating a tremendously subtle and complex problem requiring significant further study.

### 4.3.1 Ground-Based Functions

Some monitoring and control functions are best performed on the ground. A case in point is space station system modeling.

The initial station monitor/control system

**TABLE 4.1. NATURE OF, INTERFACE CHARACTER OF, AND CONTROL LOCATIONS FOR REPRESENTATIVE SYSTEMS**

| SYSTEM | NATURE OF | | PROPOSED CHARACTER OF MAN-MACHINE INTERFACE | CONTROL LOCATION |
|---|---|---|---|---|
| | MONITORING | CONTROL | | |
| Environmental Control Life Support | Continuous | Continuous | Management by Trouble | Space |
| Fleet Management | Periodic | Intermittent | Human-Directed | Ground with Space Acquiescence |
| Thermal | Continuous | Intermittent | Human-Directed | Ground with Space Acquiescence |
| Traffic | Intermittent | Intermittent | Human-Directed | Space |
| Communications Telemetry Personal | Continuous, Intermittent | | Human-Guided, Management by Trouble | Ground and Space |
| Laboratory | Extremely Variable: Continuous, Periodic, or Intermittent | | Human-Initiated, Human-Directed, or Automated | Space |
| Storage Information | Storage Automated; Retrieval on Demand | | Human-Initiated | Space |
| Primary Computation | Mainframes; Reliability through Hardware Redundancy | | Human-Directed, Human-Guided, Management by Trouble | Ground |
| On-Board Computation | Microprocessors; Parallel Processing | | Human-Initiated, Human-Directed, or Automated | Space |

will have been tested and modeled prior to its flight, but this must necessarily be incomplete since the overall system is essentially unique. In addition, the monitor/control system requires constant updating due to routine maintenance, wear, failure, and replacement of parts, and due to station component reconfiguration and changing objectives. Monitor and control, along with other operational systems, should be continually remodeled in an autonomous fashion from the initial ground testing to long-term operations in space. The model should be programmed in a format which can be automatically updated using the data stream from the test facility. While testing proceeds, the initial model is continuously improved. Once the monitor/control system is deployed on the station, selected space data are used to calibrate revisions. (This assumes the data stream from the original test facility and from space operations are handled in a compatible manner.) As the model of a particular portion of the system becomes sufficiently refined so that it is no longer changing significantly, the data stream can be gradually reduced to a lower level for monitoring. A complete historical record of the station monitor /control system would then be available.

A revised version of the current working model must be periodically transmitted to station supervisory computers. However, on the ground there is greater human support available, computer systems have larger capacity and are less expensive, and the time allotted for model upgrades can be relatively long. The proper locale for this task is the ground. Data processed on the ground can also be used to produce an audit trail for detection of possible systematic fault characteristics and behavior patterns, to update the evolving model.

Primary alarm servicing should be on the ground. When monitored space station parameters diverge from nominal, an alarm should be activated. This alarm could be serviced either by another machine or, at higher levels of urgency or complication, by individuals on the ground. This doesn't require a large crew because of the machine assistance available. Supervisory control permits alarms to be observed by another machine, and decisions or recommendations for decisions put forward by machines. The primary operator consoles would be located on the ground, where labor is cheaper. Large-scale simulations and computer-based expert systems should be situated on the ground because of their large computational and storage requirements.

### 4.3.2 Space-Based Functions

One task probably best left exclusively for space-based control is station stowage and inventory management. Skylab astronauts frequently reported misplacement of stowed items from their original locations. Items removed from one location were sometimes placed into a nearby but different stowage locker by astronauts under pressure of time and without telling anyone. The capability of rapid assessment of additions, deletions and changes in equipment stowage should be provided aboard the station (JSC, 1974).

An onboard computerized stowage and inventory management system, possibly voice-activated, could handle this problem -- an excellent opportunity for human-machine cooperation. A segment of the onboard computer system would be used to establish an initial inventory of each space station item by name, identifying number, and initial location. As an item is taken from its location the removal is noted; when the item is returned to the same or another location, that change too is noted in the computer inventory. The item removed and its initial and final locations must be detected during the usage of the item. There are many possible ways to accomplish these identifications, among them:

1. The astronaut can key in the location and number of the item removed or, preferably, announce its removal to a voice-sensitive audio pickup and give the appropriate number. When the item is returned the astronaut announces the item and its final location. Whenever a lost item is found, the item and location are announced to the computer.

2. Standard bar coding and a door light could be used to determine the removal and return of an item without active astronaut involvement. (In 1984, the Pentagon announced that in the future it will require bar codes on supplies and materiel.)

3. Coding the article into the computer using light pencils located at convenient locations. The item and storage location are both bar-coded.

4. Voice-activated, natural-language-based identification by astronauts whenever parts are removed from storage or are stowed. If the item's location is correctly noted in the computer, then annunciation of its removal site is unneccessary but may serve as a useful redundant check.

The computer inventory should be kept current on the space station where the information is needed quickly.

Data-sampling and conversion, direct digital control, and the actual manipulation of the variables in controlled station systems should also be implemented in space rather than on the ground, together with much of the supervisory control.

### 4.3.3 Shared Ground/Space Monitor and Control Functions

A few monitoring and control tasks are best shared by ground and space controllers. For example, fleet management requires detailed knowledge of relative separations, altitudes, sizes, masses, orbital rates and attitudes of each station component. This information need not be processed rapidly and normally it is of little consequence that tracking is lost over part of an orbit. Since on-orbit time is valuable it appears advantageous to monitor the fleet using a large ground computer.

However, control prerogatives such as station reboost should be initiated from space since the station is most seriously affected by the action. Reboost should not occur while local EVA, teleoperation, or gravity- or contamination-sensitive experiments are in progress; it can be scheduled well in advance and the space station and ground crews notified for concurrence. Manned modules can also maintain direct communication and radar contact with other nearby station components to avoid collisions or to effect rendezvous as required.

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# APPENDIX 4A

# COMPUTER SCIENCE AND ARTIFICIAL INTELLIGENCE CONTROL STRUCTURES FOR THE SPACE STATION

Contributed by

R.S. Wallace

Effective control of the space station requires applications of numerous artificial intelligence systems. These will include speech understanding and natural language comprehension capabilities for human-machine interaction, expert systems for fault detection and diagnosis, and problem-solving and planning systems to make judgments about crew scheduling and station resources. The space station will be generously endowed with vision and tactile sensors, and learning systems may be applied to the data to extract new rules and new heuristics. In addition, AI components of space station control must interact with the non-intelligent components and with people.

Artificial intelligence lacks a coherent methodology for linking together all of the kinds of AI programs on which researchers are working today. Apart from the fact that software integration is a very complicated task, there are at least two reasons for a lack of coherent methodology. First, there is general disagreement on the question of knowledge representation. Various representation schemes have been proposed (e.g., frames, first-order logic, semantic networks, constraints) and tried in various systems with limited success. Since the kinds of knowledge to be represented in, say, vision systems and speech understanding systems differ considerably, no single knowledge representation scheme likely will suffice for all AI programs. Second, some potentially-integrating techniques such as heuristic search cut across nearly all branches of AI.

To make the problem even more intractable, proper definitions of the components of intelligence -- a prerequisite to building interfaces among them -- do not yet exist. For example, it is clear that natural language parsing and edge-finding in vision are functionally independent processes, but that the general functions of vision and language comprehension may not be. (In totally blind people language comprehension is not linked to vision per se, but even these people make use of spatial reasoning). AI as a field is divided up into subdisciplines like vision and language understanding and so on, but there is no reason to suppose that intelligence itself is divided up functionally along the same lines.

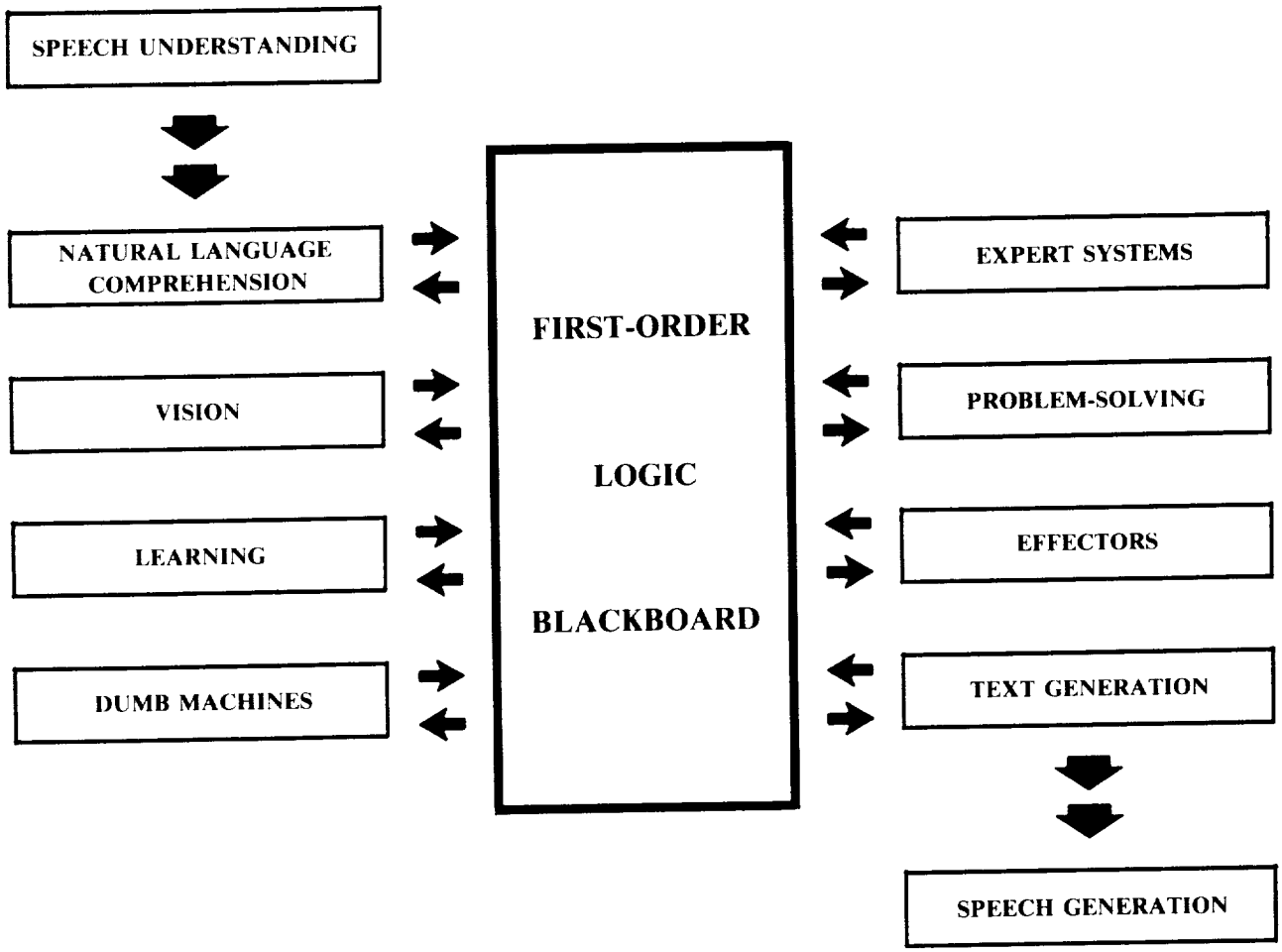
A simple approach to integrating AI systems, which would appeal to many researchers in AI and repel many others, might be to construct a "blackboard" (Figure 4.3) which holds knowledge in a first-order predicate logic representation. How might such a blackboard system work? The output from a vision system might consist of first-order relations such as "Next-to(Screwdriver, Box)" or something more sophisticated. The problem-solving system may be able to use such a fact when planning a sequence of moves for a robot manipulator. When this sequence is computed and stored on the blackboard the proper manipulator controller can recognize the sequence on the blackboard, copy it over and execute it.

Among the virtues of such a blackboard scheme is its completely unified knowledge representation. The output from and input to each of the AI processes is standardized. Notice that it does not preclude a subsystem from employing its own knowledge structure (e.g., the vision system might employ models based on generalized cones). Another virtue is that first-order logic is a well-understood system for representing knowledge -- formal logic has been known since the time of Aristotle; the properties of formal logic languages date from Frege's work in the 19th century. Indeed many mechanical problem-solvers, planners and other AI systems have been built using a first-order logic representation.

The disadvantages of such a system are legion. For one thing, first-order logic is not the most compact representation for an infinite class of sentences. A comparison of the axioms of geometry written down in logic (Tarski, 1951) and as they might appear in a grade-school geometry book is quite revealing. The formal statement of geometry axioms achieves no economy of notation. Also, the typical problems of everyday life and "commonsense reasoning" have proved especially baffling to those who have tried to write down knowledge in first-order logic. Other difficulties arise when time-dependent assertions and assertions of uncertainty or probability are desired. Systems such as Doyle's Truth Maintenance System (Doyle, 1982) are one way of dealing with some of these problems. Perhaps one would wish to append a Truth Maintenance System onto the blackboard as well.

The intelligent space station may be pictured as a hierarchy. At the lowest levels are the

FIGURE 4.3. SCHEMATIC OF FIRST-ORDER LOGIC BLACKBOARD




various sensors, effectors and subsystems which perform the bulk of all station activity. Next are basic monitoring and control systems, and above these are the high-level control and diagnostic systems (Figure 4.2). At the topmost level is man and his intelligent planning tools. So the issue is controlling the controllers. At each of these levels there is a separate question: What control structure is best for a given computational task? For the overall system there is another control question: How does one orchestrate the entire system of controlling computers? The answer is that it depends in the first case on the nature of the computational task and in the second case on why one wants to coordinate a system of controllers. Control structures appropriate to the space station are reviewed below (Ballard and Brown, 1982).

### 4A.1 Standard Control Structures

Traditional von Neumann style computer hardware is capable of carrying out actions in only very simple ways. These control structures are the basis of more advanced structures implemented on von Neumann machines. Their intrinsic importance is immense as illustrated by their centrality in nearly every computer language.

The standard control structures are:

1. Sequence. Advance the program counter to the next instruction.

2. Branch Instruction. Go to a specific address.

3. Conditional Branch. If a certain condition is true then go to a specific address; otherwise, go

to the next instruction.

4. Iteration. Repetitively execute a sequence of instructions until a terminating condition is true.

5. Subroutines. Go to a specific address and execute all the instructions stored after that address until a special "return" instruction is encountered; then go back to where the subroutine was called.

Less-standard control structures discussed below are actually implemented as combinations of these standard control structures on most machines today. The reason for defining the less-standard controls is that programmers have noticed that certain combinations of standard control structures arise again and again in applications. For convenience, they have defined these less-standard mechanisms.

### 4A.2 Recursion

The concept of recursion confuses some people because, loosely speaking, it allows a function to be defined in terms of itself. Recursion actually does not involve circular definitions, but definitions of simple cases and definitions of complicated cases broken down into simpler ones. In this sense, recursion is analogous to proof by mathematical induction.

A simple example of a recursive definition is the definition of "An ancestor of mine." An ancestor of mine is either my parent or someone who is a parent of an ancestor of mine. Recursion is an excellent way to specify computational tasks that break down naturally into simple cases and compounds of those simple cases.

### 4A.3 Automatic Backtracking

Automatic backtracking is a control structure frequently applied to problem-solving and plan-formulating procedures. Suppose one wanted to look for a golden leaf of a tree. The backtracking approach is to start at the trunk and follow a path down branches and twigs until a leaf is hit. If that leaf is golden, we stop with success. Otherwise, we back up to the last branch-point some of whose branches are unexplored and continue the search for the golden leaf. This process of following a search path right to the end and then backing up is automatic backtracking.

Although backtracking sounds like a wretched brute-force control mechanism, heuristics may be applied to limit the size of the search space by "pruning" and other techniques. The AI languages Planner and Prolog have backtracking control structures. In these languages it is easy to write programs which solve certain puzzles. Many expert systems also use a backtracking control strategy.

### 4A.4 Context Switching

Context switching allows a program to move backward and forward in time. At each step in the execution of a program, the computer might save all of the values of bound variables at that step. Context switching allows the program to return to earlier states of execution with all of the earlier values.

Fahlman (1974) has used context-switching in a program designed to construct complicated objects out of blocks with the constraint that constructs had to be stable.

### 4A.5 Modules and Messages

More "parallel" control structures are sometimes better realized on non-sequential non-von-Neumann machine architectures.

Messages may be any kind of information. Modules may be conceived as black boxes to which messages are passed. When a module gets a message it may do some internal processing and then itself transmit messages. The essential point is that the internal operations of individual modules are not accessible by other modules. The most a module may do is to send another module a message.

Each module may reside on a separate processor so that the whole collection of modules operates concurrently.

### 4A.6 Priority Job Queue

A job queue is an ordered list of jobs to be performed. A simple job queue might be first-in, first-out -- jobs are executed in the order in which they are received by the queue. A more complicated queue adds a priority value to each job, and jobs are executed in the order of highest to lowest priority. An interesting feature of such a system is that a high-priority job may execute and call jobs whose priority is higher than any in the queue. Thus many jobs in the queue are delayed even if after a time they come to have second highest priority.

As a control structure for AI programs, priority job queues are intriguing. A running job may need certain information from programs that it might call. But it may not need all of the information derivable from calls to these programs. Furthermore, the running job may need to know some of the information more than it needs to know other of the information, so it can assign a priority to each program call (and these are entered into the priority job queue).

### 4A.7 Pattern-Directed Invocation

Pattern-directed invocation refers to the execution of a procedure as soon as a certain pattern is recognized or as soon as a set of preconditions are true. Rule-based expert systems are a special case of pattern-directed inference, since each if-then rule is activated only if its preconditions are true. One can regard preconditions as patterns for which the expert system is searching.

Another popular form of pattern-directed procedure is the "demon." Demons are programs that scan databases looking for facts that will activate them. Once these facts are found, the demon program activates, performs its function, then returns to looking for another fact to activate it again. Demons have been applied with moderate success in natural language understanding.

### 4A.8 Blackboard Systems

In simplest terms a blackboard is a place

where anyone may write anything for anyone else to see. If several programs are working on different parts of the same problem (as in speech understanding or vision) each may require the output of others. The output of all software can be stored in a special globally accessible database called the blackboard (Figure 4.3).

Blackboards may be broken down into layers, each of which corresponds to the current knowledge about a particular part of the problem. In vision, for example, the layers might be: Vertices, segments, regions, surfaces, volumes, objects and schemas. Blackboards implemented on sequential machines may also encode knowledge about the order in which programs accessing the blackboard should be called, given the current state of information in the blackboard.

### 4A.9 Hierarchies and Heterarchies

Two divergent ideas on the overall architecture of AI systems have evolved. Some of the control mechanisms outlined above lend themselves to the design of control hierarchies, in which a top-level control program calls other programs as subprograms and these in turn call sub-subprograms and so on down to the lowest level of control. Such a control hierarchy might look like a NASA organizational chart, with an Administrator at the top and several levels of subordinates below.

Others among the control mechanisms outlined above, in particular the message-passing network of modules and blackboard systems, lend themselves to the design of heterarchical control assemblies. In a heterarchically controlled system each component operates autonomously from the others, although information may be passed between them. A heterarchical control regime might be depicted as a network, the nodes of which are the autonomous control systems and the arcs of which are the lines of communication (not authority) passing between them.

Which configuration provides superior effectiveness? That an AI system should be organized like a hierarchy can be argued plausibly. The very highest level corresponds to the currently active focus of attention; short-term memory resides there. The top node of the hierarchy calls upon subordinate nodes which supply it with updated information. Lower-level nodes are responsible for lower-level data reduction and decisionmaking; higher-level nodes are responsible for higher-level decisionmaking. The bottom-most nodes correspond to sensory input and long-term storage. However, it has also been argued that an AI system is best organized like a heterarchy, an idea embodied in the "society of minds" hypothesis of Minsky, as well as in Rieger's word-expert parser. Also, what little is known about the gross organization of neurons in the brain suggests a heterarchical distribution of control.

A third alternative is the "corporate society of minds" approach in which there is a mix of hierarchical and heterarchical control. Certain subsystems might be viewed as independent autonomous nodes, others as hierarchies of nodes. The hierarchies act as "corporations" and achieve goals which involve many layers of subgoals. The individual nodes act as "free agents" and may sometimes act on their own to achieve goals without many layers of subgoal decomposition. For instance, there might be a "vision corporation," a "speech corporation," a "tactile sensing corporation," and so on. This alternative seems best-suited for the autonomous space station control system.

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# CHAPTER 5

# HUMANE SPACE STATION

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In the manned component of the space station complex, people varying in training and disposition, and machines varying in capability and connectedness, reside together in what is essentially a mechanically supported ecology. In a broader sense, the real boundaries of the station are not the exterior surfaces of metal, silicon and exotic materials but the organization of individuals, groups and institutions who support the work in space and who have a stake in what is done there and how. Such factors as human and machine procedures, the settings in which people live and work, the management of communication with clients on Earth, the motives and goals of various entities, and work management policies all materially impact what can be accomplished on the station, and hence the level of human autonomy which provides maximum effectiveness. Each involves issues about which something is known, either from previous space experience or from terrestrial research in the social sciences.

For example, the long-established Soviet space station program yields valuable insights into areas of potential concern for an American space station effort. The Soviet program emphasizes the pragmatic utility of space. Their long-standing attention to social and psychological factors is interesting in view of their extensive experience with very long duration manned space flights. Even supplies to early Salyuts included special entertainment items and messages (Oberg, 1978). Bluth (1981a, b; personal communication, 1983) reports that Soviet ground control treats human relations on a par with more technical matters. By contrast, while American astronaut selection and training procedures are intensive and thoughtfully managed, human roles have generally been de-emphasized during U.S. spacecraft design.

Since the growth of manned space programs in the 1960s, some research on human and social aspects of near-space voyaging has been performed but little has found its way into actual design decisions (Helmreich, 1977). Most of this work had to do with how humans, singly or in groups, react to isolated, spatially constrained, hazardous environments -- three critical features of early spacecraft and of projected space station settings. Analogous terrestrial environments have been studied both systematically and by the recollections of participants, including Antarctic workstations (Gunderson, 1968); Arctic work environments; the undersea quarters of Project Tektite (Helmreich, 1971a,b); lengthy sea voyages; and laboratory simulations, ordinarily with students (Sullins and Rogers, 1974). Good summaries of this earlier research are given in Connors *et al.* (1984).

Experience with actual space missions has validated some of the phenomena encountered in these studies, including a rugged syndrome of response to harsh environments, and has yielded new data on relatively long-term physiological and behavioral effects of micro-gravity. These missions also demonstrated the human ability to adapt to space environments and, though not by research design, illustrated heavy performance pressures from the ground. The research focus has now broadened beyond the early issues of whether people could stand the isolation and cramped quarters, and the question of which variables, if any, could predict who would better cope with such environments.

However, the investigation of space-related human and social factors has not yet caught up with potentially relevant modern research findings in the social and behavioral sciences. Studies of group interaction phenomena, communication network arrangements, judgmental and perceptual biases, relationships between settings and behaviors, and symbolic communication are potentially applicable to space station organizational design -- but all have been largely ignored to date. Such research could be valuable in helping to anticipate and to design solutions for real problems likely to be encountered during extended residence on space stations -- problems which may materially affect astronaut work performance.

Earlier chapters focused on direct human-machine interactions in assuring the physical integrity of the station and in doing work in space, and on emerging technologies useful in this enterprise. The present chapter examines three major

sociological aspects which may significantly influence space station organization, autonomy, and effectiveness:

1. **Physical Setting** -- the intriguing challenge of designing the physical and perceptual layout of station environments for optimum integration with the behavioral and emotional needs of the astronauts; conversely, how to avoid thoughtless early design decisions which could hinder effective human action (section 5.1);

2. **Communications Methodology** -- establishing superior communications arrangements between people, for a more responsive and coherent station operation (section 5.2); and

3. **Organizational Factors** -- how best to organize for working in a small, heavily automated, distant and hazardous environment; also, issues of desirable managerial philosophies for an increasingly autonomous space station of the 1990s and beyond (section 5.3).

## 5.1 Humans in Space Settings

Long-term work and life in a space setting is a challenge much like that faced by people and groups in constrained remote terrestrial habitats. Some well-known emotional difficulties -- loneliness, the desire for play, the need for anchorage and exploration -- will be exacerbated by the unique space station environment. In addition, physical aspects of station design will significantly influence human performance in space. The physical and perceptual layout must be designed for optimum integration with the behavioral needs of the astronauts, avoiding thoughtless early design decisions which could hinder effective human action.

### 5.1.1 Emotional Difficulties of Space Station Habitation

A number of emotional difficulties may be associated with the long-term habitation of space. These include loneliness and isolation (McNeal and Bluth, 1981), the need for play and sexual release, and the need for anchorage and exploration. Without careful design, the space station may frustrate or exaggerate some or all of these normal human requirements.

Loneliness. Though painful, loneliness is an entirely expectable reaction to being away from one's customary habitat. While it is conceivable that a few may feel more "at home" in orbit, the very imagery of space can serve as a metaphor for loneliness.

During voluntary isolation at the South Pole in 1933, explorer Thomas Byrd (1938) used the following language to describe his experience: "I went topside for a look around. The night was spacious and fine. Numberless stars crowded the sky. I had never seen so many. Earlier, a monstrous red moon had climbed into the northern quadrant, but it was gone by then. The stars were everywhere. If great inward peace and exhilaration can exist together, then this, I decided my first night alone, was what should possess the senses." One morning, weeks later, during a period of great loneliness, Byrd was in a sharply different frame of mind: "It takes me some minutes to collect my wits; I seem to be groping in the cold reaches of interstellar space, lost and bewildered. The room is a non-dimensional darkness, without shadow or substance; even after all these days I sometimes ask myself: Where am I? What am I doing here? I discover myself straining, as if trying to hear something in a place where no sound could possibly exist."

This contrast between feelings of freedom and distress was also noted by Robyn Davidson (1978), a young woman who traveled across the Western Desert of Australia with several camels and no human companionship: "Some times were miserable... others were euphoric, days of extraordinary freedom." A number of aircraft pilots have reported that the experience of being alone and cut off led them to appreciate the value of life and their place in the universe.

Will space workers get lonely? A busy space station with seven crewmembers and extensive communications links to Earth seems less likely to have lonely residents than a smaller, more remote station. But this very personal, often quite painful emotion can occur in a small group or in a crowd, since loneliness is a psychological state rather than an objective situation of aloneness.

Yet problems with meaningful social contact frequently seem to be a cause of loneliness. Peplau and Perlman (1981, 1982) identify several events which can lead to loneliness: "Physical separation from family and friends" and "status changes" probably would apply to most space workers; "reduced quality of a personal relationship" could occur both in family relationships strained by lengthy missions away from home and in strained job-related interpersonal contacts, virtually inevitable in isolated groups; and "ending a close emotional relationship, as by divorce or death of a partner," might occur in some cases. Sermat (1980) adds another source of loneliness that might affect station residents in some circumstances: "Loneliness due to overreliance on roles -- prescribed, safe, but relatively impersonal 'socially pleasant' relationships."

How can loneliness be reduced on the station? Smooth, fulfilling social relationships can ease loneliness, according to Peplau and Perlman, just as disrupted relationships precipitate it. Selection of compatible crews (not just individuals), the availability of support personnel specially trained in interpersonal skills and facilitation, meaningful work assignments and the ability to explore new areas can help to alleviate the feeling of general loss and estrangement that may occur at some time during an extended stay in space. Statistically, and excepting cases of extreme isolation as in an emergency mission to a very remote location, loneliness is seldom intense enough to lead to suicide or even to cause serious disruption of activity (Sermat, 1980). Complete avoidance of loneliness may be undesirable, as the experience can be a kind of contact with reality and the self, an accurate recognition of important aspects of one's situation. Still, it is an unpleasant emotion which may detract from human performance.

Station Recreation. Will space station residents play? Astronauts have almost always shown a playful side, delighting in zero-g maneuvers and sometimes engineering practical jokes, illustrating the deep human need for play. A certain dry

wit between astronauts and mission control personnel seems to have relieved some of the psychological strain of past situations and has given rise to an informal "space culture" over the past two decades. One important factor concerning play on the space station is that schedules for work, together with time-consuming activities such as personal hygiene and cleaning/maintaining equipment, may leave little time for diversions. Since it is important to have some activities disentangled from webs of duty and responsibility (Huizinga, 1965), recreation time should be scrupulously provided. Further, playful aspects in normal work activities should be strongly considered in job conception, so that the full human resource may be utilized with better chance of activation and interest.

Perhaps the most obvious possibility is video games. Some people enjoy "busdrivers' holidays" -- arcade-like games will appeal to some and involve little cost for extra technology on the station. On the other hand, excessive reliance on work activities is a response to group strain and environmental constraint, so for many people video diversions might feel too much like work. When human-computer interaction must occur in a video mode in actual work situations, designers should attempt to engineer it to have some of the fascination and pacing of arcade games. Then, if workers play video games during spare time (if such exists) it might seem like just more of a good thing. Perhaps space residents will play more with terrestrial themes, as Earthlings frequently play video games with extraterrestrial themes.

Because of the touchiness of interpersonal relations in isolated groups, and the possibility of escalating aggression, competitive games among space residents are not recommended. This is consistent with Russian practice on the Salyut missions, where chess games were arranged between a cosmonaut and a partner on the ground but not between cosmonauts (Bluth, 1981a,b; personal communication, 1983). Since delicate interpersonal relations are likely to be inevitable in prolonged residence, very formalized group games, with careful rules to minimize or ritualize winning or losing, and aggression, could be worked out. One type might be symbolic performance games involving the group, such as Space Charades, Hide and Seek, or Name That Machine. Since physical contact and intimacy may be problematical for American residents for cultural reasons, highly formalized contact games might be developed.

To provide a broad choice of amusements, game equipment should be low in mass and volume. Zero-g acrobatics requires enough open space and boundary resilience to permit some safe variation, thus may not be feasible in early stations. However, recreational exercise could be accompanied by rhythmic music, using space versions of dancers' bars or other devices. Low-mass, compressible objects or deployable stretchable surfaces (e.g., parallel trampolines) for space caroming should be considered. Development of non-competitive skills is recommended, and psycho-therapeutic games should be investigated. Planners may find it interesting to imagine diversions for microgravity environments in cramped quarters, but space residents doubtless will invent their own games if they have the time and inclination.

From time to time there may be sexual play in space (Freitas, 1983), privately and perhaps to some extent in group context such as flirting or innuendo. Perhaps official avoidance of discussion of this matter is understandable in view of the taboo status of sexually-related matters in our culture. Of course, space dwellers are adults and can handle private matters with discretion. They deserve privacy in specific activities. But a general examination of the special situation of lengthy habitation in close quarters, though hardly unique to space, deserves careful, if discreet, examination. Sexual activity, whether associated with play aspects, or deeper aspects, stems from a powerful human response system and is linked as well to important psychological responses such as comfort, status, and self-affirmation. It can be a source of exhilaration, fascinated exploration, and coordination, as well as passionate antagonism. Since humans are ingenious and autonomous entities, sexual events probably cannot be either specified externally or totally suppressed.

Anchorage and Exploration. People have contrasting needs in "internal space" and "social space" analogous to the roles of the base station and the voyaging craft. First, humans require a reasonably stable web of reference points or "anchorages", a term from perceptual psychology which includes anchorages of the self in attitudes, beliefs, and group and personal identities (Sherif, 1934; Rokeach, 1960; Sherif and Sherif, 1969). Second, a disposition of humans which contrasts with the attraction to anchorages is the need to engage in locomotion and exploration. These impulses are a major theme in personality psychology (Bakan, 1966) and in experimental work in the area of novelty and exploration (Berlyne, 1960; White, 1959).

The anchorage notion has application to the psychological orientation of people in settings. In a social and symbolic sense, being suitably anchored has obvious relevance to the phenomena of isolation, constraint, and stress. For instance, if an individual space station resident is having problems, an Anchorage Profile Analysis might be made informally and consulted to determine areas where more solid anchorages might be sought, where conflicts or ambiguities need to be worked on, or where "loosening up" might be desirable. It seems that even well-trained, basically stable persons can become disoriented when relations are disrupted, missing, or too tightly constraining. Space work can be accomplished adequately only if the worker is suitable anchored. There is a direct analogy between physical anchoring in zero-gravity, where it is problematical, and psychological anchoring. Both provide points of resistance or departure, from which movement can be managed.

But people also need locomotion or exploration to work at a high level of activation and to maintain interest. This has been demonstrated by organizational psychologists studying the effects of boring work. The thrill of being on the trail of something, of having a destination to look forward to, of finding appealing morsels or companionship along the way, all serve to mobilize the human resource.

Unfortunately, actual physical space will be very limited on stations, EVA is expensive and hazardous, and the station itself is not a spaceship on its way to somewhere. Meaningful exploration in informational- or problem-solving-space (e.g., observational experiments or cooperative decision-making) can compensate for unfavorable physical restrictions. Creation of forms is another kind of exploration, and provision for low-mass, low-

volume artwork or device construction should be considered, particularly if the product is useful in other areas of station work or life.

Access to extensive ground/space computer-mediated knowledge libraries could also have job relevance and beneficial effects on mental health and work productivity. Information can be generated as well as explored internally. It is interesting to note that story-telling is important to Eskimos in winter isolation (see Chapter 6), and that POWs who imagine narratives and scenes from old movies (or new fantasies) withstand stress better than those with less facility for imagination (Singer, 1975). Active information-generation should be encouraged when planning both formal tasks and informal activities.

### 5.1.2 The Design of Setting Factors

Settings and behavior are inextricably linked, seemingly a simple truth. But the far-reaching implications for human performance in space have yet to be fully appreciated -- especially among people instilled with the traditional western cultural viewpoint that behavior is an inherent human property and settings merely a passive backdrop against which that behavior occurs. Three decades of research have shown that behavior is a simultaneous, synergistic property of setting and person. Both must be analyzed as an entire system rather than as two separate aspects.

The design of setting factors for the space station goes far beyond mere aesthetics or physiological requirements. Settings have a facilitating, enabling, or inhibiting influence on behavior. This directly affects all human performance, mission-related and otherwise, hence also the degree of station autonomy which a manned facility can be expected to achieve. Station settings should be intentionally designed for effective human performance, not just basic human survival. Proper attention must be paid to the most important elements of the settings-behavior system and their implications in station design, including physical, perceptual, physiological, sociocultural, and temporal dimensions.

The Physical Dimension. The most obvious dimension of a setting is the physical space itself. While widely recognized as a crucial element, the impact of physical setting on human behavioral performance typically is underestimated. Settings adjacency and proximity requirements frequently are addressed solely to minimize travel distances between settings as required to accomplish a sequence of activities in minimum time (to achieve operational efficiency). Often ignored are auditory, olfactory, visual, and kinesthetic settings properties, each an important determinant of adjacency and proximity relationships potentially overriding travel-distance/time considerations on the space station. The many behaviors to be accommodated simply cannot be addressed in the classical human factors manner (e.g., time-and-motion studies) alone. Station settings must be designed in recognition of the complex overlapping patterns and sequences of crew behaviors, which will inevitably vary in frequency and duration and which may have different physical settings requirements. Of course, to reach this level of accommodation the physical form and movement of astronauts in the enclosed space must first be adequately supported.

Human beings are bilaterally symmetric bimanous bipeds, a physical form supremely adapted by evolution for terrestrial living. But what of space life? In perpetual free-fall, might not our form become a hindrance? If the human form is not as adapted to space as it is to terrestrial conditions, and since human genetic engineering and the use of paraplegic astronauts remains strictly the province of science fiction, then the space station settings in which people live and work must accommodate the adaptational deficit for humans to achieve performance levels comparable to those on Earth. This is analogous to design-for-the-disabled concepts in present-day public architecture. Settings can be redesigned to enable people to perform otherwise physically difficult or impossible tasks -- elevator controls are lowered so that children and wheelchair-bound individuals can reach them, ramps are used in place of stairs, levers instead of doorknobs, and so forth. Similarly, the station environment can be designed to accommodate space workers, enhancing their capabilities beyond what might otherwise be possible.

For example, in zero-g the relaxed normal human body posture changes dramatically. Overall height decreases, the head thrusts forward, the line of sight drops lower, and the limbs approach a more quadruped position (Thornton et al., 1977; Griffin, 1978). Internally, body fluids migrate from the lower extremities toward the head, shifting the center of mass upward toward the thoracic region. The intervertebral discs expand, straightening the thoracolumbar curve (the convex slope of the upper back) and increasing the distance between lumbar and cervical vertebrae. There are corresponding reductions in waist and chest girth.

These anatomical changes create a new "measure of man." The height of work surfaces, the location of controls and displays, and the placement of foot restraints and handholds must be adapted to the new human zero-g posture. If this is not done, accommodation must be made by the human occupant which detracts from effectiveness. Skylab control consoles designed for normal terrestrial seated postures forced astronauts constantly to tense abdominal muscles to maintain a work position (Cooper, 1976), inducing extreme discomfort over even short periods of time. A more suitable workstation taking proper account of the zero-g envelope surrounding the neutral body posture in space has been suggested by Griffin (1978).

On the Earth's surface, movements are both constrained and enabled by gravity (which provides a constant force on all parts of the body). Humans can rotate spritely about the vertical axis by applying oblique pressure to a surface perpendicular to gravity. The upward component of the force produced by the push is not great enough to overcome gravity, yielding a turning motion. Without gravity a foot thrust imparts upward displacement plus rotation, sending the person spinning away from the surface. Conversely, it is very difficult for an astronaut to move at all in free fall once he loses contact with any surface, unless he has significant translational velocity. One Skylab astronaut found himself virtually marooned in the center of the habitat, unable to move toward a handhold unless given a push by another crewmember (Cooper, 1976).

One of the major lessons learned during Skylab (JSC, 1974) is the need for extensive handholds and footholds both inside and outside large habitable spacecraft. Translations in zero-g are often a trajectory from one temporarily restrained

position to another. The combination of altered zero-g posture and the upward shift in center of mass suppresses movements about the waist in favor of movements about the upper body. The lower two-thirds of the body (from the chest downwards) tends to remain motionless with upper body actions fluid and predominant, reminiscent of the energy-efficient brachiating motions of arboreal primates.

The center of mass shift and the direction of the human knee hinge simplify backward rotations in zero-g (Griffin, 1978) -- the enjoyability of and dexterity in performing repeated backward somersaults is evident in Skylab film recordings of cavorting U.S. astronauts. There is no reason why this enhanced capability should be used for entertainment alone. Workstation design might also be able to utilize a semi-reclining position to be rotated into and out of -- giving literal spatial meaning to the traditional concept of "circulation space". Rotations around the vertical axis in zero-g are more difficult to perform than on Earth, owing to the forward flex of the legs in the zero-g posture. Handholds may be used in conjunction with a foot push-off to effect sideways in-place rotations. Soviet cosmonauts have noted that to achieve these motions it is necessary to push away with one hand, then to strike a retracted or spread-eagled pose to speed or slow rotation.

The Perceptual Dimension. The ability to spatially orient inside the station is a basic requirement for working and living in space. Both Soviet (Leonov and Lebedev, 1971) and American (Cooper, 1976) orbital experience shows that people in free fall can become completely disoriented even in relatively confined volumes. This may be accompanied by visual inversion illusions of surrounding objects which appear to change size or rotate. Even when astronauts are strapped in, illusions can be triggered by the onset of zero-g immediately after accelerative forces have ceased. Illusions may be projected onto objects in the spacecraft cabin or even the astronaut's own proprioceptive senses (e.g., the person incorrectly feels as if he has assumed a different posture).

Vertical referencing is the sense of up and down. In free fall, this status information is no longer available from human gravity sensing organs so another source is substituted -- primarily visual, conforming to the geometry of the spacecraft (or simulator) cabin (Leonov and Lebedev, 1971; JSC, 1974). During Skylab the crew oriented themselves with respect to the interior geometry, and maintained a commensurate usage of space even when this seemed to functionally decrease the overall available volume. In general, adherence to an up-down convention is desirable as a convenience, but not as a constraint (JSC, 1974). An up-down normative convention permits easy orientation, location, and equipment identification. However, it is interesting that in larger compartment interiors Skylab crews adhered less to perceived position perpendicular to the "floor" and preferred to translate themselves "headfirst" through the interior even when traveling towards the "floor."

The space station interior probably should be designed with a visually appropriate "up-down" reference system. If the interior has windows, these should be aligned with respect to the attitude of the station in orbit, so that internal "down" and the view of Earth coincide. Soviet studies (Leonov and Lebedev, 1971) show that an interior perception of "down" is shattered when Earth is visible in a conflicting orientation in high flying aircraft -- the view of Earth dominates the perceptual orientation. However, the requirement of a visually appropriate interior reference system does not mandate a simple planar arrangement of furniture, lighting and workstations. With the small habitable volume available, what would otherwise be unused space near the "ceiling" should be made functional for living and work activities. This can be accomplished while maintaining an artifically-induced perceptual vertical.

Closely allied with the problem of disorientation in vertical referencing are visual illusions arising from a combination of the loss of vestibular information under weightlessness and the reduction of normal monaural distance cues. For example, judging distances in space against a starry background often results in gross underestimations. On Gemini IV, Astronaut McDivitt judged the distance to a docking target to be 120 meters when it was actually 600 meters. This has implications for large-scale space construction activities -- crewmen, for instance, should not have to rely on estimation of range during EVA. To date, the experienced distances to familiar objects both inside and outside of spacecraft have not really been great enough to provide an adequate test of size-distance invariance mechanisms in weightlessness.

Station occupants may also be subject to the same kinds of visual illusions frequently experienced by air travelers. For example, a "tunnel effect" is induced by the exaggerated linear perspective of a long view down an interior fuselage. Aircraft manufacturers counteract this by using widebody cabins incorporating specific curative interior design features. These include: (1) Lighting arranged to produce a perceived flow of light in a direction normal to the observers line of sight; (2) decorative patterns on interior partitions emphasizing horizontality; and (3) exterior bulkhead coverings with small scale patterns without any noticeable horizontal component. The choice of colors on interior partitions augments these ameliorative effects, due to the perceptual recession/approach effects of cool and warm colors, respectively. Although there is yet no strong evidence for enduring visual illusions in spacecraft interiors, this may simply be due to present-day small habitable volumes. On Earth, most of the visual illusions experienced in the three-dimensional natural environment (e.g., the moon illusion) involve size/distance invariance mechanisms of the visual system. These illusions occur when a quantity that the visual system is attempting to control (such as perceived size) comes under a transformation from an external source about which the visual system has no control information (Day, 1973).

A cognitive image is a mental map of the local environment, the internalized representation of the external world. Cognitive images or maps have both quantitative and qualitative connotations. One can measure the perceived distances and orientations between places on a cognitive map, or the affective meaning a place holds for an individual. Cognitive images are most frequently employed on the neighborhood or urban scale but also apply to the experience of building interiors. The cognitive map of a space station would summarize a crewmember's mental representation of that structure. How this cognitive image is formed and maintained

guides human adaptive responses within the station. For instance, cognitive images of buildings predict how people try to find their way from one point to another, explain how people proceed when attempting emergency egress, and help determine human emotional response to a particular place.

Because of the small habitable volume, crewmembers' mental maps should be composed of as many distinct images as possible. For example, the workplace and the personal place must be in different locations and should actually appear different in terms of surface finishes, lighting, and so forth. This gives the sense of having moved farther from one place to another, by substituting perceptual quality distance for actual physical distance. Also, it is crucial that station personnel be able to find their way through the station in an emergency -- if there are obscuring gases or a need for rapid head movements, the sorts of perceptual disorientations peculiar to zero-g are more likely to occur. The station interior should be color- and tactile-coded so that even under the most debilitating conditions personnel know not only where they are, but also how they are oriented and where any other location on the station is with respect to them. The need for this is not diminished because of the small interior volume -- in emergencies, people have gotten lost in their own homes or on relatively small pleasure craft.

All locations should provide an equal sense of safety for the crew. For example, if all compartments have two exits except in the case of one particular module that has only one, that module may be perceived as less safe to occupy -- a perception that will hinder its use. If more than one habitation module is employed, and they are at different distances from the "safe haven," one will be perceived as less safe and thus less preferred. There are cost tradeoffs in achieving these perceived qualities, but it should be recognized that the psychological consequences of physical design are very real and must be deliberated as carefully as other aspects of station habitability.

Physiological Dimensions: Calcium and Sunlight. Space biologists have discovered a number of physiological changes in the human body during prolonged space missions. One of the most striking examples is the loss of calcium in skeletal bones. Calcium loss begins about 10 days into a mission and continues uniformly to a projected 25% loss of the initial body pool for a one-year mission. Bedrest studies predicted some loss, but actual space results are more severe (Gazenko *et al.*, 1980; Nicogossian and Parker, 1982). Studies show 0.5%/month calcium loss from total body weight and a 5%/month calcium loss from weight-bearing bones among Gemini, Apollo and Skylab astronauts (JSC, 1982). Recovery from the loss normally occurs within 5 weeks of return to Earth, although two Skylab astronauts remained significantly deficient in bone mineral 5-7 years after their last flight. This effect, noted in 1982, supports an earlier conjecture that the imbalance between calcium intake and excretion, negative in space, might return to zero after the crew returns to Earth well before the bone calcium loss due to the flight is fully rectified, resulting in permanent skeletal change (Rambaut and Johnston, 1979).

Sunlight has played a significant role in the evolution of human physiology. Visual sensitivity peaks near the solar spectral maximum; solar ultraviolet (UV) radiation is required to produce vitamin D for bone growth and maintenance; and periodic bright sunlight helps to establish human circadian rhythms. During long space voyages astronauts are deprived of natural solar illumination, and it is likely that various deficiences of artificial lighting may cause unnecessary stresses. Further, anecdotal evidence from lengthy space flights includes occasional deep psychological stresses among individuals in space or between individuals and their separated support teams. These stresses also appear during prolonged confinements on Earth such as in Arctic and Antarctic stations and in underwater laboratories. A common feature of all these cases, perhaps not coincidentally, is the absence of strong sunlight.

Seventy years ago rickets was a common childhood bone disease, leaving its victims with a severe lack of bone calcium and phosphorus. In 1919, Huldschinsky discovered that artificial ultraviolet illumination cured rickets, and in the 1920s and 1930s vitamin D -- produced naturally by the interaction of sunlight with the skin -- was identified as the active substance. Subsequent chemical production of vitamin D and its widespread use in dairy products eradicated rickets as a common disease, although the normal quantity of dietary vitamin D is quite insufficient to cure rickets. The region of the solar spectrum which stimulates the production of vitamin D in the skin is 275-310 nm (peak at 295-300 nm; Maclaughlin *et al.*, 1982). The UV is absorbed by pro-vitamin 7-dehydrocholesterol (Fieser and Fieser, 1959), and the endogenous vitamin is converted to 25-OH vitamin D in the liver. The 25-OH vitamin D allows intestinal absorption of calcium and its use in the skeleton.

The human ability to absorb dietary calcium decreases with age, so vitamin D deficiency is especially common among the institutionalized elderly who spend much of their time indoors. Ordinary window glass transmits little UV below 310 nm, and neither incandescent nor fluorescent lamps emit well in this region. It has been postulated that osteoporosis, a common bone disease in adults and especially in women over 60, may be due to calcium deficiency brought on by a lack of vitamin D. Victims of osteoporosis develop thin, brittle bones. Exposure to artificial lighting emitting 5% of its radiant power at wavelengths between 290 and 380 nm (Vita-Lite) significantly increased intestinal absorption of calcium by elderly war veterans during a 30-day period in two successive winter exposures, while intestinal absorption declined in a control group of veterans exposed to conventional fluorescent lighting (Neer *et al.*, 1971). Significantly, dairy products fortified with vitamin D were available to both groups. The decrease in dietary calcium absorption with age and during prolonged space flight, and the lack of ultraviolet irradiation in the confines of spacecraft, may combine to strongly influence the rate of astronaut bone calcium loss.

Lead has a similar biochemistry to calcium and tends to follow similar biochemical pathways in the body (Ericson and Trites, 1983; Pounds and Mittelstaedt, 1983). Along with calcium, lead is incorporated into bone and the toxic effects of lead are thus partially immobilized in the bone tissue; correspondingly, any release of bone calcium tends to re-mobilize the lead. The gradual release of calcium thus implies the possibility of prolonged lead toxicity, depending upon the lead

content of astronauts' bones -- which may be considerable among citizens of industralized countries. Lead toxicity can interfere with the immune system and even influence psychophysiological systems, thus contributing to the psychological stresses associated with protracted space missions.

The postulated relation between spacecraft UV deficiency, bone loss in space, and possible lead toxicity should be tested using commercially available broad-spectrum fluorescent lighting either in future long-term space missions or in prolonged bedrest studies on Earth. The illumination levels required are not high. An 8-hour exposure at 50 foot-candles with 5% UV intensity gives an equivalent ultraviolet exposure of a 15-minute summertime walk at full noon in Washington D.C. (R. M. Neer, personnal communication, 1983) -- a dose approximately seven times that needed to cure rickets in children. The possible effects of vitamin D dietary supplements on astronaut calcium loss should also be investigated.

Social and Temporal Dimensions. The social/cultural dimension of space station setting factors is all too easily neglected or overlooked. Without realizing it, designers often incorporate features appropriate to their own social or cultural grouping. The traditional homogeneity of NASA's astronaut corps has already begun to erode, and this process will accelerate as people representing a broader range of nations and cultures participate in long-duration programs such as the space station.

Social and cultural groupings are powerful determinants of appropriate or acceptable behavior. A station with mixed crew cultures has the potential for misinterpretation of behavior among crewmembers. To expect a university-based principal investigator, a private commercial sector materials processing engineer, a DOD military intelligence specialist, and a NASA pilot, for example, to have the same or comparable behavioral expectations is unrealistic -- particularly as space station operations become increasingly routine.

Mixed crew cultures will place tremendous demands on setting flexibility (the ability to accommodate a range of potentially divergent behavioral expectations at any one point in time), but even homogeneous crew cultures will vary with each crew rotation and place significant demands upon setting adaptability (accommodating a range of expectations over time). These difficulties may be partially, though not entirely, offset by judicious crew selection, but the problem cannot be fully resolved without resort to "user-based design." Setting interiors should be flexible and adaptable enough to accommodate a range of potential crew cultures and their accompanying expectations regarding privacy, proxemic distance, and so forth.

The temporal dimension is another oft-neglected issue in the design of setting factors. By recognizing early that behaviors occur not only in physical locations but also at specific points in time, inefficiency in space station setting design can be greatly reduced. Unless incompatible behaviors and their potentially divergent setting requirements are viewed as occuring at specific points in time, designers may feel compelled to engineer physically dedicated settings for those behaviors to avoid conflict. But if the setting requirements of the behaviors are not irreconcilably divergent, and the behaviors need not occur at the same points in time, dedicated settings are unnecessary. Given the expected limited station habitable volume, most dedicated settings are an unaffordable luxury except where the activity is continuous (thus achieving high utilization) or so critical (life-sustaining) as to be considered essential. Even for virtually continuous behaviors, the need for a totally dedicated setting should be at least partially justified on the basis of the importance (not just frequency) of the behavior. Less-continuous behaviors demand even greater justification on the basis of their life- or mission-critical nature.

Temporal behaviors which station settings must accommodate are neither disjointed, independent, discrete entities nor are they simple linear phenomena. Purposeful behaviors are typically joined to form patterned activities over time. These activities are often composed of preparatory behaviors which may anticipate (1) an action, (2) performance behaviors, and (3) follow-up behaviors to disengage from or to clean up after the performance behaviors. Clearly the station must be designed to accommodate patterned sequential behaviors, not just discrete behaviors, which occur over time and which may have different physical setting requirements. This considerably complicates, for instance, the definition of optimum setting adjacencies and proximities.

Also, human behavior is rarely a simple linear phenomenon. Patterned sequences of behavior usually overlap rather than following one another single file, adding to the behaviors which station settings must accommodate. For example, people often engage in complex patterns of simultaneous behaviors such as socializing while eating. These patterned sequences of overlapping behaviors also vary in their frequencies and durations as well as setting requirements. Thus the design of space station setting factors both to enable and to facilitate programmed and non-programmed activities is a very complicated task requiring further study.

### 5.1.3 The Reciprocal Roles of Settings and Behavior

People believe they exercise complete, direct, personal control over their behavior. However, based on theoretical and empirical research over the past thirty years in a variety of fields, an emerging consensus holds that under many circumstances the setting is the dominant determinant of behavior, not the people themselves. This is not a regression to simplistic notions of environmental determinism in the classic sense. Rather, settings are now recognized as multi-dimensional (e.g., social, cultural, physical, temporal) phenomena possessing reciprocally deterministic relationships with people and their behaviors -- relationships whose dynamics permit settings to dominate behavioral choices in many circumstances (Danford, 1983). Most of the time, most people behave in ways that are compatible with or adaptive to their immediate socio-physical environment (Wicker, 1970), suggesting an extended role for settings in their relationships to people and behavior.

The dynamics of these relationships have been well-documented by numerous researchers. Apparently, people subconsciously "monitor" their behavioral relationship to their settings (Peterson *et al.*, 1970; Turan, 1973; Wohlwill, 1973; Cohen,

1976; Grossbart and Amedeo, 1979), adopting a relatively passive stance as if holding their own direct influence in abeyance. Only when the setting-dominated relationship to a person's behavior evolves into a pattern substantially at variance with that person's needs, values, expectations, or capabilities is he likely to choose to "override" the existing behavior-setting relationship (Barker, 1968; Wicker, 1970; Rose, 1970; Spivack, 1973; Cohen, 1976; Wandersman et al., 1979).

The issue of environmental challenge and support (Nahemov and Lawton, 1973) offers a good example. So long as the amount of challenge or support present in the "demand character" (a combination of constraints, influence and demandingness: Murray, 1938; Moos, 1975; Wandersman et al., 1979) of the setting experienced by the person is compatible with his "mastery" (a combination of skill, competence and power: Kelly, 1972; Nahemov and Lawton, 1973; Moos, 1975; Norris-Baker and Willems, 1979), that person is expected to monitor the existing behavior-setting relationship and permit it to continue under most circumstances (Barker, 1968; Wicker, 1970). But what if the degree of challenge or support present in the demand character of the setting experienced by the person is significantly at variance (Kelly, 1972) with mastery level? This violation of "tolerance threshold" -- the point at which one's willingness or ability to tolerate a setting demanding deviation from established values, expectations, or capabilities no longer balances the perceived cost of doing something about it -- can trigger an attempt to reassert personal control by overriding the disruptive behavior-setting relationship (Wicker, 1970).

Reassertion of personal control may take the form of an attempt to redesign or replace either the behavior or the environment (Bell et al., 1978), or both (Perin, 1972). Additional problems appear when the demand character of the "inappropriate" setting (Canter, 1970) is so strong, or mastery level so weak, that override attempts are futile because the person is incapable of overcoming the perceived pressure from the setting to conform to the prescribed pattern of behavior. Under these circumstances, the attempt to override will continue (Wicker, 1970). In the absence of viable setting "escape" alternatives more suited to the person's preferred pattern of behavior, these attempts will take on the appearance of inappropriate or even maladaptive behavior (Nahemov and Lawton, 1973). This may continue until the person resigns himself to behavioral demands of the setting, and the setting resumes its demanding control, a process which seems to be a significant part of the withdrawal syndrome experienced in groups isolated in extreme environments for long periods of time.

The possibility of designing space station settings which, intentionally or not, might exercise some control over behavior certainly warrants close attention. For routine programmed activities, settings which tightly constrain human behavioral options could be an asset -- quality standards are more easily maintained by limiting individual behaviors to those known to produce the most effective or efficient results.

On the other hand, deviation-intolerant setting-based control could become a liability if it locks people into inappropriate or maladaptive behavior patterns during unique or unanticipated circumstances. Perhaps the setting could be consciously overridden, but then appropriate astronaut behavior would be accomplished in spite of, not because of, the setting. Unless the setting could be redesigned or adjusted, long-term constant deviation would prove psychologically debilitating. Or, the setting's demand character may be so strong or the person's mastery level so weak that attempts to resist the setting and engage in alternative behaviors are unsuccessful. Settings that are so intolerant of deviation that they effectively block more appropriate behaviors are called "bureaucratic" because they excessively channelize the human activities within them. Worse, an astronaut repeatedly rebuffed in his attempts to get things done by other than the prescribed means may find his override behaviors gradually extinguishing for lack of reinforcement and the setting reasserting its demanding control. At that point, unless a station crewmember accedes to the setting's behavioral demands and accepts the loss of personal control over his behavior, a process of withdrawal which gerontologists call "disengagement" can occur which could prove disastrous to the onboard social climate.

Still worse, people may not even recognize that a setting is improperly constraining or delimiting their behavioral repertoires. People usually fail to recognize the effects of settings on their behaviors (Proshansky et al., 1970). Unless setting factors are explicitly recognized as a prime contributor to behavioral pathologies, other potential contributors such as ground personnel or fellow crewmembers may be wrongfully blamed, thus exacerbating the setting-induced difficulty, delaying solution of the real problem, and permitting the setting's negative influence on crew behaviors to continue unrecognized and unabated (Proshansky et al., 1970).

### 5.1.4 Setting Design for the Space Station

In considering factors impacting the design of space station settings, those surrounding the programmed activities of both individuals and groups belonging to the crew are the most easily anticipated. These factors are either essential to or supportive of mission performance, or are recognized as being causally related to effective human functioning. They tend to have strong, predictable temporal and locational dependencies, and to involve fixed behavioral sequences including preparation, accomplishment and follow-up. A major difficulty involved in designing settings for programmed activities is that such an activity is rarely a single behavior but rather just one of a range of functionally interchangeable behaviors. A second difficulty is that even this range of functionally interchangeable behaviors may overlap other causally unrelated behavioral patterns and sequences.

For example, sleep is a programmed activity for individuals. This activity, programmed into the daily schedule, tends to occur at specific times at specific locations and to involve equally predictable and desirable preparatory and follow-up sequences of behavior (e.g., personal hygiene activities).

The first difficulty in planning settings is the wide range of functionally interchangeable behaviors considered, say, "sleep" -- from simple rest and relaxation, to napping, to deep slumber -- each having somewhat different setting requirements. The second difficulty is the potential for a considerable range of overlapping, causally un-

related but often highly correlated non-sleep behaviors such as eating, reading, listening to music, planning, thinking and reflecting, and a variety of individual and socially intimate behaviors. The station setting supporting the individual programmed activity of "sleep," to be truly responsive to user needs, must accommodate the overlapping behaviors as well. This requires more than shuttle-era wall-mounted sleeping bags. Previous manned missions, including Skylab and shuttle missions, have been "flights," but space station missions will constitute working and living in space. The crew will regard the station more as a house than as a vehicle.

Eating is an example of a programmed activity for a group, also temporally and locationally dependent and involving certain preparatory, follow-up, and accomplishment behavioral sequences. Eating as a group activity might cover a range of functionally interchangeable behaviors -- from simple tasting or sampling, to snacking, to full meal ingestion -- each with somewhat different setting requirements. The greater challenge to the space setting designer is the range of overlapping, causally unrelated but highly correlated non-eating behaviors which the group eating setting must also accommodate.

Normally, a variety of social interactions could be expected to occur in a group eating setting -- dyadic conversations up to full group discussions, ranging from purely social to purely official in nature. But there may also be instances when an individual prefers to avoid social interaction and eat in solitude (e.g., just woke up and is not in a social mood; received distressing news from home; angry at fellow crewmember). This places demands on the station eating setting -- not only to enable a variety of interchangeable and potentially disparate group eating behavioral sequences, but also to permit simultaneously both sociopetal (i.e., encouraging group interaction) and sociofugal (i.e., discouraging interaction) options for each individual in the group.

In previous manned flights, crewmembers have allowed each other the occasional need for solitude even when in communal settings. In the case of the space station, however, there are a number of crucial differences suggesting that such gracious social conventions cannot be taken for granted in the future. The combination of heterogeneous crew cultures, crew rotations, and stress associated with working and living in a remote, isolated, and dangerous environment may dissipate the genteel social conventions exhibited by previous homogeneous crews. Culture-based civilities cannot be relied upon to ensure tolerance of idiosyncracy. Communal settings for group programmed activities (such as eating) must have designed characteristics permitting a wide range of social and non-social possiblities -- which may vary considerably from one individual to the next during a 3-6 month tour of duty. Station settings should be designed to accommodate actual human behavior (backed by thorough experimental data), not the behavior that systems engineers, project managers or flight directors wish that astronauts would display -- even for programmed activities.

What about setting designs for non-programmed activities? While accommodating programmed activities (as humans actually engage in them) will prove challenging, accommodation of non-programmed activities -- those not specifically scheduled for a particular location or time in the crew's day -- should prove even more difficult. Like programmed activities, non-programmed activities may prove critical to crewmember well-being and mission performance, particularly for long-duration stays expected in the space station.

Unlike programmed activities, however, non-programmed behaviors are much more difficult to anticipate and to deal with effectively. These behaviors are harder to anticipate because they may be regarded as only indirectly related to mission performance, and possibly idiosyncratic. Even when anticipated, they are far more difficult to deal with since they sometimes appear to have no necessary temporal or locational dependencies and may exist outside of any consistent, readily identifiable sequence of preparatory, accomplishment and follow-up behaviors. Setting designers must recognize that these non-programmed activities are not devoid of temporal and locational dependencies or behavioral sequencing, but rather that the activities are simply more variable in these areas than most programmed activities.

For example, impromptu conversations tend to occur where people's paths naturally converge or cross. In modern office planning, such conversations are usually not programmed into the design. Unplanned, they tend to annoy workers in the vicinity and are typically dealt with by organizational behavioral restrictions which are inevitably interpreted by workers as an assault on personal freedoms. Recently, space planners have become more sensitive to this recurrent phenomenon. They have begun specifying extra acoustical treatment in conversation-prone areas, allotting small discussion rooms to be left available on an impromptu basis, and even designing alternatives to in-person meetings such as electronic mail. All of these allow the setting to support a non-programmed activity in a way that does not force an intrusion on parallel programmed activities.

For the space station, it is constructive to ask what activities would play the same potentially intrusive role as impromptu conversations in an open plan office. Use of toilet facilities? Use of station-to-ground communications for personal calls? Variable and seemingly unpredictable, these activities must be appropriately supported by the setting design and should be investigated further by space station planners.

### 5.1.5 Fundamental Issues

Behavioral activities as humans actually perform them (as opposed to the way some managers would prefer to program them) are most often complex phenomena. They are composed of detailed sequences of discrete behaviors often overlapping other patterns and sequences of simultaneous, often causally unrelated, behaviors. They are socially/culturally influenced and need not necessarily have identical setting requirements. Designing settings for the space station with the users in mind will be a more complex and costly proposition than some have anticipated.

Faced with inevitable "budget constraints," program managers may be tempted to simplify the setting design task by reducing human behavioral options in the space station. Managers might prescribe (and program) simplified single-file versions of all essential behavioral activities, then design settings (possibly highly automated) to precisely match the activities. These settings would enable performance of prescribed activities while discouraging (due to the settings' inability

to reinforce) the emergence of functionally equivalent behavioral substitutions, complex behavioral simultaneities, and idiosyncratic behavioral clutter. While there is a certain appeal from a purely human engineering standpoint in programming human activities as though people were machines, to do so will have devastating effects on station crewmembers and ultimately on the space station program itself. The manned space program has amply demonstrated that a thoroughly dedicated and programmed "right stuff" astronaut corps is willing and able to function as required even in inadequately designed settings. But there are many reasons why the space station is sufficiently different to warrant extreme caution about overgeneralizing previous experience.

First, it is likely that the station will, after an initial start-up period, be manned by a heterogeneous and culturally diverse crew reflecting the broad population of users that the facility will be asked to serve. Despite the presence of a small "right stuff" astronaut flight crew, remaining crewmembers will hail from a variety of organizational settings including, perhaps, a university-based astrophysicist, a commercial materials processing engineer, and a national security intelligence specialist. Thus the crew as a whole is unlikely to accept an unquestioning dedication to NASA which has characterized previous manned spaceflight crew attitudes, particularly as space station assignments become routine. Each of the crewmembers will have rather narrow reasons for being there and specific responsibilities to diverse constituencies.

As a result, individual crewmembers will not placidly tolerate for long any setting factor which either directly or indirectly constrains their abilities to perform their jobs. If private-sector and other terrestrial organizations learn that station work or non-work settings limit the effectiveness of their personnel, they will not be the satisfied customers so essential for the space station program to become a viable enterprise.

Second, there is the matter of individual control over one's own behavior. For people to perform fully programmed activities, crewmembers must each be willing to surrender their individual freedom of choice of behavior and allow others, through setting designs, to prescribe "approved" ways of doing everything. While previous manned space efforts have demonstrated that astronauts are willing to do everything "by the book," these have typically been short-duration missions performed by unusually dedicated crews. It is reasonable to assume that most people could tolerate a fully programmed, setting-prescribed existence for brief periods of time, but extension to a 3-6 month space station stint seems highly improbable. Given such long-duration stays, individuals will complain bitterly about everything from setting accommodations, to the food, to the programmed activity itself, if only as a way of venting frustration at the perceived loss of freedom of choice over what, where, and how things are to be done. Numerous relevant analogs show that this perceived loss of control or choice in behavioral options has just such negative effects. And if the complaining stops and withdrawal and disengagement behaviors emerge, the situation may degenerate catastrophically.

Third, if people are subjected to programmed settings and behaviors solely to reduce system costs or complexity, then some of the distinction between a human and a purely machine presence on the space station may be lost. Inflexible designs which lock people into "approved" ways of doing things diminish the advantages of a manned presence because unique human capabilities are underutilized. If NASA continues to program human activities as tightly as it programs its machines, and extends this control to settings designed for narrowly prescribed behaviors (whether for efficiency, effectiveness, or cost savings), the people will ultimately rebel and (if not appeased) disengage. It is frightening to contemplate that in the long run the space station program could fail because of a lack of appreciation of setting factors which private industry and other agencies already recognize as important.

It is doubly ironic that the only significant competitor to the American space station program -- the orbiting Soviet Salyut complex -- has already evolved a setting that is (by current standards) exceptionally humane and flexible in its capacity to support diverse crew behaviors. If the traditional American values of personal autonomy and social heterogeneity are to be carried forward into the age of space habitation, these must be designed into the system from the outset.

### 5.1.6 Summary of Space Settings

Space station settings must be designed with humans in mind, as summarized in the following recommendations.

In general: (1) Space station settings should be intentionally designed to enable effective human performance and not just basic human survival; and (2) physical settings should be designed in coordination with anticipated nonphysical (e.g., social, organizational) influences.

On the human factors level: (1) Zero-g ergonomics must be observed in all aspects of station interiors, including height and shape of work surfaces, location of controls and displays, and foot restraints and handhold placement; (2) onboard workstation design should incorporate static postures and dynamic movements that are natural and easy to perform in zero-g; and (3) the space station interior and exterior should be equipped with extensive handholds and footholds on the basis of Skylab experiences.

On the perceptual/cognitive level: (1) Humans can become spatially disoriented even within the small confines of spacecraft cabins, a temporary effect sometimes induced by transient g-loads and a combination of head movements, visual inputs, and lack of normal-g vestibular input (instrument and equipment interfaces should be designed accordingly); (2) all space station interiors should be designed with visually consistent "vertical referencing" systems; (3) windows should be aligned so that the internal "down" and the view of the Earth as "down" coincide; (4) space station interiors should exploit lessons learned in commercial aviation experience to increase the perceived living volume and to reduce "tunnel effects"; (5) station interiors should avoid terrestrial arrangements of furniture, lighting and workstations to help maximize usable space within the limited habitable volume; (6) space station interior and exterior configurations should lend themselves easily to mental (cognitive) map formation by the crew; (7) station interiors should have as many perceptually distinct locations as possible; (8) all locations should provide an eq-

ual sense of safety for the crew, as, for example, in terms of access to safe havens and dual egress possibilities; and (9) space station interiors must be clearly and redundantly color-, sign-, and tactile-coded so that even under the most debilitating conditions onboard personnel know where they are with respect to all other locations.

On the level of ecological behaviors: (1) Space station settings should be designed in recognition of the complex, overlapping sequences of behavior that will be exhibited by crewmembers -- it is not sufficient to design for a set of static, discrete, work tasks; (2) settings should be flexible and adaptable enough to accommodate mixed crew cultures and accompanying diverse expectations; (3) given the low habitable volume of the space station, dedicated space should be employed only when the activity is continuous or so critical as to be considered essential; (4) setting design should not lock personnel into uniform or single channels of behavior which could prove detrimental under anomalous circumstances, but rather should tolerate alternative ways of doing things whenever possible; (5) settings must accommodate both functionally interchangeable and overlapping or simultaneous behaviors; and (6) communal settings should simultaneously permit either sociopetal or sociofugal options for each individual.

## 5.2 Crew Communications

The generation, transmission and processing of information lies at the heart of almost every aspect of space station activity. Remote sensing, laboratory experiments, EVA maneuvers, crew maintenance and satellite repair all require the collection, integration and movement of on-site information to the base station or ground facilities. For highly automated tasks, information exchange may be primarily machine-to-machine, a "task accomplished" display perhaps the only normal human-machine transmission. Issues surrounding machine-machine and human-machine interfacing have been considered previously, so this section deals primarily with human-to-human communication.

### 5.2.1 Face-to-Face and Telemediated Communication

Most functional models of human communication (Shannon and Weaver, 1949; Schramm, 1966; Berlo, 1960) share several elements in common. Typically one person (the source) who wishes to share a thought with another (the receiver) is depicted as encoding a message according to a culturally defined set of rules into a set of observable behaviors. Humans use several channels of transmission (e.g., voice, gestures, facial expressions) simultaneously to send interpersonal signals. The observable behaviors are perceived by the receiver, decoded according to the same set of shared cultural rules, and registered as a corresponding mental image. The receiver may echo a new set of signals to the original source to acknowledge receipt and verify correctness. Signals bounce back and forth (a dialog) until some shared understanding is achieved.

Error may occur in communication because of mistakes in encoding or decoding or because noise interferes with signal transmission. Encoding or decoding errors may result from differences in culture, in social skills, or peculiar intrapersonal information processing styles. (Perception is an active process dependent upon the motivational state of the organism and selective in line with the current needs of the individual.) Noise along the transmission path, masking or transforming the message en route, may degrade the signal and render it uninterpretable. Under these conditions, individuals project their own internal organization onto the remnants of the signal and perceive what they desire or expect to perceive.

The Function of Human-to-Human Communication. Berlo (1969) suggests that communication between two or more people typically has three classes of use: (1) Production -- communication that enables the accomplishment of some task (e.g., coordinate activities); (2) innovation -- communication whose purpose is to generate new ideas (e.g., brainstorming); and (3) maintenance -- communication designed to reinforce social ties (e.g., socializing). At an even more general level, Barmlund (1973) suggests that communication arises out of a need to reduce uncertainty. Numerous empirical studies support the idea that people tend to seek out others as sources of information when faced with ambiguity (Schachter, 1959). Uncertainty arises from doubts about the environment (What's going on here? Was that supposed to happen?) or about the self (Am I okay? Should I be feeling this way?).

A more radical view of communication processes comes from Miller's (1978) treatment of information processing as one of two basic processes of living systems. Building on this notion, Ruben (1982) defines communication as the process of information metabolism, as important to living organisms as the utilization of matter-energy. Thus we are shaped by the food we eat and by the information we consume. Taken literally, people in this view are "information eaters" who seek out sensations according to their individual appetites. Information "hunger" waxes and wanes as a function of time and environmental conditions, and consuming bad information could be as lethal as eating tainted food.

Face-to-Face Contact. As social animals (Aronson, 1972), humans engage in a tremendous amount of person-to-person contact. In addition to exchanging information regarding the coordination of work activities, humans spend a substantial portion of their time monitoring each other for the purpose of social comparison (Festinger, 1954). Much of the perceived self results from direct or indirect feedback from others (Cooley, 1902).

Historically the vast majority of human social contacts have occurred in direct face-to-face settings. Goffman (1956, 1971) uses the term "focused interaction" to describe those occasions when people purposely attempt to communicate by actively exchanging information, assumed to involve a highly skilled set of coordinated performances. Argyle and Kendon (1967) classify the behavioral components of focused interaction according to two major categories -- dynamic features and standing features. Dynamic features are rapid communicative actions during social interaction (e.g., speech, eye gaze, facial expressions, gestures), whereas standing features move more slowly (e.g., interpersonal distance, posture, orientation). Standing features set the stage for faster moving dynamic features by setting limits on each

**TABLE 5.1. COMMUNICATION CHANNELS AVAILABLE AS A FUNCTION OF COMMUNICATIONS MEDIA**

| COMMUNICATION CHANNELS AVAILABLE | COMMUNICATIONS MEDIA | | | |
|---|---|---|---|---|
| | FACE -TO- FACE | VIDEO- PHONE | TELE- PHONE | COMPUTER/ TELETYPE |
| Proxemic (distancing, orientation) | XX | | | |
| Kinesic (gestures, facial expressions) | XX | XX | | |
| Paralinguistic (speech amplitude/rate/ tenor) | XX | XX | XX | |
| Linguistic (semantic meaning) | XX | XX | XX | XX |

person's access to the other. Hall (1968, 1969) provides examples of how interpersonal distance can determine the tone or quality of an interaction by setting limits on the kinds of sensory information that can be exchanged between individuals.

Some theorists (Mehrabian, 1971; Nolan, 1975) find it convenient to distinguish verbal and nonverbal face-to-face human-to-human communication channels. Verbal communication is the exchange of vocal cues with some common symbolic meaning between two or more people, and represents the main carrier for abstract cognitive information. Nonverbal channels (e.g., kinesthetic, visual, olfactory, thermal) appear heavily laden with gross emotional information related to the quality and quantity of autonomic arousal. This is not to say that verbal communication carries no emotional meaning (e.g., paralinguistic cues) or that nonverbal channels cannot be used for symbolic exchange (e.g., sign language), but the general division is useful as a broad characterization. Verbal and nonverbal communication channels may carry parallel messages that are redundant, contradictory, or complementary with one another. Filtering or blocking information from either category results in a modification of overall message meaning.

Telemediated Contact. With the introduction of electronic media (e.g., telegraph, telephone, electronic mail, two-way video) the number and kind of social contacts made by a typical urban dweller has changed dramatically. Entire industries have evolved and prospered based on the electronic transformation and movement of human-to-human messages, a development which has allowed the coordination of individual activities on a global scale and has made possible the effective organization and management of multinational corporations. By the same token, these technologies have changed the nature of information exchanges between individuals.

Several authors have attempted to illustrate the selective filtering that occurs across communication modalities as a function of communication media (Connors et al., 1984; Kaplan & Greenberg, 1976), as presented in Table 5.1. Narrowband media greatly constrict the immediate flow of information across limited-capacity communication links, such as telegraphy; broadband media employ larger capacity links, such as full-motion video. Broadband and narrowband media vary considerably in terms of cost and desirability. For instance, a single satellite transponder that can handle up to 1000 relatively narrowband voice links (e.g., 64 Kbps for telephones) can re-transmit only one relatively broadband full-motion video link (e.g., 6.3 Mbps for picturephones).

Bit rate requirements for video transmission continue to decrease as digital compression techniques become more sophisticated. Compression Labs, Inc. of San Jose, California, offers a 1.5 Mbps color motion video codec for teleconferencing and a 19.5 Kbps "Sketchcoder" for limited motion monochrome video. Widcom (also of San Jose) has a 56 Kbps color motion video codec under development. Several other companies offer slow-scan video devices that allow the transmission of still-frame pictures over very narrow bandwidths. In general, a tradeoff is made between picture fidelity and frame rate in order to accommodate video transmission over narrow bandwidths. A useful comparison of the psychological impact of these various compression techniques has yet to be made.

Evaluation of Media. In general, energy and dollar costs rise with transmission bit rate. Likewise, as one moves closer to face-to-face communication and away from narrowband links, the perception of "social presence" increases (Short et al., 1976). The more indirectly one experiences the physical representation of an interlocutor, the more psychologically remote that person appears. The degree to which psychological distancing facilitates or hinders the accomplishment of tasks depends very much upon the task itself.

For example, Chapanis (1975) describes several experiments in which a "seeker" had to interact with a "source" to solve three types of problems involving verbal and psychomotor skills -- assembling some equipment, searching a database for information, and solving a geographical orientation task. The seeker and source were either in the same room, providing a communication-rich condition, or were situated in remote locations connected by one or more electronic communication links. The main dependent variable was time-to-completion of the tasks. Although solution times tended to increase as the channels of communication became more impoverished, the most striking result was that the presence or absence of voice alone tended to predict the outcome. The fastest five modes had voice links; the slower ones did not.

In contrast to tasks involving strictly objective information transfers, tasks that require transmitting socio-emotional information are com-

pleted faster when video channels are added. Christie (1974) notes that video is more useful than audio alone for complex group discussion and for private conversations. Williams (1974) suggests that the addition of video is more effective than audio alone for maintaining friendly relations. Johansen et al. (1979) reviewed over 130 scientific reports comparing video, voice and computer-mediated human interaction and compiled a useful chart of strengths and weaknesses of each media. Interestingly, these authors point out that narrowband computer conferencing encourages greater equality of participation and other social benefits besides reduced costs (Vallee et al., 1978).

To date, no one has created a media-by-task evaluation matrix large enough to encompass all or most variations in tasks and media available. With the proliferation of hybrid mixed media devices such as voice systems with slow-scan TV and computer graphics, plus an almost unlimited number of tasks to be performed, it is unlikely that anyone could ever undertake that kind of exhaustive comparison process. However, Geller (1980) suggests a promising but as yet untried alternative research strategy: Media might be studied according to their generic features and tasks decomposed into their component parts (Figure 5.1). Well-studied psychological mediators in the form of hypothetical constructs could then be used to predict overall system effectiveness by estimating the impact of generic media features on the performance components of the task.

### 5.2.2 Space Station Interpersonal Communication

The technological complexities of providing reliable telecommunication links for the space station are described at length by Dickinson (1983). The focus here is not on specific technical options but rather on design aspects of supportive interpersonal communication systems requiring prompt attention. Several assumptions have been made about the function and process of human-to-human space station communications:

1. Humans may be viewed as information metabolizers, their central nervous systems integrating multimodal information from the physical and social environment to produce knowledge. Behavioral adaptation is highly dependent upon accumulated knowledge. Human-to-human communication arises out of a need to reduce uncertainty; incomplete knowledge generates an appetite for information.

2. Direct face-to-face communication involves multichanneled parallel processing. Vision, audition, olfaction, touch and thermal information all contribute to message meaning. Electronic media selectively filter different information channels, thus transforming message quality and content. In general, the lower the bandwidth of communication the greater the psychological distance between interacting individuals.

3. Task accomplishment and personal adjustment are highly dependent upon adequate information exchange. Too little or too much information of a given kind can lead to maladaptive behaviors and mission failure.

Aboard the space station there must be within-crew communication; given an interior shirtsleeve environment, most of this communication will occur in direct face-to-face encounters. Between the base station and the immediate space environment there must be telecommunication among crewmembers, those out on EVA, and with the crew of piloted vehicles such as the shuttle. Telecommunication between station and ground-based personnel and communication among ground-based units is also necessary.

Onboard: Within-Crew Communication. It is now known that humans can work and live in space, and that spacecraft working/living quarters can provide a shirtsleeve environment (Cooper, 1976). However, zero-g and spacecraft design can still have considerable impact upon within-crew face-to-face contact. For instance, the redistribution of fluids within the body in zero-g causes facial puffiness which distorts an important channel of nonverbal human-to-human communication (Connors et al., 1984). Zero-g also causes changes in neutral body posture (section 5.1.2); when floating freely about the cabin, body movements become less spontaneous and communicative because of their increased importance in maintaining appropriate body positioning. Thermal and olfactory cues, which contribute to a sense of presence and affect physiological functioning, are disrupted by the operation of mechanical air handling devices and the lack of convection in zero-g. Tactile communication may be used less often because of its exaggerated impact on body movement in zero-g. And high levels of ambient noise, plus atmospheric attenuation within the space station, may interfere with vocalizing -- the principal channel for linguistic communication.

While little can be done about the effects of zero-g on human anatomy, there is no excuse for designing an environment with unnecessary impediments to human information exchange. Design criteria for space station communications settings must include a general specification that within-crew communications should be optimized. Noise abatement, perhaps by reducing fan and ductwork noise, is a high-priority item. Maintaining cabin pressures and atmospheric gases that support high-quality vocal communication should be given special attention. Visual and kinesthetic access to co-workers within the shirtsleeve environment is essential for some cooperative tasks. The roles of thermal, tactile and olfactory stimuli is unclear and should be studied further.

In addition to facilitating the accomplishment of many tasks, a good onboard communication environment can foster feelings of group solidarity. Equally important is the ability to distance oneself from others when privacy or solitude is desired. This may be especially important for groups confined within a remote, isolated habitat. New means of person-to-person communication, including but not limited to electronic mail and voice /image storage and retrieval systems, should be explored as supplements to face-to-face communication.

Local Calls: Communication in the Near-Space Neighborhood. A special requirement for space station activities is a reliable communication link for EVA crewmembers. Even if the astronaut has access to extensive databases, perhaps via a head-up helmet display to help provide construction or repair details, he still must keep in touch

with others within the base station module to monitor progress and to request aid in the event of unanticipated trouble. Tasks involving the cooperative effort of two or more astronauts on EVA require direct telelinks between co-workers in addition to the crew/station link. In the past, umbilicals or radio frequency connections have supplied voice communication and biomedical data. In an increasingly cluttered space environment, alternatives must be provided for local and remote communication. (Lightwave and infrared links are two possible candidates.) Both life support equipment and moderate physical exertion can sometimes render verbal communications unintelligible. Regional dialects can further hinder communication under stress (Popov et al., 1973), so alternatives to voice communication channels should be explored -- such as the sign language systems used by scuba divers or hand-operated voice synthesizers. These supplementary channels also provide redundancy and emergency channel capacity.

Choice of station-to-shuttle and station-to-station communication channels will vary according to the function being monitored or controlled. For example, routine docking maneuvers may be handled by highly automated processes, with voice links available as a redundant monitoring feature. Video links might supplement voice communications when spatio-temporal information must be conveyed. Continuous communication between two or more inhabited platforms requires broadband channels to facilitate teleconferencing and other media useful in group problem-solving. Potentially, station-to-station links could approach the same carrying capacity as station-to-ground or terrestrial networks.

Long Distance: Station-Earth Communication. Human-to-human communication between ground and space will reflect the nature and degree of station autonomy. As the locus of control for space missions moves from Earth to space (and as onboard expert systems are developed to replace ground personnel), fewer contacts will be needed between the station crew and operational personnel on the ground. However, the number and quality of ground-to-station links might actually grow as the number of commercial, scientific and other users increases.

Currently, most ground-to-space communication is funneled through Mission Control; messages are forwarded to the shuttle by the capcom. In the future, commercial interests will expect direct contact with their own onboard personnel and others responsible for specific projects. In light of this, multiple direct-access communication channels should be considered for human-to-human ground-to-space contact. While this represents a marked departure from the existing highly controlled access, it reflects a changing attitude that may prove essential for space station program success.

A dynamically allocated communication link that can handle multiple voice, video and data transmission is desirable for ground-station communication. A parallel-access system should provide channels for both personal and task-oriented communication, with a provision for privacy assurance. More research is needed on the use of communication media as an aid in maintaining crew morale. The availability of a "call home" social support network may also be critical in long-term missions. Tapping into the current satellite-based news/entertainment networks could help keep the crew in touch with Earth culture. Proximity is a powerful mediator of intimacy and attraction (Argyle and Dean, 1965; Heider, 1958), so communication bandwidth (representing a kind of distancing phenomena) may have a major impact on ingroup/outgroup formation, trust, compliance, conformity, and even altruistic behavior. To discourage ground/space clique formation and attitudinal dichotomies, the broadest possible bandwidth of communication between Earth and the space station is advisable.

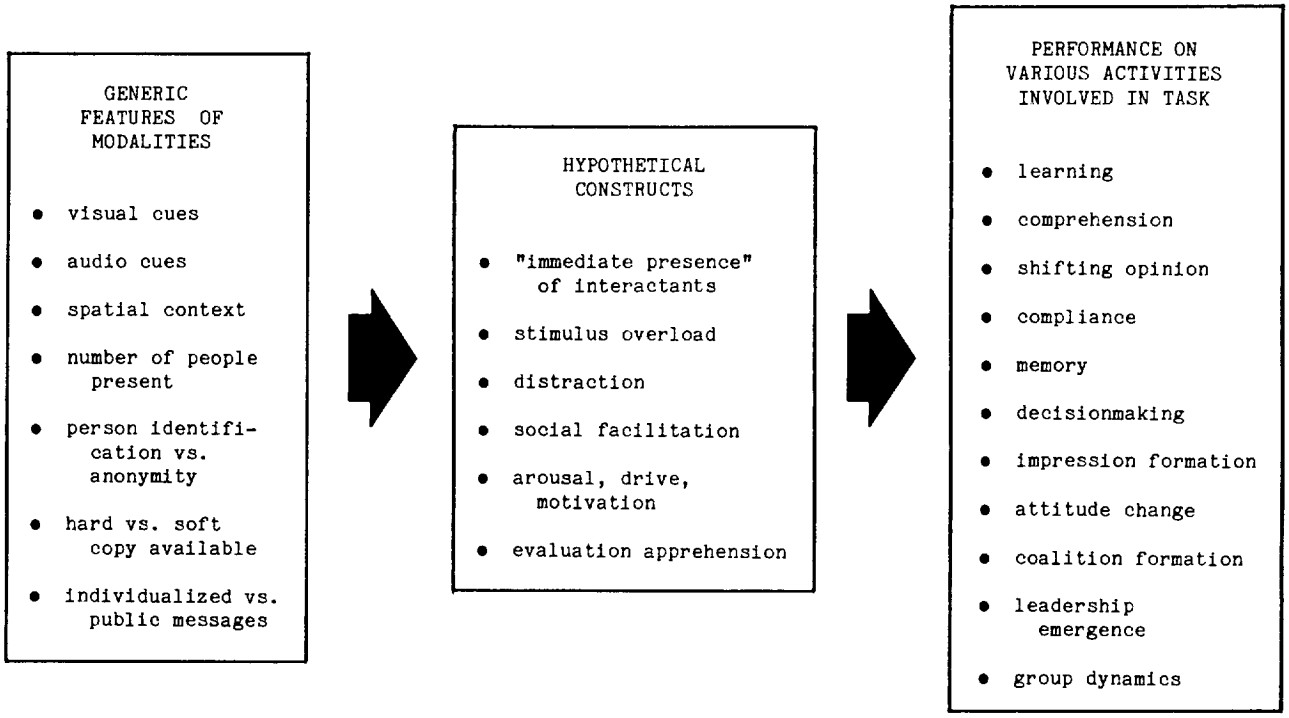
However, to prevent information overflow an intelligent communication network should be deployed that recognizes priority inputs for queuing purposes. The majority of uplinked messages should be of the personalized, store-and-forward variety to provide the crew with maximum time flexibility. Crewmember time should not be dominated by the "tyranny of communication." This applies both to task-related messages and to social and emotional support communications. A coherent set of guidelines governing crew availability for outside contact should be developed with input from experienced astronauts. If autonomy is desired for the space station crew, real-time links should probably be reserved for communications that require immediate feedback and should be negotiated in advance between ground and station personnel.

An efficient method of sorting and responding to messages is for each message to be addressed to a particular person and for that person to receive it directly. To handle parallel message input it is recommended that multiple mixed-media workstations be incorporated into space station design -- at least one terminal per crewmember. These workstations might be compact portable units similar to present-day personal computers. These could (1) double as backup display terminals for onboard monitoring and control functions; (2) serve as word processing stations for personal/scientific log-keeping and letter writing; (3) supply access to audio, video and text-oriented databases used for onboard education, training and recreation; and (4) allow the display of expert system output in the context of person-to-person teleconferencing. Multiple terminals are essential because they are likely to be used heavily both during and after work hours, and because they could be located in or moved to areas providing visual and auditory privacy such as crewmembers' personal quarters.

Terrestrial Networking: Communicating on Earth. To coordinate its activities on Earth, NASA has already established a series of human-to-human communication networks using voice and video teleconferencing as well as electronic mail. If the numerous shuttle mission control ground personnel were reduced by automation to a small staff for day-to-day space station operations, these networks might be called upon to gather expertise from individuals throughout the system in case of unforeseen events or emergencies. If such a system is to be utilized effectively, an updated and expanded teleconferencing network should be established for mixed media transmissions including audio, video, computer text, graphics, and hard copy formats. The station crew should have direct on-call access to this network as a basic resource.

If completed early enough, the updated terrestrial network could be used as a testbed for the

FIGURE 5.1. RESEARCH FRAMEWORK FOR STUDYING COMMUNICATION MODALITY EFFECTS ON TASK PERFORMANCE




development of space station communication systems and as a training device for space crews to become more familiar with the conduct of sophisticated electronic meetings. NASA already has considerable expertise in teleconferencing technology and could take better advantage of its experiences in developing a dynamic responsive network.

Conclusions. The kinds of communication systems made available to space station inhabitants will significantly affect task performance. As information consumers, station crewmembers will seek data from their machines, from other crewmembers, or from the ground, depending upon their needs. As uncertainty increases, their appetite for relevant information will grow. As information producers, the crew must communicate with terrestrial consumers. It is incumbent upon the designers of onboard, near-space, and terrestrial information/communication systems to create conditions best permitting critical information to pass from source to recipient in the most efficacious manner possible. Current technologies should be systematically compared and tested in appropriate experimental settings so that informed judgments regarding final system designs can be made.

### 5.3 Space Station Organization

Numerous questions were raised during the workshop about autonomy and the human element in space, such as: To what extent should the space station operate independently from ground control? What is the appropriate degree of autonomy of individuals within the larger organizational group structure of the station crew? To what extent should machines operate independently from direct, real-time control by humans? The answers to these questions depend to a large degree on issues of organizational design -- specifically, how best to design station organization and management systems (and relationships with ground operations) to achieve the highest levels of performance at lowest cost.

Designing for organizational performance and effectiveness is a technical discipline concerned primarily with ensuring that the right people are focusing on the right tasks, are using the proper information, technology, incentives, and controls to perform these tasks effectively and efficiently, and are coordinating their efforts so that the organization's overall objectives are advanced. Though much remains to be learned, a considerable body of data already exists on the behavior of people in formal, complex organizational settings and on the behavior and motives of organizations themselves. Perhaps the single most important result to emerge from this research is the recognition that social and organizational systems are subject to design choices much like physical and technological systems (Kotter et al., 1979).

Human autonomy is an overt design issue responsive to deliberate design decisions. The organizational relationship between space and ground is constrained by task and technology, but a wide range of feasible alternative models exists. If the underlying philosophy of organizational design is established early enough, technology can be

designed to support and facilitate the organizational system.

This section draws on theoretical and empirical research about human behavior in organizations, both on Earth and in space, to develop alternative models of space/ground and intra-station organizational systems. Human-machine and automation systems can facilitate autonomy and effectiveness. Certainly, an important variable of special concern is technology, particularly information technology in the form of computers, expert systems, and robotic tools. But the analysis cannot focus exclusively on the human-machine interface or on human-machine relations. Ignoring the system properties of a human organization while designing any part of it invites unintended negative consequences.

### 5.3.1 Space/Ground Autonomy

In recent years, the philosophy of American corporations regarding relations with subunits has shifted significantly. Overall organizational philosophy, in-house cultural norms, and communication and authority relationships among organizational subunits and individuals play a significant role from the standpoint of design. Peters and Waterman (1982) claim that the single most important element in this emerging viewpoint is "the ability to be big and yet to act small at the same time, [evoking a sense of] spirit among the people....[Excellently managed companies] push autonomy remarkably far down the line." In these successful organizations, autonomy equates to a real and significant impetus toward structural decentralization. This modern emphasis on autonomy is made possible by the interesting phenomenon of "loose-tight" organizational controls and fresh assumptions about the nature of people. Autonomous organizational designs are founded on the belief that individuals can and will respond with achievement-oriented behavior if provided substantial autonomy.

Many large successful American companies have developed sophisticated methods to provide autonomy without relinquishing overall control, by employing what are called "simultaneous loose-tight properties." Organizations operated according to the loose-tight principle are rigidly controlled while encouraging entrepreneurship and innovation from the ranks. Major characteristics of "loose-tight" include (1) a strong commitment to mission and to specific goals and objectives (an a priori achievement orientation), (2) a set of shared values and rules about discipline, details and execution, (3) evaluation and reward largely based on end-result performance and achievement, and (4) significant freedom of action and discretion within a subunit or by an individual in pursuing mission objectives.

Loose-tight control structures are made possible by modern communication and information systems. These structures emphasize monitoring end-result measures of subunits and downplay the details of how an achievement is carried out. They require timely and accurate information systems which today are routinely available and which have reduced the time lag between occurrence of critical events and subsequent awareness and corrective action. Loose-tight control systems are output-oriented due to their strong goal orientation and by their focus on evaluation of outputs (achievements) rather than inputs (process).

The principal costs of autonomy are that, in general, more time is consumed, more "blind alleys" are pursued, and short-term efficiency is not always optimal. In the space station the cost parameters are especially high because of significant transport and life support expenses. But even in this case the benefits could be substantial, including closer attention to problem-solving and decisionmaking information, higher motivation, significant improvement in quality, enhanced productivity, and superior adaptability. Industrial experience with autonomous systems has demonstrated that less surveillance of subordinates is required, resulting in lower overhead costs, less supervision, smaller staffs, faster decision times, and fewer bureaucratic entanglements. For a space station program this may translate into significant savings on ground support.

There are serious and legitimate concerns about how much human autonomy should be granted to station crewmembers. For every task or decision given to the station, the potential costs and benefits must be carefully evaluated on a function-by-function basis. An assessment of past relationships between ground and space raises the possibility of overcontrol and suggests that greater human autonomy might be more effective in many future circumstances. The space station is intended to be evolutionary, implying a goal of adaptation to changing conditions and technologies over time. Non-autonomous organizations are notorious for their failures to adapt to changing circumstances.

An interesting example of the potential demotivating influence of overcontrol from the ground occurred during the last Skylab mission in December 1973 (see also section 5.3.2). According to the flight director at the time: "We send up about six feet of instructions to the astronauts' teleprinter every day, at least 42 separate instructions telling them where to point the solar telescope and which scientific instruments to use. We lay out the whole day for them, and they normally follow it to a T. We've learned how to maximize what you can get out of a man in one day" (Balbaky, 1980). After more than a month in space, three highly trained and disciplined Skylab astronauts "turned off the radio and refused to talk with Houston Mission Control," an event which has been characterized as the first "strike in space" (Cooper, 1976).

Traditionally, daily crew scheduling (also known as work activity planning) has been done in advance by ground-based personnel, representing the low-autonomy option for a space station crew. Complete schedule preparation by space-based personnel, the high-autonomy option, has yet to be tried though it now appears likely that "expert system" AI software could perform this function on a long-term facility, increasing station crew autonomy and effectiveness at little cost. Automated schedule-planning offers greater human satisfaction, motivation, and productive efficiency, a positive sense of control over one's own life, and greater responsiveness to real-time on-site workload realities and to unforeseen delays.

Scheduling is a complex matter. Mission task requirements must be matched with constraints and resources. The end product is a timeline in which task responsibilities are allocated to specific crewmembers at specific times. Past experience shows that the complexities of preparing schedules in real-time lie beyond the human ability to fully optimize, necessitating a cumbersome trial-and-error approach. Station scheduling could not be

adequately automated using interactive PERT/CPM schedulers because these cannot easily include constraints other than time available and tasks to be performed. Alternatives include integer programming-based interactive schedulers and intelligent programs such as the frame-based expert systems (KNOBS) used for tactical air command. It appears that an "expert system" activity planner is feasible. MITRE corporation is currently working on a prototype system under contract to NASA (Mogilensky et al., 1983).

What are the design parameters that specify how the expert system should interact with the crew? The wrong approach is to design an expert system which computes an "optimal" activity plan based on objective task demands, station constraints, and station resources, which is then presented to the crew as their schedule. Such a system would still be insensitive to real-time delays and unforeseen changes. The debilitating psychological effects due to a perceived "loss of control" would continue under this low-autonomy approach.

AI technology provides an opportunity to design a human-machine system incorporating a high-autonomy, real-time interactive activity planning approach. Crewmembers would have the authority and ability to suggest, prefer, specify, even override objectively optimal timelines. Intuitive insights offered by the crew may provide superior results in cases where seemingly insignificant preferences evoke strong subjective reactions by individual astronauts. Expert schedulers could organize work cycles to respect natural circadian rhythms, or design work periods to meet involvement-in-work requirements. Ground operations personnel should specify overall mission priorities, provide detailed technical data to serve as computational parameters regarding requirements, resources, and constraints, and should undertake preliminary trial scheduling runs to help establish gross priorities (Table 5.2). But final acceptance, rejection, or modification of any timeline proposed by the expert system should remain the exclusive province of the space station crew.

### 5.3.2 A Primer of Organizational Design for Effectiveness

Organization theory is based on the proposition that the structure of an organization (its division of labor, allocation of authority, workflow, evaluation and so forth) has a significant impact upon commitment, performance and retention by its personnel -- which in turn affects system output. This does not imply that personality characteristics or leadership may not influence system performance, but merely that it is generally far simpler to modify organizational structure to influence behavior than to alter human personalities or to locate the perfect leader (Perrow, 1970).

Scientific Management Principles. Early research in organizational analysis led to the development of scientific management principles emphasizing optimization of the technical subsystem. Analysis focused on the individual or micro-level of job design, the physical features of a job, and the relationship between workers and tools. Managers plan and workers work, a distinction rigidly maintained because of the assumption that specialization in and superior aptitude for each

**TABLE 5.2. FUNCTIONAL ALLOCATION OF CREW SCHEDULING ACTIVITIES**

| SCHEDULING ACTIVITY OR TASK | LOCATION OF ACTIVITY OR TASK | | |
|---|---|---|---|
| | GROUND OPERATIONS | EXPERT SYSTEM | CREW |
| Design of Expert System | XXX | | |
| Maintenance/ Adaptation of Expert System | XXX | | |
| Assemble Input Data: Time Estimates, Resource Requirements, Constraints | XXX | | |
| Input Daily Task Priorities and Update Information | XXX | | X (minor) |
| Preliminary Timeline Computations (Days in Advance) | XXX | XXX | |
| Compute/Review Next-Day Timelines (overnight) | XXX | XXX | |
| Review/Update/ Recompute Morning Timelines | | XXX | XXX |
| Approve/Accept Final Morning Timelines | | | XXX |
| Graphically Represent Timelines | | XXX | |
| Recommend Deviations from Daily Timelines | XXX | | XXX |
| Contingent Recomputation of Daily Timelines | XXX | XXX | XXX |

function must produce optimal output and effectiveness. This gave rise to autocratic decision and authority structures. Perhaps unintentionally, practitioners of scientific management assume that workers are dull, stupid, and incapable of task planning or decisionmaking. Indeed, when describing some of his work measurement and design efforts in a steel plant, Taylor (1911) -- the founder of scientific management -- wrote that suitable workers had the mentality of an ox, that mentally alert and intelligent men would be wholly unsuited for the work, and that the workman best suited to handling pig iron is "so stupid that he must be trained by a man more intelligent than himself into the habit of working in accordance with the laws of this science before he can be successful." Echoes of these assumptions are still heard in present-day applications, as in the design of monitoring and control functions in airplanes and spacecraft. According to one NASA engineer who asked to remain anonymous (personal communication, 1983): "If you give a pilot a button or a handle, it's damned certain he'll use it and screw up the intent of the system!"

Focusing exclusively on the technical subsystem as a means for optimizing production prevents the manager or organizational designer from anticipating certain interdependencies between the technical subsystem and the social structure of the organization. The consequence of work plans and work organization focused tightly on the human-machine interface alone produces unimplemented plans, considerable unanticipated strife, inefficiency, and substantially increased costs of producing the desired product or service. Pioneered in the late 1800s by Taylor, scientific management still flourishes despite its many well-known problems.

For example, scientific management principles have been implicated in the so-called "strike in space" during the 1973 Skylab mission (Balbaky, 1980; Cooper, 1976). To maximize mission objectives in this final leg of the program, ground control removed virtually all slack from the astronauts' schedule of activities, treating the men as if they were robots. To accommodate all planned activities, ground control shortened meal times, reduced setup times for experiments, and made no allowance for unsystematically stowed equipment. Favorite leisure pastimes -- watching the Sun and Earth -- were forbidden (Weick, 1976). On December 27, 1973, the astronauts staged a day-long sitdown in space, closing off communication with mission control for twenty-four hours and refusing to work until management had prioritized its work demands. (The strike cost NASA $2.52 million, assuming $35,000/astronaut-hour in space.) A fundamental organizational problem in any extended space mission is the distribution of authority between ground and space. Skylab crewmembers had minimal autonomy in terms of the pacing, sequencing, and conditions of work -- a poor organizational design choice ultimately derived from a limited "scientific management" conception of the worker.

Another relatively recent industrial debacle caused by scientific management has been called the Lordstown Fiasco (Boyer and Shell, 1972; Business Week, 1972; Salpukas, 1972; Time, 1972; Wall Street Journal, 1972; James, 1975). In the early 1970s, Lordstown was a General Motors Vega assembly plant which produced 2,000 new cars a day using 18 miles of conveyor belt and 2,800 people on the assembly line. On the line, new Vega's moved forward every 36 seconds under computer control. Each worker performed carefully engineered and prescribed assembly duties, repeating the same motions 800 times during a single shift.

It may interest those who will determine the extent of space station automation to learn that the Lordstown plant was one of the most highly automated in industry at the time, with 26 robots making 520 welds in each car. Although the workforce had received quality awards from GM, a corporate reorganization shifted oversight of the plant to a management team still practicing undiluted scientific management. To cut costs and increase productivity, line manpower was slashed by 700 workers and the number of separate operations for which each worker was responsible was increased. Many employees could not keep up with the faster work pace, often falling so far behind that they would ride the moving belt down the line trying to complete their tasks and then run back to their assigned station to begin the cycle again. Soon after the "efficiency" layoffs, unanswered employee complaints about the work speedup resulted in a disciplinary crackdown by management, worker sabotage (e.g., slit upholstery, scratched paint, bent gear-shift levers, fire in the assembly-line control shed), a work slowdown, high absenteeism, and a strike lasting 22 days. After the speedup was rolled back, one GM executive noted that the corporation lost more in the strike alone than it anticipated saving by laying off all those workers.

Most automation development in the U.S. has stressed machinery, computer control and other technical aspects of the system while ignoring human variables. One variable which has changed in contemporary organizational systems is input characteristics of the workforce. Today, employees are more highly educated and independent than their predecessors of a few decades earlier. The workforce is increasingly capable of planning its own work, yet the basic management/labor relationship has remained constant -- managers plan and determine the technical characteristics of the work, workers are viewed as extensions of the machine, and demands of the machine remain supreme. Failure to plan and to design for interdependencies -- to appreciate organizations as complex sociotechnical systems -- inevitably leads to unanticipated difficulties.

Human Relations Management Principles. One result of the early developments in organizational analysis was the generalization that authoritarian structures are associated with low employee morale, leading to low productivity, lack of commitment, and high turnover rates where alternative job possibilities exist. Consequently, a second school of thought emerged which argued that more democratic structures emphasizing participation in decisionmaking would lead to high morale and higher levels of productivity.

Supporters of the Human Relations School of Management insist that social factors, not technical ones, are the most important determinants of performance. This idea was first articulated by Mayo (1946) and by Roethlisberger and Dickson (1933), following their exciting studies on productivity gains during the 1930s in the Western Electric Company's Hawthorne plant. They discovered that a great deal of behavior exists in organizations which is not rationally planned by management, that much behavior is not rational at all

from the organizational point of view, and that consequently there is much output and behavior which is "sub-optimal." The human relations school focuses on the informal organization, group dynamics, supervisory style, and their collective impact on the formation and maintenance of worker attitudes, values, goals, and productivity. At the time it was startling to discover that group norms existed regarding appropriate levels of production, that these informal norms were reinforced by informal associations of workers, and that work group norms were more highly correlated with actual productivity than official management standards.

Participative management and decisionmaking are cornerstone ideas in the human relations school. Relevant information must be shared with employees before decisions are made. Workers are encouraged to participate in generating alternative solutions and to be as self-directing as possible. Rather than attempting to eliminate social influences in the work setting, human relations management tries to design organizations and to tailor managerial styles to facilitate good social relations among employees and between management and workers. Work groups are viewed as the basic organizational decision unit. When participative methods are used to make decisions, implementation of a decision is less problematical if workers have played a significant role in the process and are committed to their choice. Group dynamics reduces the level of formal supervision, since informal group norms are more consistent with formal policy under participative conditions.

However, as the results of implementation were carefully studied, consistent support failed to materialize. Good leadership (defined as attention to human relations) did not necessarily result in high morale, nor did high morale always lead to high productivity. Carefully designed studies began to find inconsistencies -- some data supported the human relations approach, but much did not. The human relations approach was found to have practical shortcomings. Managers must receive specialized training to develop a repertoire of skills necessary to facilitate group decisionmaking. Participative decisionmaking is especially difficult to implement because of its many nuances and subtleties, and because it sometimes degenerates into worker manipulation. Also, it is seldom possible to find a solution everyone likes, so managers must be willing to accept dissatisfaction and conflict while facilitating decisions. Participative decisionmaking (requiring collaboration and consensus-building) is more time-consuming than centralized decisionmaking and is infeasible when quick decisions are needed. Finally, a human relations orientation demands that managers be able to suppress their need for control of the decision process and the accompanying sense of power.

Research to measure the effectiveness of scientific management and human relations approaches shows that neither is universally applicable. Each is often applied inflexibly in organizations as if it were the one best way to organize and manage, and as if variations in organizations, workforce characteristics, technologies and environments were of little consequence in organizational design. Early generalizations derived from these approaches have given way to a richer conceptualization of organizational structure and performance (Perrow, 1982).

For instance, in the modern conception there is nothing wrong <u>per se</u> with a centralized bureaucratic structure as long as tasks are routine and the technology is well understood. Workers can still be treated well and leadership can be participative. However, as tasks or environments change, rules and procedures must be appropriate for the changed circumstances -- perhaps the biggest failing of bureaucratic, centralized structures.

On the other hand, when tasks are nonroutine, centralized rule-based structures are inefficient and often ineffective because fixed rules are applied inappropriately to changed circumstances. Instead, discretion must exist at levels where unprogrammed decisions are required. There will be a correspondingly high cognitive load on the workforce, and the knowledge needed will be extensive. In organizations faced with nonroutine tasks, whether due to environmental or technological uncertainty, the relevant criterion for success is not classical efficiency but rather the facility for problem-solving and the ability to discover novel solutions under changing circumstances. Note also the new concept of organizational environment -- the environment presents problems and opportunities for the organization and can stimulate structural change.

<u>Contingency Approach to Design.</u> Attention must be given to both technical and social systems when designing organizations because of their mutual interdependence, a more balanced view sometimes called the sociotechnical approach to organizational design and change (Trist and Bamforth, 1951; Trist, 1960; Miller and Rice, 1967). More important, there is no one best way to design an organization. The appropriate design depends on a complex set of interrelations among designated technologies, tasks, goals, workforce characteristics, and an organizational environment. This approach has come to be known as "contingency theory" after the important work of Thompson (1969) and Lawrence and Lorsch (1967, 1969). A contingency approach is frequently used in contemporary organizational design because it focuses on the pragmatic concerns of effectiveness and performance. The principal assumption is that there is no one best way to organize, but that all ways of organizing are not equally effective. In fact, organizational effectiveness is contingent upon an appropriate relationship among organizational structure, environment, technology, and tasks (Galbraith, 1973).

One of the contingency approaches best applicable to space station autonomy planning stresses information flows and their influence on organizational structure (Galbraith, 1973, 1977). Among the various elements in a system, the flow of information is arguably one of the most critical (Scott, 1981). In Galbraith's approach, organizational environment and technology are major sources of systemic uncertainty. Uncertainty enters organizations by affecting the work or tasks they perform, and the greater the task uncertainty the more information that must be processed by decisionmakers during task execution to achieve a given level of performance. Thus information processing requirements increase as a function of environmental and technological uncertainty and of interdependence of workflows, an important influence on structure. Structural arrangements determine information processing capacity of an organization, and some are better than others for a given

level of uncertainty.

Organizations can make structural modifications to adapt to increased demands for information processing. Listed by increasing capacity to process information, the first four structural mechanisms comprise the "mechanistic" model and include: (1) the hierarchy of authority wherein exceptions to standard procedure are referred upward for centralized decisions; (2) rules and procedures to cover standard problems; (3) planning and goal-setting which are forms of delegation to decentralize decisionmaking; and (4) a better trained professionalized workforce. Delegation reaches its most highly developed form in professional organizations (Scott, 1981).

These common features of complex organizations are often referred to as the "characteristics of bureaucracy," where "bureaucracy" is defined value-free as a type of formal organization. Examples of organizations with these conventional structural features include government bureaucracies, military organizations, large religious organizations and many industrial firms. Using these conventional structural mechanisms, organizations confronting low or moderate levels of uncertainty and information processing requirements can respond well to their task demands. However, when the organization itself becomes more diverse or the levels of uncertainty and interdependence are higher still, the mechanistic model is inadequate to process the increased levels of information necessary to achieve a high level of performance.

As task uncertainty increases, the number of exceptions to rules increases until the hierarchy is overloaded. At this point organizational changes must be made to maintain the desired level of performance either by reducing the amount of information to be processed or by increasing processing capacity. These in combination reduce the number of exceptional cases passing through hierarchical channels in the organization. By creating slack, more resources are consumed -- scheduled times or weight allowances are increased, or more labor hours are put in on a job. Creating self-contained tasks changes the organization from a functional design to one in which each subunit has all the resources it needs to perform its tasks. This combines decentralized decisionmaking with the resources necessary to get the task done and is a substantial shift in the authority structure. Investing in a vertical information system assumes computer assistance and involves collecting information at the points of origin and transmitting it to the appropriate levels in the hierarchy. Clearly, contingency theory strongly emphasizes formal organization structure. It underemphasizes social and behavioral elements in organizations, including the significance of power relationships and coalitions in decisionmaking. It also assumes that rational, logical design choices will invariably be implemented as intended.

Framework for Space Station Organizational Design. To decide the appropriate level of autonomy for the space station, the organizational designer has a number of variables to take into account and a specific set of design tools with which to work. Initial variables include characteristics of the environment and the set of tasks or missions to be accomplished. Decisions must be made about the level of technology and the degree of machine automation. Design tools include organization structure (with reward and measurement systems) and people, determined by managerial decisions based on what characteristics to select and what skills to develop in station crew training programs.

### 5.3.3 Space Station Applications of Organizational Research

Several issues are important in deciding the appropriate level of space station autonomy. Twenty years of organizational research in contingency theory has clearly demonstrated that a single best structure for successful organizations does not exist. The systems concept of "equifinality" emphasizes multiple pathways to the same outcome. There are several satisfactory ways to structure the ground/station organization (each with different strengths and weaknesses) and many other ways that are unlikely to be successful.

Second, space station organizational structure should be regarded as adaptive and changeable, not static or fixed -- the systems concept of "morphogenesis." This structure must adjust to changing levels of technology, modifications in the number and character of space station missions, shifts in the astronaut population, and increasing knowledge about working and living in space. This is particularly applicable to the ground/station division of labor. With appropriate funding, artificial intelligence and computational technologies are likely to advance very rapidly, making it possible to shift more functions to the station itself. Organizations must maintain a balance between flexibility and stability (Weick, 1977, 1979).

Finally, different ways of organizing will be appropriate for different classes of space stations, depending upon the goals and missions pursued, the degree of task specialization, the technology in place, and so on. Many varieties of space station systems may be flown in the near future, possibly specialized according to mission such as commercial, military, scientific, and so forth. Each may best be served by different organizational structures.

Computers in Organizations. Decisions regarding the level of computer power and database facilities on board the space station will strongly influence on-orbit autonomous decisionmaking capability. Organizational research shows that power derives from access to computers and data. Early studies of the impact of computer technology on organizations focused on shifts in the organizational power structure. For example, a single, large mainframe computer system is a valued resource. Decisions on where to physically locate the machine, and regarding who would have administrative control over access and use, had strong implications for the relative authority and control of organizational subunits (Whisler, 1970). Control of essential information is a source of political power in any organization (Hickson *et al.*, 1971; Pfeffer, 1978; Pfeffer, 1982; Schoonhoven, 1983). The advent of large-capacity personal computers lessens the traditional dependence on mainframes, fragmenting political power and imparting increased autonomy to organizational subunits.

Paralleling the above is the manner in which NASA implements computer capabilities in spacecraft. Generally the most powerful and extensive

computer facilities remain on the ground, along with computer monitoring and control of spacecraft functions and operations. If extensive decision-making autonomy for the space station and its work force are desirable, this cannot be achieved unless most essential data processing capabilities reside on board the station itself. Without unrestricted access to the requisite data and data processing facilities, the space crew is unlikely to achieve its full autonomous potential. If NASA locates substantial essential computerized systems on the ground, the sophistication of possible station organizational structures will be greatly constrained. Microelectronics technology makes possible extensive redundant, distributed onboard systems, but control over which data will be accessible remains a source of organizational power.

Professional Workers and Technology. Research into the relationship between technology and organizational structure has determined that greater technical complexity is associated with greater structural complexity, except when professionals constitute a significant part of the workforce. In this latter case, structural complexity is not always manifested in traditional ways (e.g., more hierarchical levels). One alternative is to add complexity to individual job responsibilities by expanding worker skill repertoires. Rather than subdividing the work and allocating it to different work groups or departments, complexity may be surmounted using more highly qualified and flexible performers. This response is particularly effective when the work is also uncertain, a condition under which preplanning and work subdivision give poorer results (Scott, 1981). Because of the complexity of future missions and the high level of problem-solving ability that will be required, the current trend toward more diverse professionalism in astronaut selection is likely to continue. These people have a high educational attainment, high intelligence quotient, positive work attitudes and a strong achievement orientation, and come from occupations categorized as professional.

Professionals work in formal organizations most effectively under two generalized types of structures. The first are called autonomous professional organizations wherein officials delegate responsibility for defining and implementing goals, for setting performance standards, and for seeing that standards are maintained within the professional group (Scott, 1965). The professionals then organize themselves to assume these responsibilities. There is a sharp distinction between tasks for which the professionals assume responsibility and those over which administrative officials have jurisdiction, even when professionally trained people occupy administrative positions (e.g., university deans). Administrators thus have jurisdiction over issues related to keeping the organization functioning, but not over professional tasks (Goss, 1961). Substantial discretion and autonomy are granted the professionals and they are subject only to collegial review and control systems. Examples of autonomous professional organizations are general hospitals, elite psychiatric hospitals, medical clinics, research-oriented universities, elite colleges, and scientific institutes or "think tanks" (Clark, 1963; Smigel, 1964; Freidson, 1975; Scott, 1981).

The second type of structure within which professionals work well are the heteronomous (mixed authority) professional organizations, in which professional employees are subordinated to the administrative structure (Scott, 1981). The autonomy granted professionals in these organizations is substantially greater than that usually allocated to nonprofessionals, but substantially less than professionals enjoy in autonomous professional organizations. Discretion is more circumscribed and participants are subject to administrative supervision and evaluation. Examples are libraries, secondary schools, social welfare agencies, and engineering firms. The reduced level of organizational autonomy enjoyed by these professionals is strongly related to the external political and social power of the occupations (Kornhauser, 1962; Miller and Rice, 1967; Montagna, 1968; Etzioni, 1969). The distinction between autonomous and heteronomous structures can be applied to departments within organizations as well as to entire organizations. Thus scientists and engineers in the R&D section of a manufacturing organization are likely to be organized heteronomously as well.

In heteronomous professional organizations, complex and uncertain tasks are handled by delegation to the professionals. A structure of general rules and hierarchical supervision surrounds their work, but there is considerable discretion over decisions related to technical elements of the task. Managers are members of the profession themselves, and there are usually a substantial number of them relative to the professional employees. This is due to the increased information which must be processed in complex and uncertain task situations, and is an attempt to improve information transmission and the decisionmaking capacity of the organization. Project teams are common as are matrix designs, both of which support collaborative efforts across disciplinary or departmental lines. This is entirely consistent with the contingency approach of designing organizations for effectiveness. A study of 100 NASA research center scientists and engineers (working in an heteronomous structure) reported that conditions of too much or too little time pressure relative to the amount "desired" by workers elicited poorer performance. This illustrates the importance of the collaborative and participative nature of deadline-setting and of the structuring of work goals and schedules among professional employees (Farris, 1973).

What does this suggest for the organization of the space station and its relations with the ground? Because onboard tasks will be both conceptually and technologically complex, with a large amount of real-time problem-solving indicative of substantial information processing and task uncertainty, station crewmembers will be professionally trained workers. Research indicates that professionals function most effectively in either autonomous or heteronomous authority structures. In both cases there is considerable decisionmaking authority allocated to the workers, and major discretion over the timing and pacing of work and technical decisions regarding how to proceed. Decisionmaking is decentralized to that subunit where the work is to be performed. The decision process is likely to be advisory, collaborative, and collegial, with influence based on possession of relevant knowledge rather than organizational position. This suggests that the relationship between ground and space should be supportive, much as corporations provide the resources (e.g., equipment, technology, facilities) within which research and development work is conducted.

Structures contraindicated for the space station by existing research on professionals (and contingency-approach methods) are the highly bureaucratic organizations characterized by centralized decisionmaking, close supervision, work behavior governed by standardized rules, and low levels of astronaut discretion and decision autonomy. This strongly suggests that the military command model (section 5.3.4) is inappropriate except for a space station conducting a specialized military mission with no scientific research or applications duties.

Simultaneous Loose and Tight Coupling. Another important issue of space station organization is the extent to which the external environment will introduce unanticipated novelties into the work setting. When the timing and sequencing of events cannot be predicted or when uncertainties occur requiring rapid response, collaborative or participative decisionmaking is thought to be precluded because the immediate issue is neither effectiveness nor efficiency but rather survival of the system. Military command models are often suggested, but the concept of simultaneous loose and tight coupling provides a possible alternative.

Loose coupling of organizational elements implies that many of these elements are capable of autonomous action (Weick, 1976). Loose coupling is an organizational variable. In tightly-coupled mechanistic systems, the interdependence among the parts is such that their behavior is highly constrained and limited, producing a relatively rigid structure and a determinate system of relations.

Social organizations, in contrast to physical or mechanical structures, are loosely coupled systems (Scott, 1981). Noting this difference, Weick suggests that loose coupling of organizational structure may be highly adaptive and thus promote system survival. When the structure of sub-elements of a system is allowed to vary independently, behavior also varies, providing a more sensitive mechanism for detecting environmental alterations. Problems within any one sub-element are more easily isolated from the rest of the system. Moreover, adjustment by individuals or separate departments to environmental disturbances allows the rest of the system to function with greater stability. This implies that highly discretionary and autonomous behavior might be appropriate structural elements for space station organizations, even under conditions of external threat.

Whether looser or tighter coordination and coupling is adaptive for an organization depends on specific circumstances. Much remains to be learned about the space environment, and about working and living in space, before definitive recommendations can be made. Some research data are available in the case of normal station working conditions, but under abnormal or unpredictable circumstances the appropriate organizing mode is far less clear and should be investigated further.

Another alternative to the loose/tight coupling dilemma is to allow astronauts to "self-design" their organization. Weick (1977) suggests that much of the problem of distributing authority for Skylab activities between ground and space can be analyzed using the classical organizational concepts of autonomy, discretion, perceived control, self-determination, job enrichment, delegation, power, time span of discretion, and role conflict. Yet, there are features of the Skylab situation beyond these basic concepts requiring the invention of a self-design concept. For Skylab, there was some advance planning about what to do in space, but less attention was paid to planning how to plan what to do. The astronauts apparently had no onboard solution-generating procedure available to them except for trial-and-error and working to the limits of human energy. The one-day strike got results of the most unimaginative sort: The existing organizational design (in which ground personnel planned and directed, and Skylab astronauts executed) was not discredited as a result of the strike, and there was no rearrangement of activities or responsibilities.

Weick argues that self-design would enable astronauts to integrate themselves into the design. The likelihood is that sensitive self-design would have taken astronaut needs into account more consistently over a much greater portion of the mission. While organizational planning and implementation may appear to be separate activities, the two actually reinforce one another -- implementation clarifies design and design clarifies implementation. NASA should consider Weick's approach when designing space station organizational arrangements. The ideas of past and future space travelers and mission control personnel should also be solicited in planning the organizational design of future space stations.

### 5.3.4 Models for Space Station Organizational Design

A detailed analysis of all possible space station organizational designs is clearly beyond the scope of the present workshop. However, a brief discussion of several models can help clarify the focus on the organization of work and the design alternatives of authority and task assignment cultures that might emerge for station crewmembers.

Four alternative organizational models (for day-to-day normal operating conditions), ranging from lesser to greater autonomy, are: (1) military command and control, (2) traditional American industrial, (3) American collaborative, and (4) self-management (Naisbitt, 1982; Peters and Waterman, 1982). Typically only one of these modes predominates in a single organizational subunit at a given point in time. Table 5.3 summarizes the overall philosophy and specific tasks, roles, and responsibilities associated with each model.

In the military command and control model, those in authority are considered to have superior capabilities, knowledge, and talent, and are thus more qualified to undertake analysis, problem-solving, and decisionmaking. Those in the lower ranks cannot be trusted to carry out tasks where self-initiative is required. The primary motivational influence is threat of punishment and extrinsic reward systems. The implication is that individuals must be "driven," and that it is the right and the responsibility of those in authority to implement this influence mode.

In the traditional American industrial model there is less emphasis on overt symbols of authority than in the military model, but the fundamental precepts are quite similar -- the presumption that substantial gulfs in capability exist between those in authority and those who are not. The major motivators remain threat of punishment and extrinsic reward. Little effort is made to utilize intrinsic motivational factors, since the fundamental belief is that individuals lower in the

**TABLE 5.3. CHARACTERISTICS OF ALTERNATIVE ORGANIZATIONAL DESIGN MODELS**

| CHARACTERISTICS OF SUBUNIT | ORGANIZATIONAL DESIGN MODELS | | | |
|---|---|---|---|---|
| | MILITARY COMMAND AND CONTROL MODEL | TRADITIONAL AMERICAN INDUSTRIAL MODEL | CONTEMPORARY AMERICAN COLLABORATIVE MODEL | AMERICAN SELF-MANAGEMENT MODEL |
| Leader Accession | Appointed by Higher Command | Appointed by Executives | Appointed by Executives: Approved by Work Group | Elected by Work Group |
| Task Assignment | Assignment by Leader | Assignment by Leader | Assignment by Group Members: Approval by Leader | Consensus Assignment by Group Members |
| Goal Setting | Goals by Leader | Goals by Leader | Goals by Group Members: Approval by Leader | Short Term Goals by Group: Long-Term Missions and Priorities By Organization |
| Source of Influence | From Appointed Leader | From Appointed Leader | Individual Expertise and From Appointed Leader | Individual Expertise and Interpersonal Capability |
| Typical Response to Leader | Obey Orders | Carry Out Directions | "Why?" | "Why?" |
| Typical Leader Title | Commander | Supervisor Boss | Manager Administrator Coordinator | Leader Coordinator |
| Source of Discipline | From Appointed Leader | From Appointed Leader | From Appointed Leader | From Within Group |
| Motivational Emphasis | Threat of Discipline | Extrinsic Reward and Security | Intrinsic Reward | Intrinsic Reward |
| Information Sharing | Sharing on Need-to-Know Basis Only | Limited Information Sharing | Widespread Information Sharing | Share Everything |
| Feedback | Punitive Feedback | Feedback on Input Emphasized | Feedback on Output Emphasized | Elaborate and Specific Output-Oriented Feedback |
| Conflict Resolution | By Appointed Leader | By Appointed Leader | Both Leader and Group | From Within Group |
| Quality of Output | Low | Low | High | Very High |
| Flexibility of Response | Low | Low | High | Very High |
| Creativity/ Initiative | Low | Low | High | Very High |
| Surveillance Requirements | High | High | Low | Very Low |

organization would not be responsive to this opportunity. There is a strong emphasis on loyalty to the organization, and the threat of dismissal is used as a powerful negative motivational influence.

In the American collaborative model, considerably greater faith is placed in individual achievement. The assumption is that, given responsibility, people can and do respond in a positive manner. Intrinsic motivational factors play a more prominent role. Extrinsic factors remain important, but are more likely to be based on performance and contribution and not merely upon position in the hierarchy. Threat of punishment is de-emphasized; loyalty is directed to the challenging project, to the profession, or to one's self rather than to the organization. Organizational and career mobility are acceptable and expected. Creativity and initiative are valued more than the ability to carry out routine instructions. Influence is based on expertise and performance contribution rather than appointed position.

The self-management model is similar to the collaborative model, but more intense in its philosophical commitment to the idea that humans will respond productively to challenging opportunities. An important part of this philosophy is that a dedicated effort should be made to push decisionmaking down to the lowest possible level. This includes even apparently unimportant issues, since what might seem trivial to a manager may be very important to an individual employee. The rationale is threefold: (1) People actually doing a job may have access to the best information about how that job should be done; (2) motivation will improve, resulting in improved creativity, initiative, quality, productivity, and adaptability; and (3) considerably less overhead is required because surveillance requirements are decreased. Much attention has focused on blue-collar "autonomous work groups" and "self-managed work groups" (Burck, 1981). Among professional employees the philosophy of self-management is most often seen in "task force teams" where individuals come together on the basis of expertise to solve specific problems.

Effectiveness of Alternative Models. Which is the preferred organizational design model for the space station, and what is the most effective degree of individual autonomy within the organizational structure of the crew? Since an exhaustive enumeration of possibilities has not been presented here, no definitive conclusions may be made. However, existing research data do suggest that increasing levels of autonomy may improve organizational effectiveness. Furthermore, the direction of corporate culture in the United States, challenged by the success of the Japanese, has shifted significantly towards more autonomy in the last ten years.

Should the space station be organized as a self-managing work group? In all probability, the self-management model would not be the appropriate level of autonomy for the beginning stages of the station. Self-managing work groups are a remarkably effective organizational form, but there are startup expenses that require time to overcome. Given the extraordinary cost of spaceflight, the crew should be at a higher level of initial effectiveness than the self-management model could immediately provide. Also, crew rotations on a weekly or monthly schedule, plus a changing population with varying specialized mission assignments, are incompatible with self-management which works best over the long haul. In the near-term, station crewmembers should begin their missions with a relatively known and stable authority and organizational system.

Beyond the four types of model described above, there is another alternative for the space station -- an expert-power-based or "crisis response" organizational system. In this mode, authority would reside with the person who is expert or has knowledge related to a given situation, perhaps someone other than a commander or pilot. The space station crew must be able to deal with the possibility of extreme crisis. Organizational design, like other design parameters, can contribute to or detract from emergency response effectiveness. In a crisis, the authority system must be clear and the response to authority unquestioned, much as in the military command and control model. But the crisis leader may or may not be the nominal day-to-day leader of the station crew. Crisis leadership demands special qualities and training. The central idea is that the station crew may function well under one mode on a day-to-day basis, but might also be trained to function under a different mode specifically designed to meet crisis conditions.

However, there may be a few practical difficulties with this approach. Even the early American navy had sailing masters, to navigate and maneuver the ship, and gunnery officers, whose job was the care and feeding of very primitive and temperamental cannons. In each case the person in command was dependent on technical specialists, yet this did not affect the nature of command authority. It seems unlikely that electronics will completely alter this situation. Further, in a dual-mode system it might be difficult to prevent the day-to-day manager from losing power to the crisis manager, who likely is, by definition, a strong-willed, powerful-personality, leadership-oriented, "right stuff" type of person with a take-charge attitude. Such a dual hierarchy could be very unstable, leading to personal conflict in emergencies and infighting during normal times when the "man of action" cannot exercise his authority. Problems may arise because of the seemingly inevitable conflict between civilian and military mentalities, and among the people loyal to each camp. The close quarters of the station could further exacerbate the situation.

Semantics as Symbols. Words and labels play an important role in conveying hidden meanings about the nature and implicit rules of organizations. These "implicit theories of organization" imply that each individual has cognitive notions of appropriate behavior and relationships within organizations. The words frequently serve as symbols but, unfortunately, in most organizational designs key words are selected by default. Chosen in this manner, the words often reflect the past rather than what is desirable for the future. In many ways, the semantics of NASA are symbolic of an implicit theory of military organizational design.

For instance, what should be the title of the on-site individual "in charge" of the space station? Going by past precedent, the most likely candidate is "commander." The title carries many connotations, hidden assumptions and values. A commander gives orders, and it follows logically

that it is the duty of others to follow these orders. As another example, in some proposed space station layouts the word "wardroom" has been used to label a common area where the crew might meet or have meals together. This word has strong connotations of a naval ship, where the wardroom is a meeting area for naval officers. And is a space station a "flight"? Will it have a "pilot"? Or is a space station more of a "house," a "laboratory," an "office," or a "factory", led by a "director" or a "manager"?

The choice of language often conveys an implicit organizational design. If that design has not been deliberately considered and decided, then it evolves by default. The default model, to be consistent with semantics, frequently is one linked to the past -- in the case of spacecraft and space missions to date, the military. Whatever organizational design model is ultimately selected for the station, consistent language, especially labels and titles, should be a clear and deliberate choice.

Skewed Sex Ratios and Tokenism in Crew Selection. Until recently, all astronauts in the U.S. space program were white males. NASA has now added women and blacks to the corps. In both cases, members of professionally rare groups will be flying with crews in which they are the only representative of their group. The choice to send crews into space with what are called "tokens" has consequences for interaction dynamics, mental health, level of aggression, and actual mission performance. Since the space station will present conditions of long-term isolation and confinement, the presence of tokens could have serious negative consequences for future space missions.

Research shows that the relative numbers of socially and culturally different people in a group are critical in shaping the social interaction. "Skewed" groups contain a preponderance of one type (the numerical dominants) over another (the relative tokens). Kanter (1977a, b) investigated token women in a male-dominanted sales force of a large industrial corporation. The women in the sales force were under strong performance pressures. They were much more visible than their male peers, and were the subject of careful scrutiny, gossip, questioning, and of performance pressures which were standards for the tokens alone. Tokens performed under conditions different from those of dominants because they were automatically noticed and were told that their performance could affect the prospects for other women in the company.

Tokens may operate under a number of handicaps in work settings. Social isolation can result in exclusion from important task learning and task performance opportunities. Performance pressure on tokens gives them less room for error. In response to tokenism, underachievement or overachievement is typical. When informal interaction is a key to success (e.g., industrial sales, close living and working on a space station) tokens may not do well compared with members of the majority. Tokens undergo a great deal of personal stress and expend extra energy to maintain satisfactory work relationships. Among the stresses are unsatisfactory social relations, unstable self-images, frustration over rewards, and social ambiguity.

Token crewmembers should not be isolated in space station missions. Nearer-equal numbers of men and women will promote more balanced behavior by both men and women on future space missions. Social isolation and psychological stress for the token will be reduced. There should be few substantial performance differences if the pressures to overachieve or shirk from view are removed for the tokens. Social relationships should be facilitated, as overachievers among tokens will no longer fear retaliation for outperforming dominants and dominants will no longer suffer public humiliation for being outperformed. There will be more natural displays of excellence, with appropriate acceptance and encouragement of excellent performance among crewmembers. A remaining research question is how many of a category are enough to change a person's status from token to full group member. When does a group move from skewed to balanced? Evidently, even in small groups two of a kind are not enough -- for example, when women number less than 20% of the total, token dynamics operate (Kanter, 1977a, b).

### 5.3.5 Organizational Aspects of the Human-Machine Interface

Human factors engineering is so important in the design of future machines and equipment to be used in the space station that it is appropriate to examine organizational issues within NASA which are likely to facilitate or inhibit the contributions of this discipline. The following is a discussion of the human-machine interface from an organizational perspective.

An Augmented Human Factors Perspective. Human factors engineering has made substantial contributions to the space program to date by combining engineering and psychology to examine the human-machine interface. The characteristics of the isolated human thus are prominent in systems and equipment design recommendations. A recent analysis of space human factors derived from an ergonomic model of the human operator illustrates the difficulty of this perspective: "The lack of a systematic, comprehensive, and quantitative ergonomic model brings about incomplete understanding of the human operator as a system component, who is often the main determiner of the system output. Thus, technological systems relying on the human as a system component may be laid out less than optimal with respect to system performance and, therefore, are suboptimal in their output." (Kroemer, 1982)

Organizational theorists note that technological systems which rely on humans as system components will predictably be sub-optimal in their output whenever that system is imbedded in an organizational context. What is missing from the traditional human factors perspective is an awareness of the larger context of the human-machine interaction. Consider, for example, the contrasting views on humans-in-systems decisionmaking.

In human factors engineering the focus is on rational decisionmaking, based on a logical search for all relevant information and examination of all alternatives -- with an objective decisionmaking process yielding the optimal choice. Human factors engineers recognize limits but these are likely to be seen as imperfections to be overcome in the man-machine design. In contrast, organizational theorists assume that humans in organizations are rational in intention only. When problems are encountered, people search for action

alternatives or consequences of action. Finding an optimal alternative is substantially different from finding a satisfactory alternative: An alternative is optimal if (1) there exists a set of criteria that permits all alternatives to be compared and (2) the alternative in question is preferred, by these criteria, to all other alternatives. On the other hand, an alternative is satisfactory if (1) there exists a set of criteria that describes minimally satisfactory alternatives, and (2) the alternative in question meets or exceeds all these criteria (March and Simon, 1958).

Most human decisionmaking, whether individual or organizational, is concerned with the discovery and selection of satisfactory alternatives. Only in exceptional cases is it concerned with the discovery and selection of optimal alternatives. This is called "satisficing," analogous to searching in a haystack for a needle that will sew rather than seeking the sharpest needle. In organizational analysis, satisficing and cognitive limits on rationality are not necessarily imperfections. Given a fairly disordered world, the imperfections may make survival more likely (Perrow, 1982). Human factors engineers should consider expanding their model of human cognitive processes and decisionmaking to take into account the wider organizational context in which the equipment operator works.

Current results in organizational research, theory and practice indicate that negative consequences flow from a single-minded focus on human-machine relations. It is recommended that when equipment is designed for the space station to be used, maintained, or monitored by humans, a self-conscious organizational analysis should be undertaken to determine the probable impact of the design on human behavior within the organizational setting. Ignoring the system properties of organizations, which include the interrelations between people and machines, invites unintended negative consequences.

There will be increasing need for the skills of human factors engineers as NASA begins to establish the desired levels of space station technology. The contribution by human factors engineers to this project will be substantially enhanced if the background of these personnel is not limited to a combination of engineering and psychology, but also includes sociological or organizational training. This will result in a richer, more holistic view of people in organizational systems interacting with various levels of machine technology, rather than the more limited human-as-a-system-component view.

Human Factors Engineering and the Organization of NASA. Perrow (1982) has analyzed equipment and systems in which human factors appear to have been neglected. He rejects the notion that designers of such equipment are unaware of human factors or are contemptuous of them. Rather, he argues that the nature of the organization has an impact on the attention given to human factors. Perrow suggests that design engineers respond to the rewards, sanctions, and prevailing belief systems of upper management. Management can induce designers to utilize human factors principles by structuring the reward system so that it is in the interests of designers to take these principles into account.

The work of human factors personnel and design engineers should be tightly integrated within NASA to facilitate the requisite flow of information between both functions. Human factors is often viewed as a qualitative or "soft" discipline, in contrast to the quantitative or "hard" design engineers (Meister and Farr, 1967; Perrow, 1982). In high-technology organizations, "soft" translates into lower status, lower social value, and thus lower (often nominal) influence on management decisionmaking. This social devaluation process endemic to all organizations guarantees that most engineering designs will be formed using scientific management principles, tightly focused on the human-machine interface, and will in all likelihood discount social and organizational variables. Human factors engineers need not emphasize ever more quantitative ergonomic factors; rather, top management should give explicit support to necessarily qualitative socially-oriented factors via the multiple signalling devices available to them.

For instance, the following unobtrusive measures might be taken:

- Ensure that human factors psychologists and engineers are physically proximate to design engineers so they can interact informally and build individual and group bonds.

- Assign promising design engineers to the human factors group for a tour of duty, letting it be known that this is essential to their training, thereby enhancing the status of human factors engineering.

- Top managers can use the names of key human factors scientists in casual conversation -- these comments will be studied as closely as formal directives.

- Ensure that key human factors people are in attendance, and occasionally chair, meetings concerned with design specifications. Make sure everyone knows the human factors people are present, even if they play a small role in a given meeting.

- Publicize human factors contributions throughout the design and management communities.

Another more direct means is to write specifications into contracts requiring certification that human factors were taken into account, and how. Designers could be asked to explicitly describe how actual designs accommodate practical human-machine considerations. NASA should consider some of these recommendations to ensure sensible designs of space station equipment.

It is generally good policy to involve users and maintainers of equipment in the early decision and subsequent design stages of automated equipment. NASA has been commended in the past by behavioral scientists for consulting astronaut-users in design decisions. To make sure this process continues, NASA upper management should clearly state its expectations and facilitate organizational arrangements that allow close collaboration among users, design engineers, and human factors engineers. The attribution of operator error to system failures is widespread in high-technology systems outside of NASA. In many high-technology organizations, designers work in isolation from users, insulated from the consequences of their designs. The human cost includes excessive fatigue, boredom, crushing workloads, isolation, frustration, and accidents among operators. Much of this could be avoided if operators participated in



C-2

design reviews and if designers were brought into contact with experienced operators or were required to operate their own equipment or at least observe it in operation. This is, however, a top management policy decision.

High-technology organizations are too easily dominated by scientific management approaches to the design of equipment and to the subsequent management of equipment users. The result is that workers, viewed as extensions of the machine, are programmed to the closest degree possible to simulate machine reliability, with a rigid division of labor maintained between the planning of work and its actual execution. Instead, responsibility for work planning should be a joint function of both management and workers (e.g., astronauts), or delegated as far as possible to the astronauts themselves. Work plans devised exclusively by managers and scheduling engineers typically produce non-implementation, considerable unanticipated strife, inefficiency, and substantially increased costs. Conversely, allocating work planning responsibility to the workers -- especially those of the intellectual, educational, and motivational caliber of the astronauts -- more easily integrates the technical and social subsystems of the organization.

Most organizations neglect (if not deliberately defeat) the extremely flexible and creative capabilities of the human component in the system: "For want of a robot, stands an operator" (Perrow, 1982). NASA should take fuller advantage of the flexible and creative qualities of its astronauts as decisions are made regarding human-machine divisions of labor and regarding the potential ability of station personnel to self-manage their operations independent of ground control. There is little evidence that existing lists of human and machine advantages have been used in designing equipment or in determining the degree to which astronauts can be allowed to manage their own work.

To facilitate user input to equipment beyond the initial design phase, NASA should consider post-operative reviews to insure that user feedback is incorporated in the design enhancement phase of engineering. A simple questionnaire, sent with equipment and returned anonymously by operators, could be exceptionally valuable -- especially if the information flows directly to manufacturers, and NASA management implements appropriate organizational incentives to acknowledge the results in subsequent work. NASA's Aviation Safety Reporting System, operated by the Battelle Memorial Institute, has received excellent evaluations and has been suggested as a model for a human factors reporting system for space station equipment and technology development (Perrow, 1982).

Space Station Human-Machine Interface. With microprocessors readily available, the opportunity exists to distribute data processing capabilities throughout the space station. When decisions are made to locate terminals, microcomputers and the like, designers should consider the extent to which location of terminals contributes to worker isolation. Some isolation may be necessary because of various task safety requirements (e.g., biological experimentation), and intermittent isolation may be desired for privacy in a cramped work environment. Beyond this, however, astronauts should not be inadvertently isolated socially from their peers by arbitrary equipment placement. Isolation of workers and work groups promotes social introversion, stereotyping, and undermines organizational ability to produce goal-oriented integrated work.

It is a natural outcome of the automation process that people will monitor machines, but this promotes inattention and can result in the degradation of skills necessary for system intervention during failures and particularly during crises. NASA should consider designs which require the coordination of activity by two or more operators. More extensive query capability could be designed into automatic systems, allowing greater operator discretion and slowing any possible atrophy of mental skills.

An alternative to machine monitoring by operators is the monitoring of operators by machines. Systems could be designed to emphasize the control of the operator over the system and the ability of the operator to choose different ways to run the system, and could provide for frequent or constant feedback from a machine with appropriate queries, warnings, and projections of future states. Perrow (1982) remarks that the distinction, though subtle, could have considerable positive consequences for attention, skill maintenance, and especially system comprehension.

Lessons from Lordstown for the Space Station. What general principles can be drawn from the ineffective applications of scientific management in Lordstown and Skylab -- as they apply to the question of machine automation and human autonomy? Machine automation should be used, whenever technologically feasible, to relieve people of routine tasks which are dull or dangerous. However, the remaining work for humans must be intellectually stimulating. In planning a human-machine labor division, interesting and challenging subtasks should not be allocated to machines.

In automation work design, tasks are often divided into narrowly defined, simple specialized subtasks that are boring for people. Instead of being relieved of routine, monotonous tasks, workers can be forced, through poor engineering decisions, to perform even duller, more narrowly defined jobs than prior to automation. One of the problems at Lordstown was that the tasks remaining after automation did not require the mental strengths humans possess.

Some residual work always remains after automation and is assigned to a human operator. When a task or set of tasks is engineered for machine automation on the space station, it is extremely important that as much as possible of the monotony of the task be absorbed by the machine. This design rule is cost effective because it capitalizes on the strengths of people: large relational memory capacity, vast repertoire of behaviors, flexibility in organizing these behaviors in response to information inputs, and the ability to react creatively when confronting the unexpected (Haberstroh, 1965). These strengths will be expensive to synthesize in machines given current and near-term robotics and AI technologies.

If it is technologically feasible to automate only part of a routine space station task, then it may be preferable not to automate the job at all. Even many tasks regarded as routine can involve complex interrelationships. Complexity derives from two sources -- the number of elements which must be taken into account and the degree of interrelatedness and interdependence among them. It

is better not to reallocate labor between humans and machines if existing technology will not permit the people to retain complexity and interest in the remaining subtasks. As a rule of thumb, if a managerial or engineering decisionmaker would not be willing to perform the subtasks remaining after task automation, then the task probably should not be automated.

After complete or partial automation of a set of tasks, it is common to treat human operators as extensions of the machines. Scientific management enthusiasts then attempt to program people using the machine as a tool to gain increased speed and efficiency. The goal is to optimize the output of the human as a system component, as with the operation of computer-controlled assembly lines at Lordstown in which production control, management, and industrial engineers set the pace of the line.

When people are given substantial control over the timing and sequencing of their work, effectiveness often greatly improves. Consider the example of the Matsushita Corporation's television manufacturing plant in Franklin Park, Illinois. Quasar, a division of the Motorola Corporation, closed the unprofitable factory because of low-quality product, excessive reject rates, and high re-work costs. In the plant, workers tried to complete as much of their assigned job as they could before the TV component was automatically moved beyond their station by the computer-controlled assembly belt. When the plant was purchased by Matsushita, Matsushita hired from the original pool of workers to re-staff the factory, increased capital investment, emphasized quality workmanship, automated some of the assembly process, and gave production workers greater responsibility and autonomy in the conduct of their work -- especially assembly belt speed. Any worker on the line could stop the belt at any time if necessary to complete an assigned task. Using the same workers Matsushita reduced defects to 4 per hundred television sets as compared to 150 defects per hundred achieved under the prior management (Encyclopedia Brittanica Films, 1982).

The computer has been conceptualized as a technology of control (Blau et al., 1976; Pfeffer and Leblebici, 1973). As long as management retains the right to plan the conditions of work, computers can be used to enhance control over the workforce. Lordstown is not the only case of computer-dominated assembly lines operated at a speed selected to maximize productivity. Whisler (1967) has studied and recorded many other instances in which individual workers have lost control over the timing and patterning of their activities as a consequence of computer installation.

This need not be the case in space. The Matsushita experience suggests that by using distributed processing capabilities currently available, computer technology can enable allocation of a substantial amount of control to the workers themselves while coordinating necessary elements automatically among multiple distributed work sites. The combination of computer technology and worker override produces superior levels of productivity and quality, an important point to remember in space station automation design.

### 5.3.6 Summary of Needed Areas for Study

It appears that the Soviets have undertaken social and behavioral research and have utilized the results in their space program to a far greater extent than has NASA in the American space program (Bluth, 1981a, b; Connors et al., 1984). Some NASA personnel are beginning to worry about the significance of Soviet concern with astronaut behavior and social organizational issues. According to Sadin (1982), "it now seems clear that the stage is set for extending a research analysis of interrelated selection, training, and organizational problems [regarding U.S. astronauts]." At present there is little reliable information on social and organizational problems related to the space station as a technological context for work. To remedy this situation, and to help clarify the degree of human and organizational autonomy most appropriate for a manned space station, NASA should undertake research on the following issues and questions:

1. To what extent is the space environment likely to introduce uncertainties into the work setting, requiring very quick decisionmaking upon which system survival depends? When the issue is survival of the system rather than mission effectiveness or efficiency, what is the appropriate organizing mode? Under abnormal conditions the appropriate organizational structure is unclear and must be further studied. Much could be learned by intensive case analyses to determine how astronauts have conceptualized these issues in the past. In addition, the relationship between structure under normal work circumstances and the structure invoked during a period of system survival needs to be considered. There are numerous examples of Earth-based societies in which martial law was invoked during a period of crisis only to become institutionalized over time as the "normal" structure. Crises provide opportunities for substantial power shifts. These issues should be carefully thought out in advance, not just stumbled upon during an actual crisis in space.

2. Space station planners should solicit the ideas of past, present, and future astronauts and ground-based personnel regarding station organizational design. The extent to which self-design is feasible should be pursued in addition to those structures which have already been implemented and experienced.

3. Most of the research on isolated and confined working environments is concerned more with reducing the effects of isolation and confinement than in focusing on the influence of organizational structure. Research is needed on comparative organizational structures under conditions of isolation, confinement, and a hostile external environment. In the past there has been a major reliance on the military model or variations of it under these circumstances, with poor results. Some organizational variation has been introduced on oceanographic research vessels and in the Alaskan North Slope settings, but many more alternatives must be uncovered and investigated.

4. Research is also needed to examine the interactions between the formal (work) organizational structure and the social (living) structure under conditions of isolation, confinement, and a hostile external environment. The concern is with the social relationships among people who also live where they work -- a space station may be the ultimate "company town." The impact of social and economic variables both on mission performance and on the mental and emotional health of the crew may

strongly influence final space station design.

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# CHAPTER 6

# METHODOLOGIES FOR AUTONOMY

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Systematic decision methodologies are needed to help resolve many critical issues concerning space station development, and to provide clarity, precise definition, and consistency of judgment and design. While detailed development of uniform decision methodologies lies beyond the scope of the present study, the workshop sought a higher-level perspective on the most useful possible methodologies for autonomy in the context of the space program.

Workshop participants were challenged to address several broad methodological questions. For instance, what is the nature of a space station task that determines whether it is appropriate for automation? What types of tasks should be allocated to humans? What combinations of people and machines are most effective? What are the decision rules for function allocation among manned and automated systems in space and on the ground? What are the decision rules for determining whether a function can be performed better in space or on the ground?

The methodology team confronted these issues by considering rules and procedures to allocate tasks and autonomy among different types of relationships and entities including (1) humans, machines, and human-machine systems; (2) physical/intellectual; (3) space/ground; (4) locus of control; and (5) systematic relationships or cybernetic systems. The team reviewed 65 relevant decisionmaking factors (e.g., who benefits from a decision, communication channel loading, recurring and nonrecurring costs, development risks involved), 25 classes of allocated activities about which decisions could be made (e.g., sensing, data collection, data storage and retrieval, planning, scheduling), and 12 possible knowledge representations for use in decision methodologies (e.g., decision trees, rules, decision tables, task participation grids) -- see Table 6.1.

Five specific methodologies are examined here in more detail: Simple matrix methodology (ARAMIS), human-machine function allocation via expert system (SSTAAMMER), decision matrices permitting representation and analysis of uncertainty, ethnographic methodology using cultural analogs, and trend mapping. A sixth informal "scenario" methodology, not included here, involved the creation of fictional "day-in-the-life-of" sketches for various hypothetical station crewmembers, followed by a brief functional analysis to uncover possible missing components in space station planning. A sample scenario appears in Appendix 7A.

There are a number of additional considerations in choosing an appropriate decision methodology, not discussed here, which should be addressed in a more comprehensive study. For instance, some decision methodologies may have to deal with factors that are difficult to quantify. Appropriate metrics must be identified to provide the basis for making choices, such as cost, productivity, effectiveness in completing tasks, and safety, and standard definitions are critical. In particular, a measure function or metric for autonomy should be developed (see Appendix 6B.) Interconnectiveness of tasks being allocated should be addressed to determine how to deal with subsystems and supersystems most effectively -- a focus on details may obscure the larger perspective. Some means of handling evolutionary expectations should also be developed.

## 6.1 Simple Matrix Methodology: The ARAMIS Study

Prior to the present workshop, NASA sponsored another substantial study of human-machine task allocation -- known as Space Applications of Automation, Robotics and Machine Intelligence Systems (ARAMIS), conducted during 1982-83 at the Massachusetts Institute of Technology (Smith et al., 1982; Howard et al., 1982). The purpose of ARAMIS was to define and apply a generic methodology for determining the optimum mix of humans and machines in space which would yield the best performance at minimum cost. The technological choices spanned the range from fully human to fully machine, with a number of intermediate options such as humans assisted by computers and various levels of teleoperation. The ARAMIS method concentrates on the production of a matrix relating "space project tasks" to "capabilities."



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**TABLE 6.1. CRITICAL FACTORS IN SELECTING AUTONOMY DECISION METHODOLOGIES**

RELEVANT METHODOLOGICAL FACTORS

- whose benefit
- radio communication load
- other communication channel loading
- costs, recurring
- costs, nonrecurring
- preciseness
- maintenance, time duration
- maintenance, frequency
- completion time required
- useful life
- failure proneness
- development risk
- safety to humans
- safety to machines
- safety, political
- certainty of task definition
- certainty of task completion
- iterations
- human satisfaction
- human health
- machine health
- feasibility, technical
- feasibility, operational
- utility of performer doing it
- level of manned interaction
- frequency
- duration
- level of interaction with any other system
- time phasing (at what time in the operation is it done?)
- type of relationship with other elements (hierarchical, network, cyclic, non-cyclic)
- type of interdependence (sequential, reciprocal or pooled)
- type of integrating mechanism (rules, feedback, plans, schedules)
- commonality of task
- uniqueness
- effectiveness
- efficiency
- allocated task vs. negotiated
- reliance on formal authority
- capacity for accommodating evolution
- critical path length
- manual dexterity required
- number of separate parts/modules
- time critical dependencies
- energy required
- man-machine timeline chart(s)
- required strength/force
- nature of resources required (mass, availability, fragility)
- limits of perception (visual -- acuity, resolution, bandwidth; tactile; audio/aural; olfactory/smell; taste; kinesthetic)
- how long, how many for type of task performance (people, machines)

RELEVANT SPACE STATION ALLOCATED ACTIVITIES

- sensing
- data collection
- data storage
- data retrieval
- non-computational data collection/storage/retrieval
- planning
- scheduling
- decisionmaking (command)
- communication
- control
- movement
- physical manipulation
- heating
- cooling
- gathering
- cleaning
- computing
- storing
- navigating
- locating
- identifying
- specifying and marking
- energizing
- penetrating

APPROPRIATE POSSIBLE KNOWLEDGE REPRESENTATIONS

- first order logic
- frames
- trees (digraphs)
- algebraic constructions
- semantic networks
- rules
- simple tables & matrices
- systematic tables & matrices
- Venn diagrams
- decision tables
- "ten point must" tables
- "+", "-" matrices
- task participation grids

The overall study method is illustrated in schematic form in Figure 6.1. Space project tasks were identified from space project breakdowns. Four space projects were chosen for study -- (1) the Geostationary Platform (GSP), a communications relay satellite in geosynchronous orbit; (2) the Advanced X-Ray Astrophysics Facility (AXAF), an X-ray telescope spacecraft; (3) the Teleoperator Maneuvering System (TMS), a multi-purpose free-flying satellite tender; and (4) the Space Platform (SP), a versatile platform for scientific and space applications research. These four were selected because they span the expected range of space activities during 1985-2000 in communications, astronomy, satellite servicing and support, and science and applications development.

Each space project was then broken down into five successively finer levels. At the most detailed level are the smallest tasks required (e.g., Track Nearby Objects, Adjust Currents and Voltages, Position and Connect New Component). The research team selected 69 of these space project tasks, called "Generic Functional Elements" or "GFEs," for detailed study. (For clarity, the 69 tasks were grouped into 9 types: Power Handling, Checkout, Mechanical Actuation, Data Handling and Communication, Monitoring/Control, Computation, Decision and Planning, Fault Diagnosis and Handling, and Sensing.)

To clarify access to, and presentation of, information on ARAMIS, the research team developed a classification scheme for the field of Automation, Robotics, and Machine Intelligence Systems comprised of 6 general "areas" consisting of 28 specific "topics" (Table 6.2). (Note the considerable overlap between areas and between topics, a natural result of active interaction of technologies in rapid development.) This classification scheme was useful, both to identify experts on individual topics for consultation and to define candidate ARAMIS capabilities to perform each space project task.

For instance, the task "Position and Connect New Component" might be satisfied by a specialized manipulator specifically designed for this job, a human in a pressure suit with appropriate assembly tools, or a dextrous manipulator versatile enough to do many other tasks as well (Figure 6.1). Each such technological capability alone would satisfy the space project task. In the actual study a total of eight candidate capabilities were defined for this task -- (1) Dedicated Manipulator Under Computer Control, (2) Computer-Controlled Specialized Compliant Manipulator, (3) Computer-Controlled Dextrous Manipulator With Force Feedback, (4) Computer-Controlled Dextrous Manipulator With Vision And Force Feedback, (5) Human In EVA With Tools, (6) Specialized Manipulator Under Human Control, (7) Dextrous Manipulator Under Human Control, and (8) Teleoperator Maneuvering System With Manipulator Kit. Many capabilities have multiple applications, thus become candidates for several space project tasks. Ultimately, 78 specific capabilities were defined in this fashion.

The early development of some capabilities can enhance the later development of others. There is a favorable order of R&D, starting with simple concepts and building up to more complex options. Almost all of the 78 capabilities defined in the study are interrelated in this fashion. A graphical representation of capabilities which enhance others, forming a favorable sequence of

**FIGURE 6.1. ARAMIS STUDY METHOD: SPACE-PROJECT-TASK/ARAMIS-CAPABILITY MATRIX**

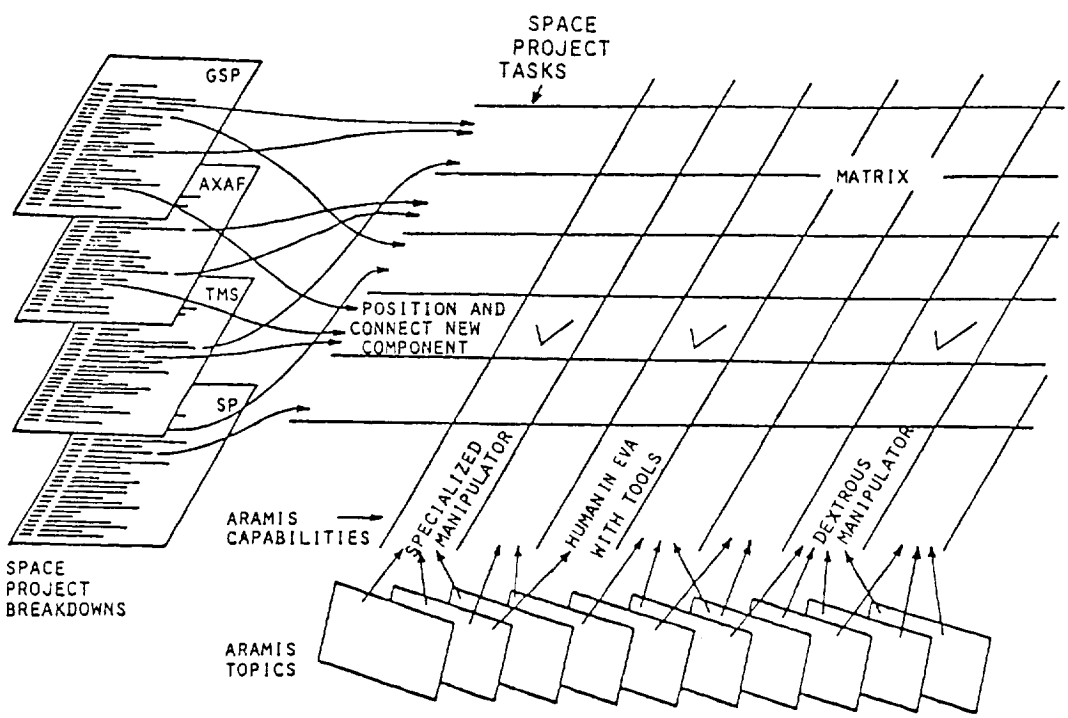

TABLE 6.2. LIST OF ARAMIS "AREAS" AND "TOPICS"

MACHINERY

- Automatic Machines
- Programmable Machines
- Intelligent Machines
- Manipulators
- Self-Replication

DATA-HANDLING

- Data Transmission Technology
- Data Storage and Retrieval
- Data and Command Coding
- Data Manipulation

SENSORS

- Range and Relative Motion
- Directional and Pointing
- Tactile Sensors
- Force and Torque Sensors
- Imaging Sensors
- Machine Vision Techniques
- Other -- Thermal, Chemical, Radiation, etc.

COMPUTER INTELLIGENCE

- Scheduling and Planning
- Automatic Programming
- Expert Consulting Systems
- Deductive Techniques (e.g., Theorem Proving)
- Computer Architecture

HUMAN-MACHINE

- Human-Machine Interfaces
- Human Augmentation and Tools
- Teleoperation Techniques
- Computer-Aided Design

FAULT DETECTION AND HANDLING

- Reliability and Fault Tolerance
- Status Monitoring and Failure Diagnosis
- Reconfiguration and Fault Recovery

development, is called a "technology tree." This large and complex technology tree was broken into eight simpler subtrees with interconnections among them.

After defining candidate capabilities for each space project task, the relative merit of each option was evaluated using Decision Criteria Comparison Charts -- one for each of the 69 space project tasks. For example, in the Chart for "Position and Connect New Component" (Table 6.3), the relative merits of each of the eight options were evaluated by rating their decision criteria on 1-to-5 scales, with 1 representing favorable performance and 5 unfavorable. A capability was judged promising if it received favorable decision criteria values in its applications to tasks. A total of 69 Decision Criteria Comparison Charts were generated.

Subsequent review of decision criteria values and technology trees identified promising applications of ARAMIS. A capability was judged promising if it received favorable decision criteria values in its applications to tasks, or if it significantly enhanced the development of other useful capabilities in the technology trees. Decision criteria values were reviewed by calculating average sums of values for each candidate capability. Space project tasks were first separated according to the 9 task types (e.g., there are eight tasks of the "Mechanical Actuation" type), and results from all candidate capabilities to perform those eight mechanical actuation tasks were combined as in Table 6.3.

This table shows that fifteen capabilities are candidates for the eight mechanical actuation tasks. The rightmost column identifies the number of tasks for which each capability is a candidate. For instance, the Automated Docking Mechanism is a candidate for only one task, whereas the Onboard Deployment/Retraction Actuator is a candidate for five tasks. The average sums (all criteria) shown in the first column were calculated by simply

## TABLE 6.3. ARAMIS DECISION CRITERIA COMPARISON CHART AND AVERAGE SUMS

TASK: POSITION AND CONNECT NEW COMPONENT

TASK TYPE: C. Mechanical Actuation

The movement, alignment, insertion, and fastening of a component to (or into) a spacecraft. This includes the fastening of mechanical, electrical, and fluid interfaces. The inverse of this task covers the disconnection and removal of components from a spacecraft. Since the task includes alignment of the component, it requires either a close-tolerance actuator in a close-tolerance worksite geometry, or compliance in actuator or worksite, or feedback to the actuator control.

DECISION CRITERIA

CANDIDATE ARAMIS CAPABILITIES:

| | TIME | MAINTENANCE | NONRECURRING COST | RECURRING COST | FAILURE PRONENESS | USEFUL LIFE | DEVELOPMENTAL RISK | |
|---|---|---|---|---|---|---|---|---|
| DEDICATED MANIPULATOR UNDER COMPUTER CONTROL | 1 | 1 | 3 | 2 | 5 | 4 | 2 | |
| COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR | 2 | 2 | 4 | 2 | 3 | 3 | 1 | |
| COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK | 2 | 2 | 4 | 2 | 4 | 2 | 4 | |
| COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK | 1 | 2 | 5 | 2 | 3 | 1 | 5 | |
| HUMAN IN EVA WITH TOOLS | 3 | 3 | 2 | 3 | 3 | 3 | 1 | C T |
| SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL | 3 | 2 | 3 | 3 | 4 | 2 | 2 | |
| DEXTROUS MANIPULATOR UNDER HUMAN CONTROL | 3 | 2 | 4 | 3 | 3 | 2 | 3 | |
| TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT | 3 | 3 | 3 | 3 | 4 | 2 | 2 | |

ARAMIS CAPABILITIES: AVERAGE SUMS:

| | ALL CRITERIA | WITHOUT TIME | WITHOUT MAINTENANCE | WITHOUT NONRECURRING COST | WITHOUT RECURRING COST | WITHOUT FAILURE-PRONENESS | WITHOUT USEFUL LIFE | WITHOUT DEVELOPMENTAL RISK | NUMBER OF TASKS TO WHICH APPLICABLE |
|---|---|---|---|---|---|---|---|---|---|
| AUTOMATED DOCKING MECHANISM | 18 | 13 | 14 | 12 | 14 | 11 | 13 | 13 | 1 |
| ONBOARD DEPLOYMENT/RETRACTION ACTUATOR | 17.6 | 15 | 14.8 | 15.4 | 15 | 14.4 | 14.4 | 16.6 | 5 |
| DOCKING UNDER ONSITE HUMAN CONTROL | 18 | 15 | 15 | 16 | 15 | 15 | 15 | 17 | 1 |
| TELEOPERATED DOCKING MECHANISM | 18 | 14 | 16 | 16 | 16 | 14 | 15 | 17 | 1 |
| STORED ENERGY DEPLOYMENT DEVICE | 20 | 17 | 17 | 18 | 17.5 | 16.5 | 15 | 19 | 2 |
| HUMAN IN EVA WITH TOOLS | 20.38 | 18 | 16 | 18.5 | 16.13 | 18.38 | 17.88 | 19.38 | 8 |
| DEDICATED MANIPULATOR UNDER COMPUTER CONTROL | 20.43 | 17.71 | 17.57 | 17.43 | 17.57 | 16.43 | 17.43 | 18.43 | 7 |
| SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL | 21 | 17.14 | 17.43 | 17.86 | 17.43 | 18.14 | 18.71 | 19.29 | 7 |
| TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT | 21.14 | 17.57 | 17.29 | 18 | 17.43 | 17.86 | 19.43 | 19.29 | 7 |
| DEXTROUS MANIPULATOR UNDER HUMAN CONTROL | 21.88 | 18 | 18.43 | 18.29 | 18.29 | 19.14 | 19.71 | 19.29 | 7 |
| COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR | 22.83 | 19.5 | 19.5 | 19.17 | 19.5 | 19.17 | 20.33 | 19.83 | 6 |
| COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK | 22.88 | 19.88 | 19.43 | 17.86 | 19.71 | 20.57 | 21.57 | 18.14 | 7 |
| COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK | 23.43 | 20.14 | 20.14 | 19.43 | 20.29 | 19.57 | 21.29 | 19.71 | 7 |
| SHAPE MEMORY ALLOYS | 26 | 23 | 23 | 22 | 22 | 23 | 21 | 22 | 1 |
| INFLATABLE STRUCTURE | 26 | 23 | 21 | 22 | 22 | 22 | 22 | 24 | 1 |

NOTE: In Columns 1 through 8, Lower Sums Indicate Better Performance.

adding the seven decision criteria values received by the capability in each of its applications, then averaging together all of these totals.

For example, the Computer-Controlled Dextrous Manipulator With Force Feedback received values 2, 2, 4, 2, 4, 2, 4 (Table 6.3), for a sum of 20 in its application to Position and Connect New Component. However, this capability applies to 6 other mechanical actuation tasks as well, and received different totals in those applications. Averaged together, these yield the average sum of 23.43 shown in Table 6.3. Since the capabilities are ordered according to their average sums (all criteria), the unfavorably high average sum of this capability gives it a low ranking. Columns 2 through 8 in the table result from the same procedure, but omitting one decision criterion in each case. This shows the sensitivity of the average sums to the criteria. The Automated Docking Mechanism, for instance, shows relatively little change if recurring cost is omitted (it is not expensive to operate) but shows significant improvement if failure-proneness is ignored (its high failure-proneness rating is due to the severity of any failures).

The best that can be said for ARAMIS is that it achieved its limited objective of making recommendations for technology development, since validated and shown to be critical for the future of space utilization. However, as a general-purpose methodology the simple matrix method leaves much to be desired. The evaluation procedure is subjective, both in its estimation and review of decision criteria values. The summing and averaging procedure assigns equal (unweighted) importance to all seven decision criteria. In specific space missions, this equivalence might not hold. For example, for maintenance tasks performed once every three years the time required may be far less important than the failure-proneness of the maintenance device performing the task. Far more detailed case studies are needed to make final decisions on the most favorable use of the ARAMIS method for specific space missions.

Additional problems arose because the ARAMIS study focused its examination at too detailed a level at the expense of larger perspectives. For example, breaking down satellite servicing operations into many small subtasks (e.g., Position and Connect New Component) makes it difficult to properly evaluate the complete operation. The methodology may recommend that one part of the servicing operation is best done by EVA and another part by telepresence, but often there are advantages to using only one of these capabilities for the entire operation. The methodology also cannot resolve parallel decision choices -- as, for example, when data clearly indicate that servicing one satellite is best done entirely by EVA and servicing another is best done by telepresence, but budgetary constraints allow only one of these technologies to be developed.

Another potential problem with this methodology is the difficulty of using its results. Both Smith et al. (1982) and Howard et al. (1982) were over 1000 pages in length, containing numerous tables and numbers. Such reports are more useful for reference than for reading, and are well-suited to computer-based operation where a computer data management system can easily guide the user to the information of interest and interact with users to change capability evaluations based on the characteristics of a particular space project. An interactive system could utilize expert system rules to make recommendations as to the choice of optimum utilization of human and machine capabilities.

ARAMIS researchers concluded that the simple matrix method could not replace the judgment of the Project Engineer and alone could not serve as an all-encompassing system to select the best capabilities for space project tasks. Rather, the best the method can accomplish is to prepare options for project engineers, to present background information and data sources on available options, and to display informed opinion on potential advantages, disadvantages, and relative merits of each option. Final decisions involve constraints and requirements specific to a particular space project. The ARAMIS method thus provides information to support the decision process and offers a systematic approach to the choice: Input data can be refined and updated, evaluations reviewed one at a time, and various weightings tried on the criteria values, to improve the decision.

## 6.2 Expert System for Task Allocation: SSTAAMMER

Simple matrix methodologies are non-interactive and have trouble incorporating the expertise of many disciplines. An alternative decision methodology for human-machine task allocation employs expert systems, a relatively new artificial intelligence technology which embodies rule-based knowledge and a weak theory of reasoning from uncertain evidence. During the present study, sample rules (knowledge) for making resource allocation decisions were coded into a computer-based expert system called SSTAAMMER (Space Station Task Allocation Among Man and Machine, an Expert Reasoner). SSTAAMMER can only be regarded as an incomplete prototype or demonstration system -- a more definitive system would have required the prior existence of a fully developed software package for which rules could have been developed during the course of the workshop.

Broadly speaking, an expert system is a computer program designed to offer advice that normally must be provided by a human expert. Expert systems are distinguished from other computer programs because their "knowledge base" (internally supplied data) is separate from the "inference engine" (the mechanism that makes decisions based upon this knowledge). The inference engine draws upon externally supplied data relating to some specific situation, then uses information in the knowledge base to resolve the problem. Further, expert systems try to capture the heuristics or rules-of-thumb that an expert uses to solve problems in the particular domain. (A mathematical model may be part of an expert system but is not a necessary feature.) Expert systems have been built to diagnose disease, analyze mass spectrographs, configure computer hardware, and to solve analytic equations. Expert systems have also been applied to planetary space mission planning and to shuttle crew activity scheduling.

A knowledge base is coded into an expert system in the form of subjunctive rules of the form:

```
IF antecedent 1 AND
   antecedent 2 AND ...
   antecedent m
----------------------
THEN consequent 1 AND
     consequent 2 AND ...
     consequent n.
```

The inference engine matches an hypothesis to a consequence of one of the rules. The antecedents then become new hypotheses which must be proven. If they are not provable from what the system knows or can find out, the system may back up and try another rule. If the consequents can be proven, then the system has succeeded in reasoning out an argument for the hypothesis.

Few things are absolutely certain, so expert systems frequently incorporate theoretically-weak techniques of reasoning from uncertain evidence. Such a technique involves attaching a certainty value to each fact and an attenuation value to each rule. Attenuation values may be combined algebraically with certainty values of antecedents to yield new certainty values for the consequents. This technique was employed in constructing SSTAAMMER. The following is an example of the kind of rule used in SSTAAMMER:

Rule 1 --

**IF** the task requires perceiving patterns in noisy data,

**THEN** there is suggestive evidence that the task should be automated.

Individual facts are assigned a certainty factor between zero and one by the user. "Certainty" is defined only vaguely; a certainty factor is neither a truth value nor a probability, since these are combined very differently. Similarly with each rule there is a built-in attenuation factor, also between zero and one. For example, a numerical attenuation factor is associated with Rule 1, indicated by the phrase "there is suggestive evidence." Similar rules were assigned attenuation factors between 0.5 and 0.7.

If a conjunction of several facts ($A_1$ and $A_2$ and ... and $A_n$) is needed in a rule R to conclude another fact C, then the certainty of C is given by the minimum of the certainty of the $A_i$ times the attenuation factor of R. Thus the evidence for a conclusion can never be stronger than the evidence for any of the claims supporting it.

If either of two facts (F1 or F2) are sufficient to conclude another fact C, then the certainty of C is given by:

$$\text{Certainty (C)} = \text{Certainty (F1)} + (1 - \text{Certainty (F1)}) \times \text{Certainty (F2)}.$$

Thus multiple reasons for concluding a fact each contribute to the overall evidence for the fact. Each time another reason is found for concluding a fact C, the certainty of C becomes closer to one.

Very often facts which are antecedents in one rule are consequents in another, as for example:

Rule 2 --

**IF** the task requires perceptual abilities beyond the range of human limits

**THEN** there is very strong evidence that the task should be automated.

The antecedent of Rule 2 is the consequent of another rule:

Rule 3 --

**IF** the task requires tactile sensation outside the range of human limits

**OR** the task requires aural sensation outside the range of human limits

**OR** ...

**THEN** the task requires perceptual abilities outside the range of human limits.

Similarly, the facts in the antecedent part of Rule 3 can be found in the consequent parts of still more specific rules.

The particular rule set used in SSTAAMMER was derived from several sources, including von Tiesenhausen (1982) and the workshop participants. The entire rule set is reproduced in Appendix 6A, together with a complete printout of the SSTAAMMER program (written in Lisp and executed on a DEC-20 computer).

Expert knowledge relating to space station automation is "bushy" in the sense that there are few hypotheses (either automate a task or leave it to a human, either do the task in space or on the ground) but many possible reasons for concluding one hypothesis or another. If the set or rules were diagrammed as a tree with the hypotheses at the roots, the tree would look like a squat bush with many branches. A particular attention-controlling technique has been developed for guiding the search through this "bush."

The bushy structure of knowledge about task allocation has a considerable influence on the design of the expert system. It was judged undesirable for SSTAAMMER to spend a long time exhausting all possible reasons for concluding that the task should be done by a human (or machine) before investigating any of the reasons for allocating it to a machine (or human). Instead, the system checks the most likely reasons to automate, then the most likely reasons to allocate the task to a human, then the next most likely reasons to automate and so on until certainty for one hypothesis or the other is reached. To thus reduce the search space in the horizontal dimension, SSTAAMMER's attention is periodically shunted from one hypothesis to the other. Shifting takes place only after a reasonable number of arguments (usually five) have been tried.

Just as it is not always desirable to search all the way across possible reasons horizontally in the tree-like knowledge structure, so it is not always desirable to search as deeply as possible vertically. The search space in the vertical dimension is reduced by asking users whether they can supply information that will prune branches from the search tree. For instance, the system might inquire whether the task under consideration demands perceptual abilities beyond the range of human limits. If the user supplies a negative or positive answer, arguments regarding individual sensory requirements need not be pursued. Specific sensory requirements are investigated only if the user cannot answer the more general question.

Finally, SSTAAMMER has some limited capability for explanation. This capability takes two forms. First, the system can say why it is asking a particular question -- if, after asking a question, the system is queried "why?" it will explain how the requested fact could be used in a rule to derive another fact. Second, SSTAAMMER can explain how it reached (or failed to reach) certain conclusions. Once it is finished and states either that it accepts one hypothesis or that neither can be concluded with any certainty, asking "how?" causes the system to display a review of the arguments used to validate (or invalidate) the hypotheses. A sample run is shown in Appendix 6A.

## 6.3 Decision Matrices: The Geometry of Uncertainty

Systematic matrices are used to represent complex systems under design, and help to understand interrelations among system elements. In more sophisticated analyses, weighted values appear in place of simple plus/minus indicators. However, most decisions are not cleanly defined and there is an element of doubt as to their correctness. This element of doubt can be expressed in terms of fuzzy logic as well as statistics, but decisionmakers often reject these methods as unclear or abstract. Three-dimensional decision matrices are a geometric representation of uncertainty which might possibly be developed into a useful decisionmaking tool -- a display of information more palatable for the spatially oriented person. Matrix analysis is traditionally the domain of the mathematician, physicist, and engineer. The introduction of heuristic geometrical methods may greatly broaden the utility of matrix methodologies.

For example, if a group of experts is making decisions regarding a particular set of tasks or is estimating contingencies of certain variables, executives may wish to know some fundamental information about the group process. This may include reliability and variation of results, comparability and reproducibility of the consensus among like groups of experts, variability of the decisionmaking process, structure of information generated, differentiation between known and unknown information, and areas requiring further research.

The experts might use a "must do" scale from 1-10 to score decisions, allowing their independent scores to be collected and the statistics of the consensus and variation of the decisions to be derived. If these numbers are simply used to construct a contingency table (much like ARAMIS; see section 6.1), the structure of the information may not be immediately apparent. Statisticians could perform a number of technical manipulations to analyze the data, but the results likely would not be readily comprehensible to decisionmakers trying to understanding the nature of the decision processes. A graphical display format would be far more effective.

For instance, consider a decision space consisting of two primary variables defining a planar matrix. The third (vertical) dimension can now be used to display the central tendency (mean, mode, or median) and its variation (standard deviation, variance, or range), or even statistical measures such as skewness or kurtosis, of the group decision score for each planar element. A small, vertical rectangular element then expresses the central tendency centered on the mean score for each cell, with variation represented by vertical extent above and below the mean. If the statistics are expressed on a cell-by-cell basis throughout the matrix a three-dimensional topography of scores is created.

The three-dimensional decision matrix permits some operations of interest. Decisions may be ordered hierarchically, the cells with highest values placed in the upper right-hand corner, those with the lowest values in the lower left-hand corner, and those with intermediate values placed in rank order using the upper right-hand rule for higher values. This creates a topography high in the upper right and low in the lower left, a surface called a "priority matrix." Decisions also may be ordered hierarchically on group consensus, with variation as a measure of the consensus. Using the right-hand rule to create this topography yields a matrix which describes the decisions with the least consensus in the upper right-hand field and those with the greatest consensus in the lower left-hand field. This surface, called a "consensus matrix," is extremely useful in understanding the structure of decisions and the reliability of answers.

It might also be useful to know something about the degree of convergence on certain variables. In the analysis of decisions, unexpected structure may appear in the ordering of the variables. Using the three-dimensional data matrix, variables represented by rows and columns could be arranged in hierarchical order using the right-hand rule. Arranged by central tendency the hierarchical matrix would express the variables with the highest to lowest priority. Arranged by variability, the hierarchical matrix would express the variables from most consensus to the least. Asymmetries in the decisionmaking process could be analyzed using kurtosis and skewness as statistics to examine bimodality of group decision or asymmetry around the central tendency. The decision matrix could show the repeatability of results or biases produced by group composition -- for example, perhaps groups of experts drawn from different fields have similar central tendencies when faced with similar decisions or problems. Also of interest is the dynamics of decisionmaking given different time and other constraints -- three-dimensional matrices might help clarify these processes.

## 6.4 Ethnography and Terrestrial Cultural Analogs

Data drawn from cultures around the world provides useful information for behavioral analysis. Ethnographic, psychological and sociological data can be used to predict, plan for, interpret, and modify behavioral conditions on the space station. Different cultures can help define the range of human response to similar environmental conditions, thus are germane to understanding the human element in space. The basis of this methodology is the examination of social science data for trends in response to comparable conditions. Similar responses suggest the potential for culture-independent causality. At least four cultures can be drawn upon to understand specific aspects of the space station (Table 6.4). Here, Eskimo culture is briefly reviewed to illustrate the usefulness of this methodology in projecting individual behavior in isolated and confined environments.

Terrestrial "analogs" suggest several behavioral factors expected to be significant during long-term spaceflight. (Analogs are any Earth-based simulation or natural working or living arrangement that can provide information useful to researchers studying space habitation -- Antarctic and Arctic stations, oceanographic research vessels, programmed environment laboratories, submarines, undersea laboratories, and space simulators.) Knowledge gained from studying these analogs may help to identify new areas of potential concern to space station designers, controllers, and crew.

### 6.4.1 The Eskimos: Cultural Adaptation to Isolation and Withdrawal

Social withdrawal of the individual in a con-

**TABLE 6.4. CONDITIONS ON THE SPACE STATION, SOCIOLOGICAL STUDY GROUPS, AND CULTURAL ANALOGS**

| CONDITION | SOCIOLOGICAL STUDY GROUP | CULTURAL ANALOG |
|---|---|---|
| Atrophy of Legs | Paraplegics | Warrau Indians (Venezuela) |
| Small Task-Directed, Male, Work Group in an Isolated and Harsh Environment (Not Confined) | Miners and Small Mines, Other Groups | Camel Herders, Trans-Saharan or Chinese Turkestan |
| Small, Isolated (6 mo.) Confined Groups in Extremely Harsh Environment | Artic Pipeline, Antartic Scientific Base, Salyut, Submarines | Eskimos |

fined and isolated environment may be one of the major psychological problems facing the future inhabitants of the space station (B.J. Bluth, personal communication, 1983). From our cultural perspective the appropriate response to social withdrawal is to socialize the person back into the group by implementing a strategy that "requires a systems approach which will harmonize the individual within the group within the environment" (McNeal and Bluth, 1981). However, primary data on Eskimo culture suggests the importance of social withdrawal and a strong need for individual autonomy under these conditions.

In winter camp the Eskimo group size averages 9 individuals, living in an 18-foot diameter house with one or more small satellites connected by a tunnel and set off at angles of 120° with respect to each other. The sleeping platform occupies roughly half of the main room. The other half of the room is the corporate work area with a window to let in light when the Sun or Moon are up. Access to this work space is negotiated by different individuals at different times. One-third of the space is used for the single hearth to thaw meat and to dry wet clothes. Storage space is available in the satellites or on the sleeping platform. The informant, Professor Lewis Binford (personal communication to J. Ericson, 10 August 1983) of the Department of Anthropology, University of New Mexico, wintered in one such house with a caribou-skin roof covered with packed and glazed moss and snow. Binford contrasted this spatial arrangement with summer camp, in which the same people spread out over kilometer-wide areas in family groups separated by 200-300 meters.

During winter camp the Eskimo is an autonomous person who strives for individuality in the confined environment. A number of social mechanisms are used to insure this. Adults do not talk about each other but rather focus on the behavior of children or pets. (It is said by Eskimos that a winter without children will be difficult.) The canine breeding cycle is carefully controlled so that pups will be born in the house during winter. In this intense and confined space individuality, not relationships or role performance, is emphasized. Children are trained very early to respect privacy and personal space. If an adult is on the sleeping platform, the children will not ask questions or play in the vicinity. Personal space is achieved by partitioning off sectors with skins to block light and sound. Marriage arrangements do not dictate role responsibilities. Intimacy is individualistic and may involve a group, anonymity by using costumes, or a ceremony. Intimacy in this fashion is an important mechanism of social interaction. Nearly every six weeks there is some form of corporate activity which requires extreme cooperation. This may be an intimate event, which would be considered immoral sexual behavior from our cultural perspective.

Among Eskimos who have not been in touch for some time the greeting is "are you upside down?" (i.e., are you mentally "up" or are you near a sleep period)? This greeting expresses the unpredictability of individual schedules. During winter, Eskimos keep their own personal eating and sleeping schedules which continually change throughout time. Within a household the schedules may be staggered for different family members. When tired from working on his kayak, a man will just go to sleep. Sleep cycles are shorter and more frequent than for average Americans. There is no corporate schedule or group schedule. If a corporate work force is required for a particular task, considerable discussions are conducted prior to the activity. Agreement on the task is considered a good idea. Corporate activities are perceived as an individual response to a situation rather than as a role responsibility. Each individual reorients his schedule to coincide with the corporate task, but returns to his staggered schedule after the task is completed. Our western tradition emphasizes cooperation, but the stress of confinement can amplify even the slightest disruption or disagreement. The fierce independence

of the Eskimos seems to reduce the number of these events. It is perfectly acceptable to withdraw socially.

Eskimos will occasionally go outside to collect firewood or other items. Extramural excursions are limited for the young and elderly. The "outside" is created psychologically by detailed and descriptive story-telling. People tell stories of the "outside" to compensate for confinement. Story-telling is a high art-form among the Eskimo people, one of the earliest skills taught to children. Eskimos generally have high verbal skills reflecting this training.

The Eskimo model might be applied to the space station. Crewmembers should be selected from among those individuals who possess the trait of extreme individualism and yet are willing, on call, to give up their individualism and enjoy being members of a group involved in an intense interaction. Crewmembers should be allowed to be autonomous in establishing their schedule, which may not conform particularly with that of other crewmembers. The crew should be sexually heterogeneous, self-motivated and responsible for their own acts. Space station design should allow for personal space as an individual haven, provide a means of achieving privacy, permit individuals to leave the main unit, and provide spaces that can serve many functions at the discretion of the crew. Pets and, in the more distant future, children may be useful during interpersonal arbitration.

### 6.4.2 Isolation and Confinement

Isolation and confinement produce numerous symptoms commonly associated with stress (Bluth, 1979, 1981a,b, 1982; Helmreich, 1983; McNeal and Bluth, 1981; Santy, 1983). Santy (1983) provides an excellent summary of behavioral and psychophysiological research, some proposed methods for future research, and a discussion of issues bearing on space exploration.

Consistent findings from analogs and simulations are that boredom, restlessness, anxiety, sleep disturbances, temporal and spatial disorientation, anger, and poorer task performance are commonplace under conditions of isolation and confinement. The most frequent complaint at remote stations is sleep disturbance, followed by depression, headache, irritability, and other somatic disorders. All these symptoms increase over time (Santy, 1983). Pre-screening and testing cannot identify susceptible individuals. A few claim that sensory deprivation, often encountered during isolation and confinement, will not be a problem in space (Berry, 1973). However, there have been no extended flights to give experience with life in an isolated space environment aside from the brief habitation (84 days) of the American Skylab and the Russian Salyut program -- and these have not been without incident (Cooper, 1976). Isolation and confinement can produce severe effects in groups of any size and must be taken into account when designing long-term manned space facilities. The Russian experience differs somewhat from that of American astronauts (Bluth, 1981a), perhaps in part because the Soviet Union has established a psychological/social support team for cosmonauts.

American researchers are now studying the effects of long-term confinement and isolation which may give insight into the human and social factors affecting performance in space (Bluth, 1981b). For instance, Antarctic bases are populated by crews of various sizes and cultural mixes. Early research results indicate significantly increased stress, though not all participants are affected similarly. Oceanographic research vessels also carry crews and scientists of widely varying backgrounds. Differences between ship crewmembers and scientific investigators have caused problems exacerbated by the lengthy tours -- but not all experiences involving ship crews have been negative (Bluth, 1981b).

None of the American space flights has lacked for work. Shuttle crew scheduling is calculated in several-minute increments. Taylor (1911) would have been proud of the extent to which scientific management is practiced in the space program. Hart and Bortolussi (1983) are studying the area of workload for commercial airline pilots and are developing a research methodology to study this subject from a scientific, rather than anecdotal, viewpoint. Other research in the industrial and academic community (Hackman and Oldham, 1980; Freeman, 1982) bears on the relationship between work on job design and the workers' reactions to design of work. Many different models and new approaches are appearing in the business community and may be useful in the space program. For example, Brady and Enuerian (Rice, 1983) at Johns Hopkins Hospital are studying how to increase productivity and decrease friction among small groups. Thus far their subjects have been restricted to students in groups of two or three, but this work may ultimately generate helpful behavioral guidelines for social and task design in a manned space station.

Because of the differences between terrestrial comparison situations and on-orbit locales, the analog methodology must be extended using social, psychological, and organizational analyses such as those described in Chapter 5. These analyses should select applicable features of known situations, and should suggest how to assess potentially novel features of space-based groups and organizations.

## 6.5 Trend Mapping Methodology

Trend analysis, a new management tool using information from networks (Bennigson, 1972), is designed to show important relationships between work groups in a project in order to diagnose problems and to aid in the design of management systems. Space station projects often involve uncertainty about real resource requirements, are done only once, and pose large planning and control problems. The manager can use this group network methodology to model coordination needs and relate these needs to solutions. Groups may include any available combination of humans and machines.

In the trend method, the groups' interdependence needs are modeled (Thompson, 1969) along with the accompanying recommended mechanism for integrating the activity of the groups. For instance, sequential activity in which one group must act before another demands a plan or schedule. Reciprocal activity between groups requires a feedback or mutual adjustment mechanism. Next, the group's level of uncertainty inherent in the activity is assessed and the interaction among groups with various degrees of uncertainty is modeled. Short-duration task-oriented functions which rely on formal authority represent a low degree of uncertainty; groups (or machines and groups) engaged in

long-duration interpersonal-oriented tasks which do not rely on formal authority are characterized as having a high degree of uncertainty.

Research shows that the interaction, say, between two groups with a high degree of uncertainty should be direct, complex, and by committee. Two groups, one with high and the other with low uncertainty, will integrate themselves by indirect, third party integrators or a separate integrating group. Groups with low degrees of uncertainty integrate their work and decisions by direct, simple mechanisms such as a management hierarchy, paperwork or contact lay representatives. The reason for these results is not yet entirely clear. Groups very different in organizational orientation literally speak different organizational languages and, if they are to relate effectively, require a third party who speaks both languages to translate and to integrate for them (Lawrence and Lorsch, 1969). Another interpretation is that more complex integrating mechanisms are required as the degree of uncertainty increases (Bennigson, 1972).

Another important characteristic of groups is their relative prestige/authority mix. Collaboration is more difficult when relative prestige and relative authority relationships are not consistent. One way in which relative authority may be established is in terms of interdependencies, where the party which is dependent is considered to have low relative authority. Conflict may be anticipated where, for example, Group A depends heavily on Group B, but Group A has much higher prestige in the organization than Group B. Estimates of relative prestige are inferred from organization charts and organizational background (Bennigson, 1972).

In summary, knowledge of groups' interdependencies, degrees of uncertainty, and relative prestige suggests the ways in which they will need to interact. The trend method allows planners to map and to draw attention to coordinating needs, much as the use of CPM draws attention to critical resource needs. Trend mapping can reveal authority or uncertainty conflict, individual groups in key positions, and relationships lying along critical paths. It is a network-based display of coordination needs. To see the overall picture, a network plan must be available which involves collections of data about precedence requirements, resource requirements and responsibility. Networks show relationships between activities; trend mapping then extracts the relationships among responsibility centers (Bennigson, 1972). A trend map thus may incorporate degrees of uncertainty, interaction in sequential or reciprocal relationships, dependency relationships, the number of critical path activities in the segment, and interactions on the critical path.

### 6.7 References


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# APPENDIX 6A

# SAMPLE RUN, DECISION RULES, AND PROGRAM LISTING FOR THE SSTAAMMER EXPERT SYSTEM

Contributed by

R.S. Wallace

## 6A.1 Sample Run

What is the task under consideration?
> monitoring-oxygen-level

You may answer the following questions with either "yes" or "no" (y or n), with a certainty factor ranging from 0 (least certain) to 10 (most certain), or with "dk" (don't know) or "dc" (don't care). Enter "how" or "why" for an explanation. For help, type HELP.

DOES MONITORING-OXYGEN-LEVEL REQUIRE PERCEPTUAL ABILITIES OUTSIDE THE RANGE OF HUMAN LIMITS ?
> dk

DOES MONITORING-OXYGEN-LEVEL REQUIRE PERCEPTION OF MORE THAN 537. DIFFERENT INTENSITIES ?
> no

DOES MONITORING-OXYGEN-LEVEL REQUIRE TACTILE PERCEPTION OUTSIDE HUMAN LIMITS ?
> yes

DOES MONITORING-OXYGEN-LEVEL REQUIRE COMPUTING ABILITY ?
> 5

DOES MONITORING-OXYGEN-LEVEL INVOLVE STORING AND RECALLING LARGE AMOUNTS OF PRECISE DATA FOR SHORT PERIODS OF TIME ?
> why

The fact MONITORING-OXYGEN-LEVEL INVOLVES STORING AND RECALLING LARGE AMOUNTS OF PRECISE DATA FOR SHORT PERIODS OF TIME may be used to establish WE SHOULD AUTOMATE MONITORING-OXYGEN-LEVEL. DOES MONITORING-OXYGEN-LEVEL INVOLVE STORING AND RECALLING LARGE AMOUNTS OF PRECISE DATA FOR SHORT PERIODS OF TIME ?
> 6

DOES MONITORING-OXYGEN-LEVEL INVOLVE ROUTINE REPETITIVE PHECISE TASKS ?
> yes

The hypothesis WE SHOULD AUTOMATE MONITORING-OXYGEN-LEVEL is confirmed with certainty 0.94176

Options are next, done, how, why, help
> how

THERE WAS VERY STRONG EVIDENCE THAT WE SHOULD AUTOMATE MONITORING-OXYGEN-LEVEL THIS FOLLOWED FROM 4. THINGS:

THERE WAS VERY STRONG EVIDENCE THAT MONITORING-OXYGEN-LEVEL INVOLVES ROUTINE REPETITIVE PRECISE TASKS

THERE WAS STRONG EVIDENCE THAT MONITORING-OXYGEN-LEVEL INVOLVES STORING AND RECALLING LARGE AMOUNTS OF PRECISE DATA FOR SHORT PERIODS OF TIME

THERE WAS WEAK EVIDENCE THAT MONITORING-OXYGEN-LEVEL REQUIRES COMPUTING ABILITY

THERE WAS STRONG EVIDENCE THAT MONITORING-OXYGEN-LEVEL REQUIRES PERCEPTUAL ABILITIES OUTSIDE THE RANGE OF HUMAN LIMITS. THIS FOLLOWED FROM 1. THINGS: THERE WAS VERY STRONG EVIDENCE THAT MONITORING-OXYGEN-LEVEL REQUIRES TACTILE PERCEPTION OUTSIDE HUMAN LIMITS

THERE WAS NO EVIDENCE THAT HUMANS SHOULD DO MONITORING-OXYGEN-LEVEL

Options are next, done, how, why, help
> done

## 6A.2 Expert System Decision Rules

The following are the rules that the expert system SSTAAMMER uses. While examining them, bear in mind that they represent a first pass. A complete system would require considerably more development time than was available.

RULE 1:
IF THE-TASK REQUIRES PERCEPTUAL ABILITIES OUTSIDE THE RANGE OF HUMAN LIMITS THEN THERE IS STRONG EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 2:
IF THE-TASK INVOLVES SAFETY OR HEALTH RISKS OUTSIDE TOLERABLE LIMITS FOR HUMANS THEN THERE IS STRONG EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 3:
IF THE-TASK REQUIRES COMPUTING ABILITY THEN THERE IS STRONG EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 4:
IF IT IS TECHNICALLY FEASIBLE TO AUTOMATE THE-TASK THEN THERE IS WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 5:
IF IT IS ECONOMICALLY FEASIBLE TO AUTOMATE THE-TASK THEN THERE IS WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 6:
IF THE-TASK INVOLVES STORING AND RECALLING LARGE AMOUNTS OF PRECISE DATA FOR SHORT PERIODS OF TIME THEN THERE IS WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 7:
IF THE-TASK INVOLVES ROUTINE REPETITIVE PRECISE TASKS THEN THERE IS WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 8:
IF THE-TASK REQUIRES REGULARLY AN ATTENTION SPAN OF MORE THAN 20. MINS THEN THERE IS WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 9:
IF THE-TASK ENTAILS DETECTION OF INFREQUENT OR RARE EVENTS THEN THERE IS WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 10:
IF HUMANS DON'T LIKE TO DO THE-TASK THEN THERE IS WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 11:
IF THE-TASK REQUIRES MONITORING MEN OR MACHINES THEN THERE IS WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 12:
IF THE-TASK REQUIRES HANDLING OF HIGHLY COMPLEX OPERATIONS SUCH AS DOING MANY THINGS AT ONCE THEN THERE IS WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 13:
IF THE-TASK REQUIRES EVA THEN THERE IS VERY WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 14:
IF THE-TASK REQUIRES QUICK RESPONSE TO SIGNALS THEN THERE IS VERY WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 15:
IF THE-TASK REQUIRES DEDUCTIVE REASONING ABILITY THEN THERE IS VERY WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 16:
IF THE-TASK REQUIRES EXERTING LARGE AMOUNTS OF FORCE SMOOTHLY THEN THERE IS VERY WEAK EVIDENCE THAT WE SHOULD AUTOMATE THE-TASK

RULE 17:
IF HUMANS LIKE TO DO THE-TASK THEN THERE IS STRONG EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 18:
IF THE-TASK REQUIRES THE ABILITY TO ARRIVE AT NEW AND COMPLETELY DIFFERENT SOLUTIONS TO PROBLEMS THEN THERE IS STRONG EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 19:
IF THE-TASK REQUIRES ABILITY TO DETECT SIGNALS IN HIGH NOISE ENVIRONMENTS THEN THERE IS STRONG EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 20:
IF THE-TASK REQUIRES THE ABILITY TO PROFIT FROM EXPERIENCE THEN THERE IS WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 21:
IF THE-TASK ENTAILS THE ABILITY TO REASON INDUCTIVELY THEN THERE IS WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 22:
IF THE-TASK REQUIRES ABILITY TO PERCEIVE PATTERNS AND THE-TASK REQUIRES ABILITY TO GENERALIZE ABOUT PATTERNS
THEN THERE IS WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 23:
IF THE-TASK REQUIRES ABILITY TO STORE LARGE AMOUNTS OF INFORMATION FOR LONG PERIODS AND THE-TASK REQUIRES ABILITY TO REMEMBER RELEVANT FACTS AT THE APPROPRIATE TIME
THEN THERE IS WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 24:
IF OPERATIONS IN THE-TASK CANNOT BE REDUCED TO A SERIES OF PRESET PROCEDURES THEN THERE IS WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 25:
IF THE-TASK ENTAILS MANY UNEXPECTED OR UNPREDICTABLE EVENTS THEN THERE IS WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 26:
IF THE-TASK REQUIRES ABILITY TO IMPROVISE AND ADOPT FLEXIBLE PROCEDURES THEN THERE IS WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 27:
IF THE-TASK REQUIRES SENSITIVITY TO A WIDE VARIETY OF STIMULI THEN THERE IS WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 28:
IF THE-TASK REQUIRES ABILITY TO USE JUDGMENT THEN THERE IS WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 29:
IF THE-TASK ENTAILS THE ABILITY TO PERFORM FINE MANIPULATIONS THEN THERE IS VERY WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 30:
IF THE-TASK ENTAILS THE ABILITY TO PERFORM WHEN OVERLOADED THEN THERE IS VERY WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 31:
IF THE-TASK INVOLVES THE ABILITY TO TRACK IN A WIDE VARIETY OF SITUATIONS THEN THERE IS VERY WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 32:
IF THE-TASK REQUIRES ABILITY TO DETECT CERTAIN FORMS OF ENERGY THEN THERE IS VERY WEAK EVIDENCE THAT HUMANS SHOULD DO THE-TASK

RULE 33:
IF THE-TASK REQUIRES DELIVERY OF FORCE GREATER THAN 3000. NT THEN THERE IS VERY STRONG EVIDENCE THAT THE-TASK REQUIRES EXERTING LARGE AMOUNTS OF FORCE SMOOTHLY

RULE 34:
IF AUTOMATION OF THE-TASK WILL BE MORE COST-EFFECTIVE THAN USING A HUMAN TO PERFORM THAT TASK AND ALL THE NECESSARY COSTS OF DEVELOPMENT DESIGN TESTING INSTALLATION AND AUTOMATION CAN BE COVERED BY KNOWN FINANCIAL RESOURCES THEN THERE IS STRONG EVIDENCE THAT IT IS ECONOMICALLY FEASIBLE TO AUTOMATE THE-TASK

RULE 35:
IF THE NECESSARY HARDWARE AND SOFTWARE COMPONENTS FOR THE-TASK ARE AVAILABLE OFF-THE-SHELF
AND THE FINAL DEVELOPMENT OF AN AUTOMATED SYSTEM FOR THE-TASK CAN BE DONE WITHIN THE SCHEDULED LIFE-CYCLE DEVELOPMENT FOR THE SYSTEM OR THAT LIMIT CAN BE REVISED
AND SYSTEMS EVENTS FOR THE-TASK CAN BE PREDICTED AND HANDLED BY AUTOMATION
AND THE EXPECTED RELIABILITY OF THE PROPOSED SYSTEM FOR THE-TASK MEETS SYSTEM PERFORMANCE REQUIREMENTS
AND CONSEQUENCES OF EXPECTED SYSTEM FAILURES CAN BE COMPENSATED FOR BY AUTOMATIC BACK-UP OR OTHERWISE PREVENTED FROM EXCEEDING ACCEPTABLE LIMITS
AND ADEQUATE SAFEGUARDS AGAINST DANGERS TO HEALTH FROM THE-TASK CAN BE FULLY AUTOMATED
THEN THERE IS STRONG EVIDENCE THAT IT IS TECHNICALLY FEASIBLE TO AUTOMATE THE-TASK

RULE 36:
IF THE-TASK IS NECESSARILY DONE IN SPACE AND HUMANS SHOULD DO THE-TASK THEN THERE IS VERY STRONG EVIDENCE THAT HUMANS IN SPACE SHOULD DO THE-TASK

RULE 37:
IF HUMANS SHOULD DO THE-TASK AND THE-TASK REQUIRES MORE THAN 8. PERSONS THEN THERE IS VERY STRONG EVIDENCE THAT HUMANS ON THE GROUND SHOULD DO THE-TASK

RULE 38:
IF THE-TASK REQUIRES PERCEPTION OF MORE THAN 537. DIFFERENT INTENSITIES THEN THERE IS VERY STRONG EVIDENCE THAT THE-TASK REQUIRES PERCEPTUAL ABILITIES OUTSIDE THE RANGE OF HUMAN LIMITS

RULE 39:
IF THE-TASK REQUIRES TACTILE PERCEPTION OUTSIDE HUMAN LIMITS THEN THERE IS STRONG EVIDENCE THAT THE-TASK REQUIRES PERCEPTUAL ABILITIES OUTSIDE THE RANGE OF HUMAN LIMITS

RULE 40:
IF THE-TASK REQUIRES DETECTION FOR FORCE MORE FINELY THAN 1. NT THEN THERE IS STRONG EVIDENCE THAT THE-TASK REQUIRES TACTILE PERCEPTION OUTSIDE HUMAN LIMITS

RULE 41:
IF THE-TASK REQUIRES TEXTURE DISCRIMINATION FINER THAN 1. CM THEN THERE IS STRONG EVIDENCE THAT THE-TASK REQUIRES TACTILE PERCEPTION OUTSIDE HUMAN LIMITS

### 6A.3 Lisp Program Code for SSTAAMMER Expert System

```
(setq yes (setq y 10.0))
(setq n (setq no (setq dc 0)))
(setq maybe (setq may (setq ma (setq m 5))))
(setq probably (setq prob (setq pr (setq p 7))))
(setq likely (setq like (setq li (setq l probably))))
(setq nl 3)

(setq *hypotheses '(
        (we should automate *) (humans should do *)))

;(msg t "*hypotheses " t)

(defun start-expert-system ()
  (prog ()
    (msg t t t " An Expert System to Aid in Making Decisions " t
           " about Automating Tasks on the Space Station " t t t)
    (setq first-round-flag nil)
    (expert-system)))

(defun expert-system ()
  (prog (response)
    iter
    (cond (first-round-flag
           (msg t t "     Options are next, done, how, why, help" t)
           (prompt)
           (setq response (read))
           (cond ((not (member response '(n next d done e how why help)))
                  (msg t response "      invalid response" t)
                  (go iter))
                 ((member response '(? help ))
                  (msg t "     Possible responses are:"
                       t "     next -- to evaluate another task"
                       t "     done -- to exit"
                       t "     how, why -- to see an explanation of results"
                       t "     help -- to see this message" t)
                  (go iter))
                 ((member response '(q x ex none stop quit halt d exit done))
                  (return 'done))
                 ((member response '(how why explain))
                  (mapcar 'explain hypothesesnodes) (go iter))
                 (t t))))
    (setq first-round-flag t)
    (msg t t "*********************************************" t t)
    helploop
    (msg t "     What is the task under consideration?"
         t "     Please enter the name of a task as a single string "
         t "     e.g. say wash-windows rather than wash windows " t)
    (prompt)
    (setq task (read))
    (cond ((member task '(help ? what))
           (msg t "     Please enter the name of a task as a single string "
                t "     e.g. say wash-windows rather than wash windows " t)
           (go helploop)))

    (cond ((member task '(q x ex none stop quit halt d exit done))
           (return 'done)))
    (msg t t "         You may answer the following questions with " t
         "      either a yes or a no (or y or n) or a certainty " t
         "      factor ranging between 0 (for least certain) to " t
         "      10 (for most certain) or a maybe or a probably" t
         "      or a dk (for don't know)" t
         "       or a dc (for don't care)." t
         "          Enter a how or a why to see an explanation."  t
         "          To get help type HELP." t)

    (diagnose)     ; should task be automated?
                       ; (and what is locale of control?)
    (remember)     ;save results in <N.ANDERSON>EXPERT.RESULTS
    (go iter)))
```

```
(defun prompt ()
  (msg t t t t t"     > "))

(defun newsym (s)
        (readlist (append (explode s)
                          (explode (putprop s
                                            (1+ (cond ((get s 'count))
                                                      (t 0)))
                                            'count)))))
;(msg t "newsym" t)
                                     ;ILISP OLDSYM (but quote s)
(defun oldsym (s)
        (readlist (append (explode s)
                          (explode (cond ((get s 'count)) (t 1))))))

;(msg t "oldsym" t)

(defun fassoc (key a-list)
        (cond ((assoc key (cdr a-list)))
              (t (cadr (rplacd (last a-list)
                               (list (list key)))))))
;(msg t "fassoc" t)

(defun fremove (frame slot facet value)
  (prog (slots facets values target)
    (setq slots (fgetframe frame))
    (setq facets (assoc slot (cdr slots)))
    (setq values (assoc facet (cdr facets)))
    (setq target (assoc value (cdr values)))
    (delete target values)
    (cond ((null (cdr values))
           (delete values facets)))
    (cond ((null (cdr facets))
           (delete facets slots)))
    (return (not (null target)))))

(defun fput (frame slot facet value)
        (cond ((member value (fget frame slot facet)) nil)
              (t (fassoc value
                         (fassoc                                                    facet
       (fassoc slot
                                        (fgetframe frame))))
                 value)))

;(msg t "fput" t)

(defun fget (frame slot facet)
   (reverse (mapcar 'car
                (cdr (assoc facet
                            (cdr (assoc slot
                                        (cdr (get frame 'frame))))))))

;(msg t "fget" t)

(defun fgetframe (frame)
        (cond ((get frame 'frame))
              (t (putprop frame (list frame) 'frame))))

;(msg t "fgetframe" t)

(defun maketree ()
        (prog ()
        (setq topnodes (mapcar '(lambda (a) (makesubtree a)) *rules))
        (setq hypothesesnodes
                (delete nil (mapcar
                                '(lambda (a)
                                      (cond ((member
                                                (car (fget a 'fact 'value))
                                                *hypotheses)
                                             a)
                                            (t nil)))
                                 topnodes)))
        (mapcar '(lambda (a)
                         (cond ((not (member a hypothesesnodes))
```

```
                                    (mapcar '(lambda (b)
                                                (search-and-splice a b))
                                            hypothesesnodes))))
                topnodes)
        (mapcar '(lambda (a) (msg ".")
                        (fput a 'count 'value 0)) hypothesesnodes)
          ;initialize counts on all hypotheses frames to zero
        (linkup-competing-hypotheses hypothesesnodes)))

;(msg t "maketree" t)

(defun search-and-splice (frameA frameB)
        (cond ((equal (fget frameA 'fact 'value)
                      (fget frameB 'fact 'value))
               (fput frameA 'use 'used-by (car (fget frameB 'use 'used-by)))
               (putprop frameB (get frameA 'frame) 'frame)
               (fput frameB 'ask 'ask? t))
              ((null (fget frameB 'use 'uses)) nil)
              (t (mapcar '(lambda (a) (search-and-splice frameA a))
                         (preconditions frameB )))))

;(msg t "search-and-splice" t)

(defun flatten (x)
       (cond ((null x) nil)
             ((atom (car x)) (cons (car x) (flatten (cdr x))))
             (t (append (flatten (car x)) (flatten (cdr x))))))

;(msg t "flatten" t)

(defun preconditions (frame)
        (delete nil (mapcar '(lambda (a) (cond ((numberp a) nil) (t a)))
                            (flatten (fget frame 'use 'uses)))))

;(msg t "preconditions " t)

(defun linkup-competing-hypotheses (hypothesesnodes)
        (prog (hyps)
        (setq hyps (append (last hypothesesnodes) hypothesesnodes))
        iter
        (msg ".")
        (cond ((equal (length hyps) 1) (return t)))
        (fput (car hyps) 'competes-with 'value (cadr hyps))
        (setq hyps (cdr hyps))
        (go iter)))

;(msg t "linkup-competing-hypotheses" t)

(defun makesubtree (rule)
        (prog (framename)
        (setq framename (newsym 'frame))
        (fput framename 'fact 'value (car rule))
        (fput framename 'certainty 'value 0)
        (mapcar '(lambda (a) (msg ".")
                    (cond ((equal (cadr a) 'and)
                           (fput framename 'use 'uses
                                (append (mapcar '(lambda (b)
                                                  (make-precondition-frame
                                                     framename b (newsym 'frame))
                                                  (oldsym 'frame))
                                                (cddr a))
                                        (list (car a)))))
                          (t
                            (fput framename 'use
                                  'uses (list (newsym 'frame) (car a)))
                            (make-precondition-frame framename
                                        (cdr a) (oldsym 'frame)))))
                (cdadr rule))
        (return framename)))

;(msg t "makesubtree" t)

(defun make-precondition-frame (parent-framename precondition precond-name)
        (prog ()
```

```
        (fput precond-name 'fact 'value precondition)
        (fput precond-name 'certainty 'value 0)
        (fput precond-name 'ask 'ask? t)
        (fput precond-name 'use 'used-by parent-framename)))

;(msg t "make-precondition-frame" t)

(setq *rules '(
((we should automate *)
    (or
        (7.0 * requires perceptual abilities outside
             the range of human limits)
        (6.0 * involves safety or health risks outside tolerable
             limits for humans)
        (6.0 * requires computing ability)
        (5.0 it is technically feasible to automate *)
        (5.0 it is economically feasible to automate *)
        (3.0 * involves storing and recalling large
             amounts of precise data for short periods of time)
        (3.0 * involves routine repetitive precise tasks)
        (3.0 * requires regularly an attention span of more than 20 mins)
        (3.0 * entails detection of infrequent or rare events)
        (3.0 humans don't like to do *)
        (2.0 * requires monitoring men or machines)
        (2.0 * requires handling of highly complex operations
             such as doing many things at once)
        (1.0 * requires EVA)
        (1.0 * requires quick response to signals)
        (1.0 * requires deductive reasoning ability)
        (1.0 * requires exerting large amounts of force smoothly)))
((humans should do *)
   (or  (8.0 humans like to do *)
        (7.0 * requires the ability to arrive at new and completely
             different solutions to problems)
        (6.0 * requires ability to detect signals in high noise environments)
        (5.0 * requires the ability to profit from experience)
        (5.0 * entails the ability to reason inductively)
        (5.0 and (* requires ability to perceive patterns)
                 (* requires ability to generalize about patterns))
        (5.0 and (* requires ability to store large amounts
                    of information for long periods)
                 (* requires ability to remember relevant facts
                    at the appropriate time))
        (4.0 operations in * cannot be reduced to a series
             of preset procedures)
        (4.0 * entails many unexpected or unpredictable events)
        (4.0 * requires ability to improvise and adopt flexible procedures)
        (3.0 * requires sensitivity to a wide variety of stimuli)
        (3.0 * requires ability to use judgment)
        (1.0 * entails the ability to perform fine manipulations)
        (1.0 * entails the ability to perform when overloaded)
        (1.0 * involves the ability to track in a wide variety of
             situations)
        (1.0 * requires ability to detect certain forms of energy)))
((* requires exerting large amounts of force smoothly)
    (or (9.0 * requires delivery of force greater than 3000 nt)))
((it is economically feasible to automate *)
    (or (8.0 and (automation of * will be more cost-effective
                            than using a human to perform that task)
                 (all the necessary costs of development design
                      testing installation and automation can
                      be covered by known financial resources))))
((it is technically feasible to automate *)
    (or (8.0 and (the necessary hardware and software components
                      for * are available off-the-shelf)
                 (the final development of an automated system for *
                      can be done within the scheduled life-cycle
                      development for the system or that limit
                      can be revised)
                 (systems events for * can be predicted and handled
                      by automation)
                 (the expected reliability of the proposed system for *
                      meets system performance requirements)
                 (consequences of expected system failures can be
```

```
                    compensated for by automatic back-up or
                    otherwise prevented from exceeding
                    acceptable limits)
                (adequate safeguards against dangers to health from *
                         can be fully automated))))
((humans in space should do *)
    (or (9.0 and (* is necessarily done in space)
                (humans should do *))))
((humans on the ground should do *)
    (or (9.0 and (humans should do *)
                (* requires more than 8 persons))))
((* requires perceptual abilities outside the range of human limits)
    (or (9.0 * requires visual perception outside human limits)
        (8.0 * requires tactile perception outside human limits)
        (8.0 * requires aural perception outside human limits)))
((* requires tactile perception outside human limits)
    (or (8.0 * requires detection for force more finely than 1 nt)
        (8.0 * requires texture discrimination finer than 1 cm)
        (8.0 * requires detection of vibration finer than 10K Hz)))
((* requires requires visual perception outside human limits)
    (or (8.0 * requires perception of intensity outside the
             range 3e-10 to 0.3 cd per m**2)
        (8.0 * requieres perception of light wavelengths outside
             the range 300 nm to 1500 nm)))
((* requires aural perception outside human limits)
    (or (8.0 * requires perception of sonic intensity outside
             the range 10E-16 to 10E-2 J per cm**2)
        (8.0 * requires perception of sonic frequency outside the
             range 20 to 20000 HZ)))))
;(msg t "*rules" t)

(defun diagnose ()
  (prog ()
    (msg t "    Wait...")
    (maketree)
    (initialize-path-pointers hypothesesnodes)
    (setq current-hypothesis (car hypothesesnodes))
    (msg t t)
    iter
    (cond ((null (delete nil (mapcar '(lambda (a) (car
                                                  (fget a 'use 'use-next)))
                                     hypothesesnodes)))
           ; if there are no more paths to check
           (msg t)
           (prettyprintsentence
            '(No hypothesis can be confirmed with certainty))
           (msg t)
           (status-of-hypotheses)
           (return nil))
          ((greaterp (car (fget current-hypothesis 'certainty 'value)) 0.9)
           (msg t "     The hypothesis" t)
           (prettyprintsentence
                   (subst task '* (car (fget current-hypothesis
                                       'fact 'value))))
           (msg t "     is confirmed with certainty" t)
           (prettyprintsentence
            (list (car (fget current-hypothesis 'certainty 'value))))
           (msg t)
           (return t))

          ((or (and (greaterp (car (fget current-hypothesis 'count 'value)) 3)
                    (lessp (car (fget current-hypothesis
                                    'certainty 'value)) 0.8))
               (null (car (fget current-hypothesis 'use 'use-next))))
           ; if either the count is too large
           ; or the branches are exhausted
           (mapcar '(lambda (a) (fremove current-hypothesis 'count 'value a))
                   (fget current-hypothesis 'count 'value))
           (fput current-hypothesis 'count 'value 0)
           ; reset the count to zero
           (setq current-hypothesis (car (fget current-hypothesis
                                         'competes-with
                                         'value)))
           ; and go check the next hypothesis
```

```
          (go iter)))
    (fput current-hypothesis 'certainty 'value
          (plus (car (fget current-hypothesis 'certainty 'value))
                (times (difference 1.0
                                   (car (fget current-hypothesis
                                              'certainty 'value)))
                       (ask-next-question-about
                        (car (fget current-hypothesis 'use 'use-next))))))
;(msg t "     certainty of " current-hypothesis " is "
;     (fget current-hypothesis 'certainty 'value) t)
    (fput current-hypothesis 'count 'value
          (add1 (car (fget current-hypothesis 'count 'value))))

    (fput current-hypothesis 'use 'use-next
          (cadr (member (car (fget current-hypothesis 'use 'use-next))
                        (reverse (fget current-hypothesis 'use 'uses)))))

    (go iter)))
(defun initialize-path-pointers (nodelist)
  (mapcar 'recursice-initialize-path-pointers nodelist))

(defun recursice-initialize-path-pointers (node)
  (cond ((null (preconditions node)) (msg ".") nil)
        (t (msg ".")
           (fput node 'use 'use-next (car (reverse (fget node 'use 'uses))))
           (initialize-path-pointers (preconditions node)))))

;(msg t "initialize-path-pointers" t)

(defun ask-next-question-about (facts-and-attenuation)
  (cond ((null facts-and-attenuation) 0)
        ((equal (length facts-and-attenuation) 2) ; single or branch
         (times (quotient (cadr facts-and-attenuation) 10)
                (ask-about (car facts-and-attenuation))))
        (t (times (quotient (car (last facts-and-attenuation)) 10)
                  (eval (cons 'min (mapcar 'ask-about
                                           (reverse
                                            (cdr (reverse
                                                  facts-and-attenuation))))))))))

;(msg t "ask-next-question-about" t)

(defun ask-about (fact)
  (prog (answer)
  errorloop
  (cond ((and (fget fact 'ask 'ask?)
              (pretty-ask (subst task '* (car (fget fact 'fact 'value))))
              (prompt)
              (not (equal (setq answer (read)) 'dk))
              (cond ((member answer '(done stop halt exit quit q x))
                     (status-of-hypotheses)
                     (expert-system) (break nil))
                    ((member answer '(help what ?))
                     (msg t "    Options are: "
                          t "    done -- quit here "
                          t "    help -- this message "
                          t "    why, how --explain why this question is asked"
                          t "      yes -- definitely"
                          t "      maybe -- maybe"
                          t "      probably, likely -- likely"
                          t "      nl -- not likely"
                          t "      no -- definitely not"
                          t "      dk -- dont know"
                          t "      dc -- dont care"
                          t "      a number between 0 and 10 --certainty value"
                          t "          where 10 is most certain (same as yes)"
                          t "          and 0 is least certain (same as no)" t)
                     (go errorloop))
                    ((member answer '(why how))
                     (msg t "     The fact " t)
                     (prettyprintsentence
                      (subst task '* (car (fget fact 'fact 'value))))
                     (msg t "     may be used to establish " t)
                     (prettyprintsentence
```

```
                    (subst task '* (car
                                    (fget (car (fget fact 'use 'used-by))
                                          'fact
                                          'value))))
                   (msg t)
                   (go errorloop))
                  ((not (or (and (numberp answer)
                                 (lessp answer 10.001)
                                 (greaterp answer -0.0001))
                            (member answer '(yes no y n dc
                                             maybe may ma m probably
                                             prob pr p likely like li
                                             l nl))))
                   (msg t answer "      invalid certainty factor." t)
                   (go errorloop))
                  ((greaterp (eval answer) 0)
                   (fput (car (fget fact 'use 'used-by))
                         'use 'used fact)
                   (fput fact 'certainty 'value (quotient
                                                 (eval answer) 10.0)) t)
                  (t t)))
        (return (quotient (eval answer) 10.0)))
       (t (setq answer 0)
          (mapcar '(lambda (a)
                     (setq answer
                           (plus answer
                                 (times (difference 1 answer)
                                        (ask-next-question-about a)))))
                  (reverse (fget fact 'use 'uses)))
          (cond ((greaterp (eval answer) 0)
                 (fput (car (fget fact 'use 'used-by))
                       'use 'used fact)
                 (fput fact 'certainty 'value answer)))
          (return answer)))))

;(msg t "ask-about" t)

(defun pretty-ask (fact)
  (cond ((equal (cadr fact) 'is)
         (msg t)
         (prettyprintsentence
          (append (cons 'is (cons (car fact) (cddr fact)))))
         (msg "?" t))
        ((member (cadr fact) verbs)
         (msg t)
         (prettyprintsentence
          (append (cons 'does
                        (cons (car fact)
                              (cons (splice (cadr fact))
                                    (cddr fact))))))
         (msg "?" t))
        (t (msg  t "      With what certanty can you assert:" t)
           (prettyprintsentence fact)
           (msg "?" t))))

(defun splice (verb)
  (implode (reverse (cdr (reverse (explode verb))))))

(setq verbs '(involves requires entails))

(defun prettyprintsentence (list)
  (prog (counter list1 max-length)
    (setq counter 0)
    (setq list1 list)
    (setq max-length 50)
    (princ "     ")
    loop
    (cond ((null list1) (return t))
          ((greaterp counter max-length)
           (setq counter 0)
           (terpri) (princ "      "))
    (princ (car list1)) (princ " ")
    (setq list1 (cdr list1))
    (setq counter (plus counter (add1 (length (explode (car list1))))))
```

```
    (go loop)))

(defun status-of-hypotheses ()
  (mapcar '(lambda (a) (msg t "     Hypothesis ")
                       (prettyprintsentence
                        (subst task '*
                               (car (fget a 'fact 'value))))
                       (msg "     has certainty "
                            (car (fget a 'certainty 'value)) t))
          hypothesesnodes) t)

(defun evidence-adjective (n)
  (cond ((or (equal n 0) (equal n 0.0)) '(no))
        ((lessp n 0.2) '(very weak))
        ((greaterp n 0.8) '(very strong))
        ((greaterp n 0.5) '(strong))
        (t '(weak))))

(defun explain (fact)
  (cond ((null (fget fact 'use 'used))
         (msg t) (prettyprintsentence
                 (append '(there was)
                         (evidence-adjective (car (fget fact 'certainty
                                                        'value)))
                         '(evidence that)
                         (car (subst task '* (fget fact 'fact 'value)))))
         (msg t))
        (t (msg t)
           (prettyprintsentence
                 (append '(there was)
                         (evidence-adjective (car (fget fact 'certainty
                                                        'value)))
                         '(evidence that)
                         (car (subst task '* (fget fact 'fact 'value)))))
           (msg t)
           (prettyprintsentence
            (append '(this)
                    '(followed from)
                    (list (length (fget fact 'use 'used)))
                    '(things:)))
           (msg t)
           (mapcar 'explain (fget fact 'use 'used)))))

(defun rotate (list)
  (cons (car (last list)) (delete (car (last list)) list)))

(defun print-rule (rule)
  (print-rule-sub-fn (car rule) (cadr rule)))

(defun print-rule-sub-fn (consequent antecedents)
  (cond ((equal (car antecedents) 'or)
         (mapcar '(lambda (a) (print-rule-sub-fn consequent a))
                 (cdr antecedents)))
        ((equal (cadr antecedents) 'and)
         )))

(defun savecontents (markedfile)
  (prog (i next final)
    (setq i (open markedfile 'in))
    (setq final nil)
    iter
    (cond ((equal (setq next (read i)) 'eof)
           (setq final (cons 'eof final))
           (close i)
           (return (reverse final))))
    (setq final (cons next final))
    (go iter)))

(defun append-to-file (list-of-items markedfile)
  (prog (o oldcontents newcontents)
    (setq oldcontents (savecontents markedfile))
    (setq newcontents (append list-of-items oldcontents))
    (setq o (open markedfile 'out))
    iter
```

```
    (cond ((null newcontents) (close o) (return t)))
    (print (car newcontents) o)
    (setq newcontents (cdr newcontents))
    (go iter)))

(defun remember ()
  (append-to-file
   (list '************ (cadr (uwrite))
         (mapcan '(lambda (a) (subst task '*
                                      (list (car (fget a 'fact 'value))
                                            (car (fget a 'certainty 'value)))))
                 hypothesesnodes))
   "<N.ANDERSON>EXPERT.RESULTS"))

(defun print-rules ()
  (mapcar 'print-rule (subst 'the-task '* *rules)) t)

(defun print-rule (rule)
  (prog (head tail count)
    (setq head (car rule))
    (setq tail (cdadr rule))
    (setq count 1)
    iter
    (cond ((null tail) (return t)))
    (msg t "--------------------------------" t (newsym 'Rule) ":" t t)
    (setq count (add1 count))
    (cond ((equal (cadar tail) 'AND)
           (prog (conjunct)
             (setq conjunct (cddar tail))
             (msg t "IF" t)
             iter
             (msg t)
             (cond ((equal (length conjunct) 1)
                    (prettyprintsentence (car conjunct))
                    (return t)))
             (prettyprintsentence (car conjunct))
             (msg t t "AND" t)
             (setq conjunct (cdr conjunct))
             (go iter)))
          (t (prettyprintsentence (cons 'IF (cdar tail)))))
    (msg t t)
    (prettyprintsentence (append '(THEN THERE IS)
                                 (evidence-adjective (quotient (caar tail)
                                                               10.0))
                                 '(EVIDENCE THAT) head))
    (msg t)
    (setq tail (cdr tail))
    (go iter)))

(comment bps 23000.)
(alloc '(list (0 nil 0.10) fixnum (0 nil 0.10)))        ;
(setq ibase 10.)
(setq base 10.)

(defun msg nargs
  (apply 'or
         (mapcar '(lambda (e)
                    (cond ((equal e t) (terpri))
                          (t (princ e))))
                 (listify (arg nil)))))

(defun tab (n) (implode (tab-sub-fun n)))

(defun tab-sub-fun (n)
  (cond ((lessp n 1) '(" "))
        (t (cons " " (tab-sub-fun (sub1 n))))))

(defun nequal (a b) (not (equal a b)))

(msg t t (append '(hello there) (cdr (uwrite))) t t)
```

# APPENDIX 6B

## AUTONOMY MEASURE FUNCTION AND SYMMETRY RELATIONS

Contributed by

J.A. Wise

The workshop briefly investigated the possibility of developing a measure function for autonomy, modeled, at first, after the development of utility theory which purports to measure preferences. The primitive binary relation "x controls y" was used to construct a "weak order" to allow ordinal measurement. Unfortunately, an autonomy measure defined in this way has limited usefulness because it is constrained within one type of control loop only and thus must be "renormalized" each time a different type of control relation is established.

For example, consider control as a binary relation on a set S of ordered pairs (x,y) with x contained in S and y contained in S. Let xCy = "x controls some behavioral property of y." Then xCy is irreflexive because not-xCx for all x in S, and xCy can be (1) asymmetric, because if xCy then not-yCx for every x and y in S; (2) symmetric, because xCy implies yCx under some manifestations of control; and (3) negatively transitive, because if (not-xCy, not-yCz) then not-xCz for every x, y, and z in S. If xCy is determined to be irreflexive, asymmetric, and negatively transitive for a set S, then the binary relation C imposes a "weak order" on the set S. Now, suppose that "independence" is defined as the absence of a strict control relation, C, just as indifference may be described as an absence of preference in utility theory. If I = independence and K = control relation, then xIy implies (not-xKy, not-yKx). With independence as the basis for an equivalence class in S, and control as a weak order, then there is a real-valued function A, on S, such that xKy implies A(x)KA(y) for all x and y in S. This function measures the autonomy of any element with respect to any other.

Such weak order is the very minimum requirement for establishing a simple ordinal autonomy measure (i.e., first, second, third), let alone interval or ratio measurement. But even the conditions for satisfying the requirements of weak order are questionable in any use beyond the most restricted sense of a control relation. Two elements may share a variety of different control relationships, but the autonomy scale presented above can only recognize one of them. For instance, suppose that a space station vernier rocket must be ignited (by a preset program or by a human operator). When ignited, the rocket itself is under external control, but its firing may necessitate a curtailment of EVA or laboratory activities due to induced vibration or exhaust product space pollution. In effect these other activities are controlled by the source of control for the rocket -- but such second-order control relations are not part of the autonomy scale derivation because they are not strict binary control relations as originally defined. Two sources may also show a reciprocal control over a single controlled quantity, as when both partners to a conversation mutually maintain the appropriate speaking distance between them. Similarly, grazing herd animals or flocking birds mutually maintain an appropriate spacing during feeding. Here, xCy implies yCx, which makes control in this sense a "symmetric" relation like "brotherhood". Under such relations, one cannot contrive a scale that imputes more or less of a derived measure to the entities involved.

These considerations suggest that it may not be appropriate to measure autonomy in a system of control relationships the way utility is measured against a set of choice objects. In its different manifestations, autonomy appears much more like a symmetry than a utility measure. This is because its usefulness as an organizing principle is best appreciated in terms of how autonomies are broken. In contemporary particle physics, hierarchies of broken symmetries are the basis of particle relations and interactions.

Symmetry is based on the primitive notion of invariance, which describes how a property of an entity is maintained under a transformation. For example, a circle shows an infinite set of both rotational and reflection symmetries through its center. A circular saw blade shows only rotational symmetry limited by the aliquot angles that move the teeth of the blade into correspondence with one another. A square is more symmetric than a rectangle because its group table (the listing of its symmetries) shows it to be invariant under eight transformations whereas the rectangle is only invariant under four. (The square's extra symmetries are two rotations about the center of $90^{\circ}$ and $270^{\circ}$, and two reflections about the diagonals.) However, symmetries do not add unidimensionally, and squares are not regarded as "twice as symmetric" as rectangles.

It may be more valuable to measure autonomy the way symmetry is measured, in terms of automorphisms that conserve a type of control relation between two entities. Consider a measure of autonomy based on the notion of control the way symmetry is based on invariance. This requires a description of the types of autonomy that an entity can express. If autonomy is "freedom from control", then perhaps the best way to express autonomies is inversely, in terms of controls and how autonomies may be broken or constrained.

The following is a non-exhaustive list of candidate types of autonomy, arranged in descending order from most important to least important to conserve. Using symmetry as an analogy, the Euclidean transformations (rotations, reflections, translations) provide the complete set of motions by which the symmetries of plane figures or solid bodies may be compared. As yet there exists no analogous classification of controls that could be used to organize autonomies. Instead, the value of these meanings of autonomy is heuristic as they suggest some useful principles for the role of the human element in space:

Inclusion/Exclusion Autonomies -- Given a behavioral repertoire, S, of an element x: Element x can be said to be inclusively or exclusively autonomous of element y if y cannot insert/exclude an action from the behavioral repertoire of x. "Johnny, pick up your room" and "never draw to an inside straight" are examples of instructions that break this sort of autonomy. A shopping list (that is attended to) is another example.

Priority Autonomy -- Given a behavioral repertoire S, of an element x: Element x is said to be priority autonomous of element y if y cannot affect the sequence of behavioral states exhibited by x. Waiting in line, a Congressional filibuster, and the instruction "Brush your teeth before you go to bed" are examples of situations that constrain or break this kind of autonomy.

Bounded Autonomy -- Given a behavioral repertoire S, of an element x: Element x is said to be boundedly autonomous of element y if y cannot restrict the range of a controlled quantity in any act within the behavioral repertoire of x. The control of pH level of blood, the sign "low bridge ahead", and the notice "above 1.5 is a passing grade" are examples of situations that break this type of autonomy.

Synchronous Autonomy -- Given behavioral repertoires $S_x$, $S_y$, of elements x and y: These elements are said to be synchronously autonomous of each other to the degree that their mutual controls on each other's behavioral repertoires are in one-to-one correspondence. Thus, synchronous autonomy is not a new "type" of autonomy, but rather a special case where the reciprocal controls between two elements overlap. Examples include mutual control of speaking distance, the avoidance of eye contact in elevators, and the mutual maintenance of personal space by seat selection.

# CHAPTER 7

# EVOLUTION OF SPACE STATION AUTONOMY

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One of the key concepts of evolution, whether biological, cultural, social, or technological, is natural selection -- the idea that systems vary and are selected for superior survival and growth. This also may involve notions of resourcefulness and competition among organisms or systems. But there is a crucial difference between technological (or cultural) and biological evolution. The latter is essentially a slow, wasteful, seemingly random process. Technical evolution, on the other hand, is a rapid, efficient, nonrandom intellectual activity -- a flexible, guided selection process.

In the near-term evolution of space station systems and autonomy, guided selection might take many forms. Computer memory modules may be replaced by faster or higher-capacity plug-compatible units. Advanced machine or human-machine systems may replace or augment some functions previously performed either by humans alone or by humans and machines together in earlier less-capable formats. The station and other space activities will motivate the development of modular machine technology. The telepresence-to-robotics transition should engender many new kinds of autonomous systems beyond space manufacturing robots analogous to those used in terrestrial industry today.

Another important concept is the ecology or environment in which evolution takes place. There are really two ecologies of a space station: First, the harsh physical environment of space which affects human and machine performance as well as transportation costs; second, and perhaps more important, there is the human context on Earth. This context provides goals, organizations, support, politics -- the entire sociocultural arena within which space systems vary, compete, and, ultimately, are selected or not.

The principle of variation in evolution is important too. Variation provides the raw materials upon which selection operates. Future manned and unmanned orbital activity will generate variation and permit selection of machines and procedures both for LEO and for longer-term lunar and interplanetary ventures. The space station itself is a variational mechanism for technological and organizational evolution. For instance, once the station is in place, ground-based entities may find that they are just one player, powerful but far from omnipotent. (NASA should study game-theoretic concepts as applied to competition among multiple players for limited resources, leading directly to the concept of niche or evolutionary equilibrium strategy.)

As greater effectiveness is sought in space systems, evolution of station automation could result in a near-autonomous unit. One can imagine a progressive development including a LEO "branch station" for close contact and servicing of expanding orbital activities, becoming, later, the hub of a space city. An interesting ecological relationship could emerge between LEO and lunar activities -- the lunar ecology, sufficiently developed for materials, might serve roughly the analogous function for the station as the farm serves for the city on Earth. A near-space waystation or departure facility for manned translunar forays is yet another possibility for far-future stations.

It is now almost 500 years since Columbus sailed into the unknown aboard several very fragile ships, seeking something he didn't quite get, and helped launch the greatest expansion of technological and social evolution in human history. In 1992, on the eve of the 500th anniversary of the first significant exploratory and colonization mission into this hemisphere, the American permanent space station may become a reality. But the end of this bold new adventure for mankind is nowhere in sight. Let us recall that North America, a pristine continent discovered during the pioneering voyages and settlements of Columbus half a millennium ago, today is the home of the greatest technological, economic, and military power on Earth. The prospects for space settlement and industrialization in the decades and centuries ahead are no less exciting.

## 7.1 Near-Term Station Evolution

The first-generation space station will offer a balanced set of capabilities to satisfy the many competing interests and users from whom project support derives. Near-term station evolution beyond the initial design may take many different directions, but likely will include increasing module specialization, greater on-orbit operational and machine system autonomy, increased capability for growth and self-maintenance, and a broader diversification of user communities served by the multi-element space facility.

The fictional scenario in Appendix 7A depicts a day in the life of a space station crewmember who, in concert with fellow astronauts, teleoperators, and advanced semi-autonomous devices, must rendezvous with and repair a stricken commercial satellite. Numerous design concepts and desirable station features (Appendix 7B) became apparent to workshop participants as they constructed this and other scenarios of daily station life.

### 7.1.1 Near-Term Capabilities of the Space Station

The space station's capabilities derive from NASA's goals as an organization, the functions which the station must perform, and the needs of users. Estimated to cost $7.5-9.0 billion, the base station (at 28.5°) will function as a habitat for crew and users; as a science, applications, and technology laboratory; as a permanent observatory and manufacturing facility; as a free-flyer servicing facility and a communications/data-processing node; as a transportation node; and as an assembly and storage facility (Pivirotto, 1983).

To support these many functions, the space station offers a number of specific capabilities. Fundamental to its design are the station's power and thermal properties. The station will have access to 60 kw of power in the main buses (Pivirotto, 1983; Tilton, 1983). System loads, battery potentials, and solar array electrical generation must be balanced simultaneously, so the power production and distribution system will be automatically controlled, perhaps by expert systems (Martin Marietta, 1983). The station's thermal control design is influenced by the facility's multi-year life expectancy, the large quantities of waste heat requiring dissipation, and the great variety of payloads and missions which the station must service. The linked modules need a highly versatile thermal "utility" or bus system, analogous to a municipal public utility, and will utilize waste heat, minimize electrical heaters, and require minimum crew attention through automated control (Ellis and Rankin, 1983).

The 6-8 person crew will dwell in the space station's core habitat and activity area. Past space vehicles and modules were designed along utilitarian lines to ensure human survival and successful accomplishment of relatively brief missions. By contrast, the space station of the early 1990s must provide a more pleasant habitat in which people thrive psychologically, socially and physically.

To enhance work productivity as well as habitability, the space station core system requires sophisticated environmental control and life support -- such as atmospheric revitalization and cabin thermal control, metabolic water and waste management, and cabin support for EVA. Fundamental habitability will include separate onboard facilities for work, food preparation, eating, personal privacy, and sleeping. Noise, excessive light, and physical interference which might decrease comfort must be avoided. Food storage and preparation areas will allow astronauts to cook their own meals. Rather than the reconstituted food of earlier days, the space station will offer a diet similar to that enjoyed on Earth. A large gymnasium for daily exercise will be serviced by an enhanced version of the environmental control system, thus ensuring that body heat and odors generated by physical exertion are properly controlled so astronauts can exercise in relative comfort.

The habitation module should contain a health maintenance clinic and a small operating theater for trauma treatment. This area can maintain a sterile working environment as needed to ensure quality medical and surgical care. The space station will also have intra-station, extra-station, and station-to-ground communications. The latter provides a phone-home capability for astronauts. Ease of access and frequent contact with family and friends on Earth will help to more closely simulate the normal ground-based working environment.

Onboard station functions will be more autonomous than in any previous manned spacecraft. Extensive operational data formerly managed by ground control should be available to the crew in a user-friendly format. Systems control and display, power management and distribution, data processing, inventory control of expendables and equipment, flight management (e.g., formation flights, shuttle interaction, altitude reboosts, TMS checkout and launch), malfunction warning and reconfigurations will all be managed with the assistance of multi-redundant computer systems. The shift from predominantly ground-based mission control to greater orbital autonomy requires an extensive onboard tracking, communication and command center (Dickinson, 1983). The station crew should generate and modify its own work schedules using an interactive expert system designed for this purpose.

The space station can have payloads attached to it. Payloads will be given berthing space, power sources, and other facilities as needed. Mission specialists (scientist- or engineer-astronauts trained extensively for payload operations) and payload specialists (trained to handle specific packages) will provide human expertise for successful payload deployment. Expected modules may include National Research and Development Laboratories, satellite servicing bays, and a smart-front-end TMS. The space station can serve the multiple needs of materials processing, life sciences experiments, commercial and scientific ventures, national security concerns, and even contaminant containment missions -- although, over time, personnel rotation and onboard experiments involving animals could expose stabilized, susceptible crewmembers to new pathogens (Chambers, 1983).

Satellite servicing is a key capability. The space station will be equipped with grappling equipment, conceptually similar to that used by Earth-based stevedores. The equipment will be housed in and near the bays where satellites are secured for servicing. With scores of astronaut and mission specialist hours of labor devoted to extra-vehicular activities such as satellite servicing and reconfiguration, the station should be equipped with a semi-automated "personal valet" system for cleaning and refurbishing spacesuits after each use. Suits currently require 60-72

hours for refurbishing after EVA; the valet could allow astronauts to clean a suit in less than two hours. Hooked to one of several outlets, the suit would be thoroughly vacuumed of moisture, sweat, aromatics, human exhaust and other contaminants. Suit electrical, thermal, radiative, and atmospheric properties would be evaluated prior to the next usage.

### 7.1.2 Factors and Options in Near-Term Evolution

The space station will be a multifunctional system capable of sustaining human life while providing a research laboratory for basic academic investigations as well as commercial/industrial feasibility trials. It must be self-sustaining and serve as a workplace for the construction and repair of other space hardware. Fortunately, the concept of "space station" has been broadened to include an ever-changing system of numerous free flyers and unmanned platforms flying in formation around a base station and in alternative orbits. The term "evolution" suggests systematic, adaptive advancement in the use and structure of the space station. Implicit in the term is the notion that the facility will become more diverse in function and more complex in structure over time. A related term, "metamorphosis," would better apply to sudden changes that radically transform the space station or its mission (e.g., converting the LEO habitat to an L5 waystation or lunar orbiter.)

There are many evolutionary courses the space station could take. For example, the station could begin small, growing in size and developing into a large monolithic space complex with hundreds or thousands of human inhabitants (O'Neill, 1976). An alternative evolutionary strategy is smaller but more numerous modules -- the key to evolution is survival, not necessarily bigness. A careful examination of current and projected evolutionary pressures should be undertaken to plot the most appropriate course for space station survival.

Two driving forces may substantially affect station architecture -- technological advances (e.g., in microprocessors, robotics, artificial intelligence) and social transformations (e.g., national political-economic conditions, management-organizational structure). Both can induce change not only in space station structure but also in mission patterns and in human-machine autonomy. For example, microchips have replaced rooms full of computer hardware, resulting in greater data processing power at less cost. Hair-thin glass fibers are replacing bulky coaxial cables. Space-rated hardware is now more compact and more intelligent than just a few years ago. Assuming these trends continue, unmanned platforms are expected to become more efficient and autonomous, requiring less and less human intervention. Likewise, habitable spacecraft should become more highly automated, freeing human inhabitants from mundane monitoring and control duties and allowing more exploratory and creative activity.

Changes in the social milieu are less predictable. As the gross national products of participating nations fluctuate, so might funding patterns for space activities. As international conflict waxes and wanes, so might defense-related missions for the space station.

Within the station itself, changes in crew size and makeup may alter habitat size, design, even onboard "culture." Experiments in the physical and biological sciences could affect life on the space station and on Earth. The development of new medical procedures, new construction and management techniques, experiments in communication and transportation, and novel energy generation techniques could have a reciprocal evolutionary effect on space station development and on earthbound enterprises.

Current economic and political projections indicate that the space station will begin small. It must have the potential to survive and to grow at an affordable initial price. It must be able to take advantage of new technologies and social factors without the need for complete retrofitting. To this end, hardware should be modular, upgradable and plug-compatible with standard terrestrial devices, and station social organization should be flexible enough to allow for innovative change.

## 7.2 Commercialization of the Space Station

The space station will have a useful life of at least several decades. It will begin as a research and development facility, heavily dependent on the space shuttle and ground control for support, and later evolving into an autonomously operated manufacturing and service facility linked to a family of auxiliary platforms and spacecraft. The estimated initial cost for a 1991 deployment is $7-9 billion, plus large additional subsidies to meet continuing capital and operating expenses. The space station must be regarded as a long-term investment in national technological and economic strength. This investment will produce scientific knowledge throughout its life and may lead to significant economic benefits by the year 2000 and beyond.

The American private sector is distinguished by its ability to develop new products and services from innovative applications of scientific knowledge. The goal of space commercialization is to encourage companies to invest in the space station. If this goal is realized, some share of station funding will gradually shift from the public to the private sector. U.S. companies will benefit from an enhanced ability to compete in world markets because of their long-range commitments to research, development, industrial and service operations in space. Station facilities will enable manufacturers to create unique, high-value, low-volume products which could not be duplicated on Earth, and to market terrestrial spin-offs of automated processes developed for use aboard the station. The American public thus also benefits from a greater range of goods and services available and a decreasing tax burden.

Both private companies and the federal government recognize the great expense and enormous risk of space station investments. Costs are generally higher than investments in similar activities undertaken on Earth, and risks to the private investor include the uncertainty of earning adequate return on capital and the need to wait up to a decade before significant returns are realized. At present the two most promising areas of commercial activity are materials processing in space (MPS) and launching/servicing communications satellites. However, with one exception (a joint venture in electrophoresis by McDonnell Douglas and Johnson & Johnson), neither activity will yield significant revenue during the station's initial decade. It will take about ten years of MPS lab-

oratory research and development work to identify which manufacturing processes are commercially feasible for producing unique products in space. And before the station can be used as a communications satellite launch and service base, a reusable orbital transfer vehicle (OTV) must be developed for cost-effective transport between LEO and GEO.

The traditional planning horizon of American companies is shorter than one decade. To extend this horizon, private industry must gain confidence that the U.S. government has a sustained commitment to space commercialization and to the station. In the past an adversarial relationship has sometimes existed between public and private sectors. In the future, the federal government should take the initiative to develop cooperative relationships with private industry to promote the commercialization of space, thus ensuring the American station will remain commercially competitive with foreign manned facilities, launch vehicles, and satellites.

### 7.2.1 Materials Processing in Space (MPS)

The objective of MPS is to advance scientific knowledge and to identify commercially feasible space processing techniques. Microgravity is a unique property of space that may allow some materials to be manufactured with greater precision and fewer defects than on Earth. But MPS is a new science, and a decade or more of basic research may be required before commercially feasible processes can be developed. Perhaps a majority of MPS experiments will fail to result in profitable processes. The possibility of new technologies designed to minimize the effect of gravity illustrates the risks of investing in MPS. For instance, a company working with NASA recently developed a containerless system for making special glass products on Earth (OTA, 1982). As another example, electrophoresis operations in space (EOS) was developed several years prior to genetic engineering. It is possible that genetic engineering on Earth may be a more economical way to purify vaccines than EOS (Bieman, personal communication, 1983).

After commercially feasible processes have been demonstrated, large-scale production facilities can be deployed on dedicated space platforms supported by the American station. NASA's near-term plan is to establish an orbital MPS laboratory to conduct basic research. The principal challenge is to find inducements for private sector companies (1) to make long-term commitments of money and resources, and (2) to participate in MPS experiments.

To encourage commercial investment in MPS, NASA should take the following steps to reduce the risks faced by private investors (OTA, 1982; Weinberg, 1983):

(1) In conjunction with representatives from industry, NASA should identify and publicize those MPS research ventures which show the greatest promise of commercial feasibility. Useful guidelines include the existence of a market (without markets for a new product, no company will invest in research to produce it), high product value per pound (many activities will compete for limited station facilities), low labor-intensiveness (only a limited number of people can be supported on a space station), requirement of a unique property of space such as microgravity (if space is essential for production, the product probably cannot be made more cheaply on Earth), and low probability of rapid technological obsolescence.

(2) NASA should continue to create various cooperative arrangements with private industry such as its Joint Endeavor Agreements (JEAs).

(3) NASA should offer financial incentives to private companies to support an MPS laboratory. For example, the fee for commercial participation could be indexed to the sign-up date. The earlier this date, the lower the annual fee NASA charges the company. As another example, under a JEA NASA could allow use of an MPS laboratory at reduced cost in return for a royalty fee based on future profits. Other branches of government could also help out. For instance, Congress could legislate preferred tax treatment for companies participating in MPS.

(4) NASA should encourage companies interested in MPS to form research consortia to allow joint funding of the MPS laboratory. In 1980, Justice Department guidelines suggested sympathetic consideration for cooperative basic research ventures open to all prospective participants. Recently, computer and semiconductor manufacturers have formed a research consortium to challenge Japanese competition.

(5) Rules must be promulgated to protect and to share intellectual property rights, rights to patents, and trade secrets.

(6) NASA must guarantee that, throughout the life of the space station, space facilities will be easily accessible by a dependable transportation service.

Product Areas for MPS. Five major product areas are targeted for research in an MPS laboratory (OTA, 1982). The production of materials in these areas -- (1) crystal growth, (2) solidification of metals and alloys, (3) containerless processing of glass, (4) fluid and chemical processing, and (5) pharmaceuticals -- will be enhanced by the microgravity environment of space.

Crystal Growth: When semiconductor LSI chips used in computers and communications devices are grown on Earth, they contain imperfections which reduce their electrical performance. Similarly, ground-produced infrared detectors contain defects limiting their ability to detect small currents. Semiconductor and infrared crystals grown in an MPS laboratory will be of far higher purity and thus should be capable of superior performance.

Solidification: Gravitational effects greatly influence the physical structures of metals and alloys. Directional solidification in microgravity allows complex shapes such as turbine blades to be melted and directionally resolidified to increase axial strength. Miscibility-gap alloys, which cannot be prepared in bulk quantities on Earth, might be produced in microgravity for such diverse applications as electrical contacts and self-lubricating bearings.

Containerless Processing: One advantage to manufacturing in space is that materials can be processed without absorbing impurities from container walls. Containerless processing may make it

possible to extend the glass-forming range of many materials, even metals, resulting in new glasses with unique properties. Possible applications are optical waveguides, fiber optics, and fusion energy lasers.

Fluid and Chemical Processing: By eliminating the effects of convection and sedimentation, microgravity allows components to be isolated for study with a higher degree of freedom than is possible on Earth. A potential application is the production of monodisperse latex spheres in space. These spheres, now available only in research quantities, are used in calibrating electron microscopes, in the measurement of membrane pore size, and in serological tests for a variety of diseases.

Pharmaceuticals: Electrophoresis, the separation of particles of different charge/mass ratios in an electric field, is the only MPS activity likely to succeed commercially within the next decade. Tests of prototype electrophoresis operations in space (EOS) have already been conducted aboard the space shuttle. EOS can produce a higher-purity immune serum than is available on Earth for treating viral infections afflicting 185,000 patients annually in the United States alone (MDAC, 1983). Other biomedical applications of microgravity may yield such products as human insulin, collagen for artificial corneas, and artificial skin for wound and burn treatment.

Role of the Space Station in Support of MPS. The role of the station is to provide a readily accessible MPS laboratory offering versatile, modular, basic materials processing facilities which permit easy replacement as existing technology becomes outdated (Martin Marietta, 1983). The MPS laboratory could perform experiments developed by universities, NASA, private industry, or other research groups. Equipment should be compact enough for transport via shuttle to the space station. Small commercial MPS development hardware could be leased for short periods of time as space and utilities are available, but on a lower-priority basis than units dedicated to basic research (the primary objective of the laboratory). Large commercial production hardware such as EOS units could be externally attached to the station, leasing electrical power and other services as required. EOS units would be resupplied by a station-controlled TMS unit. Exhaust gases from commercial production platforms must be vented without contaminating other platforms, free flyers, or station modules.

The near-term human presence in an MPS laboratory is very important. Human operators can monitor and control experiments, service and resupply the facilities, adjust equipment to accommodate new processing sequences, intervene in response to unanticipated problems, and alter procedures when necessary. Their presence minimizes the time needed to conduct experimental research.

Some MPS laboratory tasks could be accomplished by automation and telepresence (see Appendix 7C). However, in the near-term not all desired experiments could be performed in this manner. Those experiments which could be performed by automation and telepresence would take more time to complete than if they had been performed by a crew member. Thus in the near-term a laboratory relying solely upon automation and telepresence must have lower productivity than one employing human operators. Furthermore, commercial firms are unlikely to invest in MPS unless they are certain a human operator will be available on site.

While an MPS laboratory cannot be operated at full capacity without a human operator, people need not be continuously present. Astronauts need only be continuously available, on a part-time basis. Martin Marietta (1983) has estimated MPS lab requirements as one crewman for 50% of a workday -- that is, the lab operates at 100% capability when staffed by one person working half-time for 360 days per year. If commercial users can accept a lab with reduced productivity, then less human presence is required. If operating efficiency is directly proportional to half-time human workdays per year available, then if a person is available 140 days/year (e.g., 20 one-week shuttle flights) the operating efficiency is approximately 38%. In this example, a given set of experiments would take 100%/38% = 2.63 times longer to perform than if the lab were permanently attended, though possibly at far less cost.

### 7.2.2 Communications Satellites

Cumulative commercial investment in domestic communications satellite systems, including ground stations, has increased from $170 million in 1974 to $1.6 billion in 1982. Rising demand for international communications has been even more dramatic. Rapid growth is expected to continue beyond the year 2000. Two factors may restrict the ability of communications satellites to satisfy this increased demand -- the limited number of satellite positions within the usable geostationary arc and the limited usable frequency slots. A number of technologies are under development to improve satellite capabilities to more fully utilize the available space (Martin Marietta, 1983). None of these technologies requires a space station, nor is one needed to support the expansion or modernization of the satellite communications industry.

However, the station can serve as (1) a test facility for new hardware for use in communications satellites, (2) a base for launching communications satellites into GEO, and (3) a base for servicing communications satellites deployed in GEO. A commercial communications carrier will pay for these services only if they are cheaper than alternative means of achieving its objectives. The first of these services can be offered in the near-term, but the others await the development of a reusable launch vehicle which can carry satellites from LEO to GEO. New equipment such as antennas, transponders, and switching circuits can be carried into orbit for testing and space qualification, eliminating the need for a dedicated satellite to demonstrate new technologies. None of the three services requires a permanent human presence in space. All could equally well be provided by an unmanned space platform periodically visited by satellite servicing crews in shuttle sorties lasting several days.

Presently, communications satellites are launched both by expendable booster rockets (such as the Ariane) and by the reusable space shuttle which has an expendable upper stage to send payloads into GEO. As satellites continue to grow in size and weight, larger upper stages will be required. NASA is considering the development of a station-based reusable upper stage, the OTV, to transfer satellites from LEO to GEO after initial delivery to LEO by the shuttle. If NASA develops an economical, reusable OTV, the shuttle/station

combination could capture a large segment of the market for launching high-altitude communications satellites.

Satellite technology is changing so rapidly that commercial carriers find it economical to replace their on-orbit equipment every 7-10 years, although most satellites could continue to relay signals for much longer periods (Martin, 1978). If the space station is to serve as a base for servicing communications satellites, NASA must convince communications carriers that it is cheaper to incrementally repair and upgrade than to replace. To do this, a reusable OTV must be available and comsats must be modular in design and constructed for easy on-orbit servicing. The removal of an old module and its replacement by a new or functioning unit must be possible in GEO via a TMS servicing unit transported by a reusable OTV.

Most communications carriers now keep a spare satellite on the ground ready for launching. If a satellite fails in orbit, the antennas at its Earth stations are redirected to another satellite until the spare is deployed (Martin, 1978). If satellites can be repaired in orbit, communications carriers need not purchase and maintain spares on the ground or at the space station. NASA (or a private insurance group) could maintain one modular, general-purpose utility satellite at the space station. Whenever a commercial satellite fails in orbit, the OTV could deploy the utility satellite until repairs on the failed device had been completed.

If the policy of servicing geosynchronous satellites is successful, NASA will reduce the number of new satellites launched from the space station, thereby lowering the revenue it will earn from launching satellites. The revenue earned by satellite manufacturers will also be reduced. Since geosynchronous satellites can be designed to have a useful life much longer than seven years, a policy of repairing and upgrading satellites in orbit rather than launching new satellites every seven years will reduce expenses to the communications carriers and produce more robust satellite designs.

## 7.3 Advanced Stations and the Evolution of Autonomy

While no specific predictions are possible, a general scenario of evolution of NASA missions over the next 30 years can be described. Assuming the space station project proceeds as have other NASA projects, with heavy government backing and no major technical failures, the project will persist and gradually expand. As this process unfolds, the corporate world will begin investing in orbital R&D. Many of these investments will be successful -- foamed metals, zero-g separation of cells, and containerless production of semiconductors are likely to produce high value-added products -- both in commercial and mass markets.

NASA will extend the space station concept to include free-flying platforms, formation flying, tether assemblies, and so forth, whose success will strain the capabilities of first-generation facilities. These facilities will be characterized by prefabricated modules constructed and in some cases serviced back on Earth. Module dimensions will be limited by the shuttle cargo bay capacity. Station architectures will be simple cylindrical networks. Prefabricated modules are a conservative way of prototyping, providing the most data at least risk. However, modules do not provide sufficient space to scale up space manufacturing and research efforts after the initial phases are complete.

### 7.3.1 Second-Generation Stations, Lunar Bases, and Beyond

The second phase of space station development requires greater contiguous volume. This reduces reconfiguration costs, simplifies life and habitability support, adds to station safety, and augments efficiency as LEO utilization increases. One indication that this second phase has been reached will be the on-orbit conversion of shuttle External Tanks into pressure vessels, construction frames, and raw materials for small-scale local fabrication. Contiguous volume is best provided by stations constructed in space. The minimum structural mass per liter of contained pressurized gas and the minimum surface area per enclosed volume (hence minimum leakage rate) are provided by spherical pressure vessels -- a shape poorly-suited for shuttle transport.

Increased volume requirements thus demand the construction of entire space stations in orbit, probably in the form of geodesic spheres. A practical size for a second-generation station is a 20-meter-diameter structure, which could be constructed in perhaps 6 months using 5 shuttle-loads of materials including 4 tons of air, an open-cycle environmental control system, and interior fittings. This station would be roughly the size of a 3-story building from top to bottom, ideal for an orbital corporate R&D laboratory. Cheap HLLV boosters could provide replenishment of station expendables such as food, air, water, and scrubber chemicals.

It seems possible that the demand for space goods may become fairly large, followed by a considerable orbital market for consumables and construction materials. Such a market would be heavily influenced by transportation costs, although not, perhaps, dominated by them. In the near-term, Earth resupply is favored. In the longer run, as market size increases, a capital investment in lunar resupply could become attractive. A solar- or nuclear-powered electromagnetic catapult, assisted by aerobraking at the delivery end, may be used to efficiently transport supplies to LEO from the lunar surface.

The first such supplies could be consumables such as oxygen and food. Organic station wastes could be sent to the moon for agricultural applications or reprocessing. Lunar materials also may be essential in the construction of manned stations at or above GEO. These stations may be required for certain ambitious telecommunications and data processing schemes, and for the construction of solar power satellites, but require massive bulk shielding from solar flare and Van Allen Belt radiation. It is unlikely that such shielding can be economically supplied from Earth.

As capital and experience accumulate at the lunar base, further projects involving lesser value-added items might become feasible. One such project would be fabrication of aluminum or basalt items for use in LEO construction projects. The lunar base would be valuable as a materials supply node for all extraterrestrial construction projects. This would include, eventually, large-scale space telescopes as well as expeditions to Mars

and the closer asteroids. It would also serve as a necessary precursor to scientific installations on the lunar farside. The advent of highly automated space manufacturing systems, including self-replicating systems (SRS), will greatly increase the speed of this development (Freitas and Gilbreath, 1982). But a moon base able to support greatly expanded LEO operations will become available only if basic questions of lunar resource availability, extraction technology, selenoculture, and lunar habitability are resolved -- questions which, realistically, can only be pursued by NASA.

### 7.3.2 Autonomy and the Human-Machine Symbiosis

Some have suggested that the greatest space station effectiveness at lowest cost will be achieved by developing and implementing an advanced human-machine symbiosis. Within this symbiosis, a relatively few humans would cooperatively direct many machines, providing goals and guidance especially in unforeseen circumstances. NASA must not lose sight of the fact that it is now an active participant in evolution, controlling environments for living beings and influencing their evolution. A space station is a landmark in this process, representing the first time people have ventured completely beyond the life-supporting terrestrial habitat to work in a totally artificial and utterly alien environment.

Developments in genetic engineering may also play an important role in mankind's future in space. For example, biological molecular electronic devices may be used as implants for humans, especially for sensory prosthesis (Carter, 1983). These will have been developed by mankind participating in its own evolution, an example of an intelligent evolutionary feedback loop that has never before existed in nature and whose impact is greatly amplified by technology. Ultimately the distinctions among man, his technological extensions, and his environment may begin to blur because of human-directed co-evolution of the environment and the organism, both on Earth and in space.

Humans (and other mammals) possess what seems to be a necessary and sufficient set of physical senses, adequate for procreation and survival in the "wild." But which human danger-senses are the most important for survival in space? The conditions and hazards in orbit are vastly different from those on the ground. For instance, senses which help detect air leaks could preserve life on a space station but would have little relevance on Earth where there is almost always enough air. Conceivably, the optimum mix of senses could involve symbiotic sensors -- say, human ears combined with a sound-oriented radar display, or spacesuit EVA glove bolometers with thermal feedback (e.g., touching a hot surface causes a wrist pad to warm slightly). Another intriguing possibility is computer-generated scent-alarms (the human nose can distinguish literally thousands of odors, though our languages are too poor to describe them all). The olfactory cortex is wired into one of the oldest, deepest parts of the human brain, thus odor alarms are guaranteed to attract attention in an emergency situation.

Then there is the broader issue of human evolution. Industrialized humanity now exists in air-conditioned artificial caves (cities). The conditions and rules of survival to reproductive age have changed. Rather than fending off charging rhinos, people now must look both ways before crossing the street; instead of being skilled with a lance in order to hunt and kill their dinner, workers must build, write or speak well to earn money to pay for food at the cafeteria. The wheels of evolution never stop, they merely change direction -- but what is the new direction? A whole new set of behavioral rules for survival in space will emerge as habitation proceeds from first-generation station astronauts to whole families living and working in space cities. The technological environment will define, reinforce, and augment these new behavioral rules.

### 7.3.3 The Space Station as an Autonomous Intelligent Organism

The advancement of man and machine into space is a unique event of evolutionary significance no less important than the emergence of sea-dwelling creatures onto the land. The space station may become a living entity adapted for survival in space, a symbiotic organism comprised of humans and machines much like the first clusters of dissimilar cells which joined together to form primitive plants. Early stations will be dependent upon the resources of Earth, but in time their descendants may need Earth no more than land-dwelling reptiles and mammals are dependent upon the ocean.

To make the station more flexible and independent, computers will monitor and control many of the functions now performed by people, thereby reducing ground-based personnel. Astronauts will make more of their own decisions. Advanced-station computers will be far more intelligent and sophisticated than any that have flown in space before. There will be perhaps thousands of microprocessors, each with fantastic memory and processing power, decreased error susceptibility, and superior error recoverability. A few larger computers will house expert systems, intelligent programs able to diagnose and repair malfunctioning station components. Other computers, "friendly" and "smart," will communicate with people.

Does the space station have free will? The answer must be yes, if humans do. The station is comprised of both men and machines with people making the important decisions guiding the course of the station's future. The space station will depend upon Earth-dwellers for its survival. By simple analogy, a human infant is an autonomous organism but is highly dependent on its parents. There comes a point, however, when a pair of organisms are not one but two. The two organisms may still be dependent upon one another for survival, yet function independently with respect to the principal decisions of their lives. This seems less like the relation between mother and child and more like the one between free adults in everyday life. It is this latter kind of autonomy that will be designed into the advanced station and its descendants.

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# APPENDIX 7A

## A DAY IN THE LIFE OF A SPACE STATION CREWMAN

Contributed by

J.A. Wise

It was Jupiter.

From this distance, just outside Io's orbit at a quarter-million kilometers, it amply filled the sky, the eyes, and the imagination.

The molten, sulfurous hell of a moon began its transit of the jovian disk. The two bodies seemed connected somehow. Suddenly Io elongated impossibly, coiling through its orbital path around the limb of the planet. In response, Jupiter fissured at the equator, yawning like a starving clam hungry for a moon...

The image abruptly vanished. He was awake, staring at his own hand floating just inches from his face. The most exhuberant passage of Holtz's symphony rang in his ears. Station crewman Richard Sherif smiled faintly, recalling old stories of astronauts who awoke to a frightful start upon seeing their own hands looming over them. He still wasn't quite used to it.

Inside his pod the night lights had come on along with the preprogrammed tape, which he decided to let play awhile longer. He usually preferred wakening to something a bit less stimulating than this particular passage. But this was Day 59, his big day -- and he felt, well, off. The psych officer had briefed them all on how depression tends to set in near the midpoint of a tour of duty on the space station, but that had just been theory to him, until now.

He reached out from the rollaway thermal blanket, flicked on a terminal that lay recessed almost directly overhead, and logged in, bringing the keyboard down to snuggle against his chest. It was time to see what the scheduling program had done to the day's workplan he'd submitted the night before.

In this and the adjacent orbital habitation module, six men were somewhere in their staggered morning sequences of doing almost the same thing. Station life was like that -- you were always a part of one programmed sequence or another. On-orbit personnel time was perhaps the single most expensive commodity in the space program. Around him now, even through the soundproofed walls of his personal pod, he heard -- no, felt -- the rest of the station coming to life.

Each man's pod was the closest thing to a "home" during the 90-day mission. The pods, Dick reflected, combined the best of an old-fashioned mountain tent and an egg. There were four of them in each habitation module, four human cartridges packed around the inside circumference like shells in a revolver. Within each fiberglass pod was a compact berth reminiscent of the pocket hotel rooms that had sprung up in Tokyo to save space more than a decade before.

Pods had the volume of a small coat closet, but offered controlled lighting, temperature, and ventilation. One bulkhead contained the sleeping pad with its dual blankets and restraints that could be pulled over the body like a horizontal rollup window shade. Another side was dominated by the personal televideo screen -- an information display, message center, and visual link between those onboard and earthside. The third bulkhead was a mass of storage compartments, plastic photo displays, and, most importantly, a private window.

Dick finished reviewing his schedule, then quickly scanned his electronic mail. There were some letters from colleagues and one from an old classmate about their upcoming Stanford reunion. He'd have to read it later, as his time frame for lavatory usage had nearly arrived.

He removed, folded and stored away the featherweight headphones that had given him his morning reveries. Then he logged off, replaced the terminal, and unfastened the thermal blanket, allowing it to retract and roll up to one side of the pod. From a bin directly above it, he pulled a fresh supersuit, the standard duty apparel. Dressed, he reached for the hatch but paused a moment to peer outward at the daylit Earth that lay almost 500 kilometers below. They had just passed over the terminator, that hazy line separating night from day. This view of the most beautiful water planet in the cosmos overwhelmed all.

Once during a few spare moments on EVA early in his tour, while watching the North American continent pass majestically below, he'd been gripped by a startlingly powerful revelation of the pettiness of human differences that fractured mankind. National boundaries were invisible from space, and the comforting blue-green haven of life seemed so fragile against the cold eternity of stars and foreboding blackness. From that day he knew why, a quarter-century earlier when men had just walked the Moon, astronauts had returned from their voyages profoundly moved and utterly changed

by the experience.

He pushed, rotating away from the window and sliding back the panel that opened into the central passageway.

"Good morning, Dick."

"Morning, Don," he responded, a little too automatically, to the mellow biochemist who passed him.

Don Hayes was a middle-aged civilian scientist employed by a major pharmaceutical firm, one of the first to lay down money for a chance to perform critical drug-manufacturing studies in weightlessness. Although the proprietary nature of his work did not allow him to share much of it with the rest of the crew, they had all quickly taken to Don's easygoing style and droll mannerisms. Frequently, when they made a public news telecast to Earth, Don would be chosen to give the voice-over monologue. He had, according to Pete "Spiker" Caul, their commander, "a natural DJ's voice that women die over and men kill for ...." And we need good PR, he'd say, convincing Don to tape yet another program.

Don swung easily out of his pod and proceeded headfirst toward the conical end of the module that converged on the central circulation spine. The two men guided themselves from one handhold to another, using fluid motions that always reminded Dick of scenes from a Tarzan movie. Throughout the station, edges of every partition, cabinet, and panel sported handholds for just this purpose. Maintaining motion was the key. Everyone knew the story about the Skylab astronaut who spent 20 minutes trying to propel himself toward a handhold after inadvertently drifting beyond reach of his anchorage. Nobody wanted to be the first to be placed at the mercy of his crewmates in such a undignified predicament.

They came to the connecting hatch and parted company, Don heading for the kitchen/dining module and Dick turning the opposite direction, toward the logistics module housing the lavatory. The logistics module was the only major component of the space station that was refurbished on Earth every 90 days. Water and air were recycled, and power came from two acres of solar cells that stretched out like huge wings on either side of the central spine. But food and laboratory supplies arrived in a new logistics module with each shuttle visit, and all the solid waste, garbage, packing materials, lab refuse, and anything else they didn't want went down with the spent module.

Thus on its return leg the STS became the most expensive garbage truck in history. Of course, it was also bringing home a crew who had been among the most valuable workers in history -- to support a person in orbit in 1993 cost about $20,000 an hour. Little wonder astronauts spent 12 hours a day, six days a week on active duty. Strangely, neither Dick nor any other crewmember really minded. In fact, their schedule had to program in leisure time to make them stop working.

On his way into the logistics module, Dick met Ted Cheston, their metallurgist and another industry scientist, on the way out.

"Morning, Dick," said Ted as they passed. "Hey, if you want to see something that'll really knock your socks off, come by the processing lab after breakfast."

"I'll try," Dick responded, opening the entry hatch.

"Take it easy in there," Ted cautioned. "The old slinger's acting up again."

Dick scowled in disgust. If anything stopped the human colonization of space, he reflected glumly, it would be the failure to design an absolutely foolproof zero-g toilet.

Every day, the personnel of America's first manned space station tried to have one meal together. Today, it would not be breakfast. Instead, their schedules, constantly revised to make the most of time and opportunities, created a breakfast scene in the wardroom/galley that looked like an outtake from one of those big-family sitcoms on television in the 1970s.

During Apollo, crews ate together in their flight couches at strictly programmed times, slurping reconstituted foodstuffs through straws from plastic bags. Skylab was a slight improvement -- the three crewmen dined at a triangular dining table next to a round picture window overlooking the Earth. Meals came freeze-dried in prepackaged trays, and were reconstituted by adding hot water to the food pouches. Many recipes included agglutinants so food would stick to a fork, providing something like normal eating in zero-g.

There was no problem ingesting food -- the human digestive tract worked on peristaltic contractions, almost as if it had been designed for space living. The real difficulty was getting food into the mouth. A carelessly bitten cookie could produce floating crumbs resembling a swarm of gnats. Fluids could not be drunk from a glass since the liquid would literally crawl up the sides and disperse itself into millions of tiny droplets. And peas would not stay on a fork, nor cereal on a spoon. The design breakthroughs that made eating in space more of a pleasure than a chore came from three distinct contributions.

First came a pantry food storage system that allowed a limited variety in daily menu choices. What one ate at a given meal no longer had to be decided six months earlier. No more pre-established menus -- anyone could eat what he wanted, more or less when he wanted. The second major innovation was zero-g utensils, one of which looked like a marriage of Occidental and Oriental technologies -- a hinged-fork/chopstick tool that permitted ready grasping and manipulation of food items. The third innovation was actually an idea. Planners realized that food preparation and food sharing have deep psychological roots, and are part and parcel of every significant social event. When the galley was designed, a large stock of raw materials was included so crewmembers could create impromptu recipes of their own.

Right now, an unplanned cookoff was developing between Dick and Kurt Cliffman, another astronaut who had just last week succeeded in preparing the first flat crepe in orbit.

"Hey, Dick, when are we going to see that chili of yours that you keep bragging about?" Kurt had inched up alongside him in front of the pantry as he made his morning selections. Both were restrained upright, their slipper toes tucked under the lower rail running the length of the galley bulkhead.

"Someday when neither you nor I have to go EVA for at least 24 hours afterwards," Dick shot back. "My stuff's high-test. Strictly JPL."

Kurt chuckled. "Jet Propulsion Lavatory?"

"In that case," intoned a familiar drawl, "maybe we oughta let the Defense Department git it first."

The voice belonged to Spiker, the skipper. At 54, he was one of the few "white-scarf" astro-

nauts still on active duty. He had come to NASA as many had before -- Navy fighter jock, then test pilot, then astronaut. Now, as their shuttle pilot and station commander, he seemed to be in his natural element. He beamed broadly, motioning them over to where he'd webbed himself in for breakfast.

Dick and Kurt snapped the food pouches onto their trays, then pushed over to Spiker's SPUF (Space Packaged Utility Frame) -- a modular, flexible framework that could be reconfigured for many different furniture arrangements. Fitted with trays, the SPUF formed a hexagonal table large enough for three crewmen. There were several such SPUFs in the wardroom, left over from the previous evening's activities. Tonight, they would be reconfigured again into a single table for the "family" meal.

Kurt and Dick webbed in on either side of Spiker, allowing restraint belts and foot bars to keep them in the nearly relaxed zero-g position.

"Well, boys, seems like you got yourselves a little job today," Spiker intoned.

Kurt and Dick nodded at the understatement. "Yeah, Spiker," Dick responded. "You know, we've planned and trained for a year and still I wonder if we've thought of everything."

"I don't know a better way to find out, but if you fellows have any second thoughts we can patch up another simulation."

"No, no, nothing, really...." Dick trailed off.

"For me," said Kurt, "it's the hydrazine question. External scans tell us nothing. I don't feel as confident as the contractor's rep."

"That's right," broke in Dick. "If that stuff's gotten inside the circuitry, replacing the boards sure won't help."

"Which means," Kurt continued, "we don't know <u>what</u> we're going to find when Dick opens up that Solus. Hydrazine pockets? Massive corrosion? Dead circuits? If Dick's work sets off a short and sparks start hopping...."

"Which is why I want you boys to follow the book <u>exactly</u> on this one. Remember, that Solus was never designed to be taken apart on EVA. Anytime you don't like what you see, you abort and we'll OTV that hunkajunk into the sink. Hokay?"

"Yeah," Kurt agreed, looking at Dick. "The Solus Corporation won't be any worse off than they are now. They're lucky NASA's even letting us try this little replacement."

"True," said Dick, "but if we pull this off we've demonstrated a real capability for handling contingencies. That was one of the main arguments for a manned station to begin with."

Dick was on his way down the central spine toward the main airlock when he remembered Ted's invitation. He reached for an overhead handhold, stopping his forward momentum and rotating nearly upright. He peered through a small window into the lab module, not wanting to bother Ted if the metallurgist was in the middle of an experiment. He saw the wiry, intense man hunched over some equipment, halfway up the exterior bulkhead. The hatchway latch was ajar, indicating the occupant was accepting visitors. Dick entered.

"Hi, Ted. I've got a minute now if you do."

"Aha!" Ted responded gleefully. He pushed himself away from the workstation and executed a tight backward somersault that carried him upright to Dick's side. It was the most common maneuver aboard for egressing an overhead workstation, though each man had his own peculiar style. This time, Ted threw his right arm over his head, and kept his left at his waist to initiate a twist in midair to bring himself around 90°. He was the only crewman who was small, slender and agile enough to perform the motion in the cramped lab module.

"I'm going to give a demonstration this evening, but <u>you</u> get to see the dress rehearsal. After all, you'll probably be deploying this thing's big brother before long."

More perplexed than ever, Dick followed the excited scientist back to his original position. As Ted fitted himself into the workstation restraints, Dick found the hand- and foot-holds for a participant-observer.

"Now look at that, and tell me what you see," Ted challenged.

Before them on the workbench was a pair of clamps set approximately 30 centimeters apart. Between these there seemed to be nothing at all. Dick moved his hand forward, exploringly.

"Uh-uh," Ted blocked the motion. "You might cut yourself badly. Here, use this blade as your probe."

Taking the scalpel between his fingers, Dick gingerly brought it down between the clamps. It stopped and refused to budge.

"What the...?"

"Go ahead. Try to push through."

To no avail, Dick pushed, braced and pushed harder, and finally sawed away at the invisible obstruction. When he inspected the scalpel closely, it had become nicked and dulled along the blade edge. Dick's puzzlement deepened.

"Now, look very closely," said Ted. He switched off the ambient light and directed a collimated beam across the opening between the jaws of the clamps. "This will help." There seemed to be a single strand of something finer than a spider's web. Dick's jaw dropped in astonishment.

"I...I see it! How can a filament be so strong, yet so thin?"

"It's a crystal. A single crystal. I grew it!" Ted chattered exultantly. "You can only grow it in zero-g. And I've tested this one to a tensile strength of 200 kilos. You'd need a laser to cut it."

"So this is what's costing your company a quarter million a day! Quite a show-stopper! What do they plan to do with it?"

"We think...," Ted hesitated, as if about to divulge a deep secret, "that this is the way to make orbital tethers."

Dick whistled softly. "Of course. If we can get filaments a few hundred kilometers long, we can tether satellites, or space labs, induce gravity on them by towing, maybe even run something like a cable car back and forth...."

"Exactly. It opens up a whole new, inexpensive way of getting to higher-energy orbits, or of having a bit of gravity without the old Coriolis effect getting in the way. But right now I just like to look at it, even though I can't see it very well!"

"Congratulations, Ted," said Dick warmly, offering his hand. "It's a great achievement, and you deserve it."

"Oh, no...no," Ted demurred. "It wasn't just me, and there's a lot of work left yet. But it is a real success for our research program -- and -- I really wanted to see the look on that unflappable astronaut's face of yours when you tried to

cut it!"

"Well, save your next demo til I get back from EVA, then we'll both get to watch Spiker try it, okay?"

"Sure...oh, that's right, you're going out to the Solus today, aren't you?" He was suddenly solemn.

"Yeah. The OTV parked it on an aft sled. Kurt and I are going to take a look, and see what we can do."

"Has anyone ever tried this sort of repair before?"

"No, but as you've just shown me there's a first time for everything. Maybe this'll be my day, too."

A half hour later, Dick was braced in the airlock of the multiple berthing adapter, waiting for it to cycle out the last of its precious, manufactured atmosphere.

Behind him in this module were the central control consoles, including the TMS (Teleoperator Maneuvering System) and RMS (Remote Manipulator System) stations where Kurt now waited. Next to them was the suit storage and safe haven -- the last chance for life should some catastrophe befall the station. There, seven men could huddle, breathe, and wait in a shielded cell up to 30 days for a rescue shuttle to arrive. Dick hoped that the haven, like the emergency instructions one reads in passenger aircraft, would never really be necessary. But if it ever was....he was glad it was there.

Now he made a final, n'th recheck of his suit systems before the indicator showed that a near-vacuum had been reached in the chamber. He wore the latest hard spacesuit, which had become available only at the turn of the decade. It was an advance desired by every astronaut since Gemini. Before, suit pressure had to be about 5 psi less than cabin pressure, with oxygen-enriched air to keep $O_2$ partial pressure constant. To avoid the bends, astronauts had to prebreathe for 2-3 hours in their suit, marking time in the airlock, even to go EVA for just a few minutes. No one had figured out how to inflate a soft suit to 14.7 psi and still maintain the manual dexterity necessary for work in space. So it was a real luxury to suit up, check yourself out, then open the airlock....

The hatch swung away noiselessly.

It was pitch black outside. They were over the Pacific Ocean at night. There was no moonlight to provide relief on the roiling masses of clouds he thought he could see far below.

He moved into the hatchway.

"TMS control, this is EVA five-niner-one. Do you copy?"

"Roger, five-niner-one," came Kurt's steady response. "Loud and clear. Everything is go at this end."

Dick leaned out through the hatch, pushed away, then replaced his hands on the Extravehicular Maneuvering Unit (EMU) support arms that curved around him like a protective carapace. Wearing it, a space worker could go anywhere and do anything necessary in the station vicinity. It had cryogenic thrusters and verniers, a toolpack, cameras, and the most sophisticated navigation system that could be fitted onto a man's back. The latter worked with a Head Up Display (HUD) that projected critical information onto the inside surface of the spacesuit faceplate, in response to spoken queries and commands.

Dick activated the system from a switch on one of the EMU control arms.

"DISPLAY TARGET RANGE AND RELATIVE VELOCITY," he commanded, after moving far enough away from the airlock to sight the Solus resting on the OTV sled.

From where he floated, the stricken satellite looked like a golden peanut in the glow of the sled's lamps. On the faceplate, in red phosphor, appeared the data "321 m" and "-0.02 m/sec," which Dick unquestioningly accepted as accurate. Ever since the early Apollo docking attempts, astronauts had grossly underestimated distances in space when "eyeballing," mostly because of the lack of customary terrestrial distance cues.

"COMPUTE INTERCEPT," came Dick's next command.

A set of reference lines and crosshairs replaced the range and velocity information, which were moved to the lower left corner of the visor display. The navigational computer would adjust the crosshairs to compensate for his relative motion to the Solus. All he had to do was keep the target satellite centered in his sights.

He fingered the thrusters and felt a brief surge of forward motion. The range number began falling and the velocity changed to +0.9 m/sec. Soon he could see the satellite and sled slowly growing before his eyes. He fingered the thrusters again, raising his velocity to +1.5 m/sec. Ahead of him, he saw the humped, rounded shape of the TMS move out from behind the Solus.

Kurt watched Dick on the TMS video display. Although he was comfortably aboard the station, he had adopted the convention of transferring his psychological presence to the robotic device he manipulated. Its cameras became his eyes, its arms his arms. To Dick, Kurt knew, it was much the same. Out there he would respond to the teleoperator as if it were his friend and colleague -- which, in a sense, was true.

With a few deft shots of the gas jets, Dick brought himself to a halt 10 meters from the satellite. Its six-meter height and two-meter diameter dwarfed him.

"I'm moving around for a visual inspection."

At such close quarters, the incredibly erosive effects of the space environment on the satellite became apparent. Where gold foil had once glistened brightly there was now only a dull sheen. Orbiting at 16,000 km for eight years, the Solus had resided within the Van Allen radiation belts, and had been subjected to micrometeoroid impacts, high-energy particles, cosmic radiation, and impingement of free nuclei. All had taken their toll.

"I don't see any hydrazine damage. You?"

"I'll check again." Kurt maneuvered the TMS for at least the third time, zoom lenses spinning, looking for something he might have missed during the pre EVA inspections. "Still nothing. I'm beginning to wonder if it wasn't a sensor failure after all."

"Affirmative," Dick acknowledged. "Target panel spotted. I'm moving in."

Gingerly, Dick moved to within an arm's length of the panel he needed to remove. Before he could get started, he had to attach support clips to the exterior satellite panels. Then he could steady himself like a mountain climber with pitons, enabling him to drill, pry and remove bolts without every tiny movement causing rotation

or translation from the worksite. In free-fall, Newton's First Law of Motion was a constant annoyance to space workers.

He finished this just as they crossed the terminator to a sunlit Earth. To an unprepared observer the scene would suddenly have exploded into one of dazzling brilliance. But the solar-sensitive glass on Dick's faceplate instantly adjusted itself to maximum opacity. He also heard the suit's extra cooling fans kick on, as the external temperature began its rapid ascent. Finally secured on a portable T-bar foot restraint, Dick examined the panel he had to remove. It was secured by a tracing of posidrive screws -- 54 of them, to be exact.

"They really wanted this to stay on," he groused to himself. "Wonder who they thought would mess with it out here." He removed the hardware-store battery-powered screwdriver that had been adapted and space-certified a few years before. It was one of the few tools that hadn't been designed from scratch for space work. He tried the device on the first screwhead, which remained stubbornly stuck. The torque kept trying to counterrotate him from his perch. "They must have tightened these with a pneumatic driver."

The zoom lens on the TMS rotated, stopped. "Looks like corrosion."

"Yeah." Dick holstered the electric driver and tried to remove the screw by hand, placing the driver head in the largest-diameter handle available. For several long moments he strained in silence, but the bolt refused to budge. "Any suggestions?"

"Get a bigger hammer."

Dick stared at the robotic entity that had seemed to make the observation. "The TMS impact driver?"

"Right. My problem is lack of fine control and zero force feedback. I could punch holes in the Solus. Something slips, you could be injured. It's risky."

But Dick was already moving aside, repositioning his restraint attachments. His mind was made up. "Come in slow. I'll guide you and position the driver. It's worth a shot. We've got to get this job done."

"Affirmative."

The TMS inched forward on several wisps of propulsive gas, then halted a meter from the satellite. One of the robot arms unfolded, extended, and grasped a restraint attachment that Dick had left for it. Dick reached out, looped a webbed strap over a tool fixture on the other side of the TMS and cinched it tight. Then he took the other free TMS arm in his gloved hand, attached the impact tool, and guided it carefully to the screw head.

"OK. Inserted. Give it a jolt of plus-theta."

There was a dull thunk as mechanical joints strained and locked, the sound transmitted through Dick's helmet where it touched the satellite. No movement.

"Again." Dick's helmet had lost contact, but as he watched the screwhead jerked noiselessly a quarter-turn. "OK, back off. I think we've got it." He reached past the TMS arm with his electric hand tool, made the connection, and squeezed the trigger. The screw spun off easily, trapped in the magnetic grasp of his driver. "One down, 53 to go."

For another complete orbit they labored together, man and machine in new-found partnership against a recalcitrant satellite that refused to yield up its treasure without a fight. At last the final screw was gone. Dick removed the panel and inspected the internal circuitry.

"DISPLAY SECTION 00A-2," he called to his HUD, which obediently retrieved the requested data from an onboard databank and sent it to Dick's display processor, which presented the information diagrammatically on his visor.

Suddenly, a flashing red dot on the visor caught his attention.

Kurt was there. "We read an alert on your suit temp. How do you check?"

"That's affirmative," Dick acknowledged. "DISPLAY TEMP." Immediately, 79.4°F appeared in the upper left visual field. As he was about to call for a secondary check, it changed to 80.6°F.

He realized his sweating had not been entirely from his exertions. He watched the display jump to 82.4°F. For some reason, his suit wasn't dumping its thermal load as fast as it should. He listened carefully for ignored background noises. Ah, yes.

"One of my fans isn't up to speed. Sounds low. If it dropped earlier while we were making noise, I might've missed it."

"Can you stabilize?" The TMS edged forward, eyeing him like a possessive mother hen. "37 minutes sunside remaining this orbit."

"I'm not sure. It's not critical yet. I only need another hour. Maybe less."

"Better come in."

"No. No, wait. Here's an idea. Can you steady an SP?"

Kurt hesitated, then made his decision. "I can try. Be right back." The TMS turned away and jetted to the far end of the TMS sled. It reached out, opened a storage cover, and removed a solar parasol -- a foil umbrella sometimes used to shield sensitive instruments as they are removed or fitted to observing platforms.

Dick's suit temperature went to 90.2°F. A few more minutes and he'd have to abort -- a failure.

The TMS returned from a different angle, positioning itself between the EVA astronaut and the sun. "Okay, Dick. It's up to you to open it."

The mechanical arm gingerly extended forward. Dick took the package, fumbling clumsily with its latches. When a TMS was built with as much dexterity as a human hand, he wondered, would humans even need to go EVA again?

He got it open and handed it back. The TMS jets spurted once, then again. The parasol unfurled smoothly. Kurt maneuvered the TMS again. In a few moments, Dick was in artificial shadow, his suit and worksite mostly shaded. His temperature indicator topped at 94.2°F.

He got back to work.

About an hour and a half later, Dick found himself propped in front of the suit-room ventilator fan, drinking deep droughts of cool breeze and idly watching globules of sweat swirl around him. He basked in the sweet exhaustion of success, but still felt like a limp dish rag. The lack of convection in weightlessness caused the heat to hang around him like a suffocating shroud, even out of his suit. He began planning the two hours it would take him to clean out his suit and prepare the fault diagnosis on his errant fan. For the latter, he'd call up an expert system programmed on station computers. By giving him the

most efficient testing sequence and extracting every bit of diagnostivity from test results, the program would save him hours of time on the turnaround.

Within the normal hums, whines, whooshes, clicks, clanks, thermal crackles, and voices of station activity, he thought he heard a whistle. Kurt's head, canted at a cockeyed angle, jutted around the open hatchway.

"Hey, hotshot, don't get too comfortable. We've got our mandatory '90s on the exercycles tonight!"

"That was nice work out there today."

In the after-dinner ward, Dick looked up from his microfiche tech manual into the soft eyes of Dr. Conrad Daume, their onboard medical and psych officer.

"May I join you?" he asked, webbing his lean six-foot frame into the place indicated by Dick's nod. "I mean it," he continued. "The two of you showed real ingenuity and teamwork."

"All in a day's work," said Dick, noncommittally.

"One thing I've wondered about is why you didn't come in when your suit started overheating? I mean, if it had shut down completely...."

"I don't know. It just didn't seem all that critical to me at the time. You know, we have a lot of heat stress drills and suit emergency simulations. I never felt I couldn't get back if I had to."

The doctor smiled. "I was flight surgeon with NASA ten years ago. Back then, if an astronaut hiccuped we yanked him, fast. We'd send a few million bucks' worth of mission performance down the drain if we even smelled a malfunction in an ECLS."

"Sure, but that was a hell of a way to run a mission, wasn't it?"

"Maybe. But we never lost anyone, either. Not anyone, not ever, on space operations. We've all become so ... certain ... of our technology. Often I wonder if sometimes we don't push that trust a little too far."

"You mean me, today?"

Conrad smiled reassuringly. It was well-known that in the old days, flight surgeons grounded pilots, hence were natural adversaries. Even on the station, physicians still had the duty to seek physical or medical reasons for grounding someone -- except that a tour of station duty was rarely interrupted unless something really serious came up.

"What I'm trying to say is that before, when NASA was in the business of discovering space technology, we could afford to be very cautious. The attempt alone justified the cost. Now, NASA is more in the business of making space technology available and profitable, and it's <u>results</u> that justify the cost. It is no longer enough just to learn, or to push the human frontier, because now there's a cost/benefit ratio to all we do."

"So I'm willing," Dick picked up the implication, "to push myself as far as I can, because I know that somewhere, if I don't, someone tallies up another dollar as a reason why humans shouldn't be in space." It was both an admission and a question.

"And once you, or I, or anyone else thinks of it that way, we're inevitably on the economic treadmill, looking for corners to cut, more efficiency, higher net output."

"Doc, it sounds like you feel we're here for some other reason than to get the job done."

Conrad smiled again. "Guess I'm a bit of a romantic." He unsnapped the restraints to leave, gliding around the SPUF, his ranginess somehow compacting by the weightless motion.

Dick's eyes followed Conrad out the hatchway, then spotted someone waving to him from a webbed-in position high on the exterior bulkhead. It was Doug Wu, their onboard computer scientist. Doug gestured again, more insistently. Dick glided over, harnessing himself in as indicated. Doug handed him a pair of earphones connected to a lapboard-mounted keyboard synthesizer.

"Ah, Dick. Knowing your love of classical music, I thought you might want to share this with me. After 59 days of practicing, I'm finally ready."

Dick grinned, put on the earphones and settled in. Doug was an accomplished classical pianist, but his favorite instrument was too massive to bring along. So he patched together a keyboard synthesizer system. As Doug began to play, Dick recognized the work as a Chopin Nocturne -- a particularly difficult piece that the pianist had been practicing almost from the day they arrived. Soon both were caught up in the intricately patterned beauty of the piece. As Dick closed his eyes, the last thing he saw was Doug's foot pumping reflexively against the pedals of the piano that wasn't there.

Finally, it ended, the synthesizer holding the last chord as if reluctant to give up the wonder it had created.

"Incredible."

Doug was lost in his own reverie. "That's the first time I've ever been able to play it in its entirety. Now I've really accomplished something up here."

It was dark in the pod, with only the luminescent patches of control keys, knobs and handles giving outline to the chamber. Dick's thermal blanket pressed him gently into the bed. His hands were folded behind his head as he gazed at the dying amber phosphors of his overhead screen.

He'd tried, but was unable, to finish the daily electronic letter to his wife he usually sent.

"Today," he had written, "I was fortunate to witness two triumphs. One of these was scientific, one artistic. One was objective, the other personal. One will help create the future, the other fills a timeless present. But both of my crewmates felt fulfilled by what they did. As for myself, I spent the better part of six hours on EVA at a satellite, removing and replacing 54 screws and a couple of circuit boards, almost baking myself in the process..." He had erased that last part, then found he could not go on.

What was he trying to tell her? Certainly his work had gone as well as any other's. The satellite would be reboosted way ahead of schedule, a corporation could turn on its computers again, and a lobbyist would sit down to lunch somewhere with a congressman and describe how a man in a spacesuit had made it all possible and, by the way, about that next appropriations bill....

Then he saw it.

Ted and Doug had judged their work for the act itself. Basic research was like that, as was artistic accomplishment. It could stand alone, and often did. But he had judged his achievement in terms of all the external economic criteria

that had been applied to the space program as a whole. There was no way you could do that without wanting to make the performance a little higher, the cost a little less.

But from another perspective, his had been a virtuoso performance of equal magnitude. What was he doing on the station, after all, but giving hope to the folks back earthside? A chance for mankind, a chance for his kids, and for untold billions yet unborn, to dream of a more exciting tomorrow. The station sent down crystals, biotics, alloys, land (and space) data. It got the job done and, to paraphase the official motto, it delivered. But there was more, much more. The dreams of humanity flowed upward and outward through the human presence on the station.

Through <u>his</u> presence. By saving the satellite, he became the bearer of the collective vision of humanity. His achievement too could stand alone.

He flicked on the screen to finish his letter home.

# APPENDIX 7B

# DESIGN CONCEPTS AND DESIRABLE STATION FEATURES

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The fictional scenario in Appendix 7A (and others, unpublished) was constructed to more closely examine the details of daily work and life aboard America's first-generation space station. This process uncovered a number of design concepts and desirable station features which may be valuable for NASA to consider during formal space station planning. These ideas are summarized briefly below (not in order of importance or preference).

## 7B.1 Integrated Text-Handling and Communication System

All report-writing and log-keeping activities could be greatly enhanced by computer-supported word processing. This would help to organize onboard recordkeeping activities, make available a continuously updated database for interested parties, and eliminate paper proliferation. Diary-keeping helps reduce psychological withdrawal and interpersonal tensions in isolated groups by providing a cathartic outlet (Connors et al., 1984). Electronic storage of diaries may provide a future database for studying crew mood changes, although the right to privacy would be a major issue.

Electronic mail (including store-and-forward schemes) gives an alternative to face-to-face communication within the crew. Some messages might be depersonalized or even sent anonymously. Routine Earth/station communication (including family mail) could also be exchanged in this way. Individuals could read and send their own mail according to their personal schedule.

Electronic voice and video links could be used to transmit immediate information between EVA astronauts and the station or between station and ground. These more expensive links could be reserved for instances when immediate feedback is needed or when visual detail is essential. Personal (one-to-one) audio links not tied into the regular network should also be provided to crewmembers for private conversations.

## 7B.2 Personal Nest

The need for individual territory has been stressed by Bluth (1981) and Connors et al. (1984) for psychological well being. This would be a place to retreat to for reading, relaxation or meditation and could double as a sleeping place. Personal items brought from home and hobby activities can reinforce a sense of personal identity. It may be satisfying just to have a window that each crewmember can call his own (Richard Carlisle, personal communication, 1983).

## 7B.3 Instructional/Planning Center

For long-term missions, a method for onboard learning (as opposed to ground-based training) is needed. This might include the use of computer-aided instruction and even a computer-aided design station for problem-solving.

## 7B.4 Multiple Toilet Facilities

The first-generation station needs more than one toilet for a crew of 6-8 persons. With one toilet, there will inevitably be a waiting line to use it immediately after wakeup, especially with a single-shift operation. This delay will be longer than that experienced by a comparable number of bunkmates on Earth, because it seems to take proportionally longer to use zero-g facilities.

Also, there will be a loss of privacy as lines form, along with the increased sense of frustration at having to wait to perform such a simple biological act. As a general rule, for any group to function at a high level of purposefulness, they must not be distracted by constant low-level (priority-breaking) intrusions on their autonomous activities. Such intrusions generally induce an exaggerated negative reaction far in excess of the actual physical inconvenience. The minimum for a 6-8 person crew is one toilet and one urinal that can be used independently and privately.

Another innovation is the EVA comfort module -- a box with a basic airlock, minimal life support, and a simple zero-g toilet. For lengthy EVA or construction projects a great distance from the station, the one-man comfort module could save time and could double as an emergency refuge or oxygen cache as required.

### 7B.5 Plants and Pets

The introduction of plants and pets needs to be considered even for the first-generation station. The main reasons are twofold — Maruyama's "unprogrammed complexity" and the power of dependent living things to elicit care and nurturant behavior from humans.

Unprogrammed complexity refers to those aspects of settings that are not under predictable external control. The habitable volume of a space station has virtually no such elements, aside from the crewmembers themselves. Yet people seem to need such events or things in their daily lives as temporary points of unplanned attention and interaction. Because the behavior of plants and pets is somewhat unpredictable, they are sources of such complexity and provide opportunities for a healthy exchange between crewmembers and their habitable world that would otherwise be unavailable.

Apparent vulnerability and the need for care by another being elicits nurturance in a way that brings people out of private psychological shells. This is known as the power of dependency. Numerous studies with prisoners, psychiatric patients, and nursing home residents show similar patterns extending across a wide range of species (humans, dogs, cats, birds, fish, even plants). The critical factor is the projection of one's feelings onto the living thing and then interpreting the entity's resultant behavior in a somewhat anthropomorphic or self-justifying manner. The results are strikingly consistent, leading to the speculation that pets or plants might be useful in deterring personal withdrawal syndromes that frequently plague isolated work groups.

### 7B.6 Food Preparation

Studies of extended missions at sea (surface ships and submarines) or in cold climates show the exceptional importance that food plays in preserving morale. Proper attention to this factor can substantially improve space station habitability. Unlike Skylab and the shuttle, there should be a high degree of freedom of choice in menus, amounts of food, and times at which food is available. There should be a great deal of menu substitutability in pre-prepared foods, as well as a large number and variety of unprepared foods that the crew may utilize in different ways. Gourmet cooking should be enabled and encouraged. For those who enjoy it, cooking is a leisure time activity and a means of fostering socialization and reciprocal exchange. Eating then becomes a social, not just biological, event. This also has implications for galley layout -- it should be possible for two or more people to cooperatively prepare a meal.

The "Zero-G Salt Shaker" is an old but still interesting problem. Conventional shakers won't work because of the "Jack-in-the-Box" effect (salt grains are in constant motion due to small disturbances and tend to escape through holes in the cap). Corrosion caused by free-floating salt grains could play havoc with electrical devices and become a painful eye irritant. One possible solution is to keep salt in stick form, grinding it into fine particles on demand and then moving the particles electrostatically. In operation, one would move the shaker's snout close to moist food, press the button, and see a small burst of salt deposited onto the food.

### 7B.7 Unassigned Stowage Space

Stowage was a major problem on Skylab. One crew put things where the next crew could not find them, and the design of the lockers themselves induced a pernicious breakaway effect when the doors were opened. Another problem for stowage in a long-duration space station is the likelihood that the crew will introduce new stowage parts and categories by the occasional cannibalization of onboard machinery, refuse, and spares. The need to stow extra bits and leftover pieces, and to recategorize as changing conditions warrant, will grow considerably as personnel make ad hoc repairs and alterations to equipment. The stowage and inventory system must be able to accept all such changes which produce new parts and new categories of nomenclature.

### 7B.8 Recreation Space

A recreation space for large-musculature activity is a critical component of the space station. Participation in noncompetitive games can relieve the continuous pressures of confinement without arousing aggression and violence (which has been observed in competitive sports games among isolated groups). This recreation space can be a large zero-g environment that promotes free-fall games or acrobatics. Geodesic spheres or hemispheres enclose maximum space for minimum weight penalty. There should be a shirtsleeve environment inside the space, perhaps physically separate from the station but accessible through an umbilical tether. Several science fiction authors have written of the potential for new gymnastic and dance forms in zero-g.

### 7B.9 Repair Shop and Work Bench

A small, shared repair shop is suggested: (1) To provide the onboard flexibility of a repair shop to accommodate small-scale design changes and to fabricate, construct, dismantle, and repair tools, parts, components, and new items for use on the space station; and (2) to provide a recreational area for those among the crew who have hobbies requiring such a facility.

The work bench should have a surface area of at least 1-2 square meters and a volume of at least 1 cubic meter for tools, a variety of raw materials, and instrument storage. The repair shop should include jigs, tools and machines capable of hammering, screwing, torquing, cutting, sawing, drilling, soldering, welding, grinding, weighing, casting, lathing, punching, riveting, fastening, filing, and reaming. Storage should be densely packed, and all supplies retrievable by bar code. Particle and vapor removal should be provided in the work area to preserve environmental quality.

### 7B.10 Clean Laboratory and Controlled Laboratory Environments

A sealed, ultraclean laboratory should be provided for environmental science experiments. All surfaces should be free of terrestrial particulates. Requirements include lab benches (25 square meters), fume hoods, ultrapure water supply (e.g., several water distillation units in tandem with deionizing columns), and air processing (closed loop, using several processing units combining passive filters, electrostatic and chemical precipitators). For environmental science, positive pressure over ambient is necessary; for some life science experiments (e.g., genetic engineering, viral research), a negative pressure with respect to ambient is needed to provide a fail-operational/fail-operational/fail-operational/fail-safe mode. A plug-in Portable Automated Laboratory (PAL) assistant could monitor experiments or processes in racks, turn systems on or off, and communicate with space workers and with station computer systems. The laboratory module should be attached to the station using a separator/jettison mechanism for use in the event of health- or life-endangering emergencies.

### 7B.11 Umbilical Tether Tube

An umbilical tether tube would be an access corridor for human traffic between the base station and an external facility such as a recreation space. The tube would be highly elastic and modeled after high-rise fire escape tubes now commercially available. Internal tube skin is surrounded by a coil of spring steel to provide structural support and prevent unplanned collapse. However, the tube should be collapsible or extensible to accommodate the position of the two endpoints which will have a slight relative motion.

### 7B.12 Generic Operational Modes

There is some concern that boosting events may occur during EVA (possibly jeopardizing crew safety) or while acceleration-sensitive experiments are being conducted. This concern is a serious one to the extent that (1) station boosting by occasional firing of high impulse or long-duration low-impulse rockets is frequently required to neutralize the effects of atmospheric drag; (2) EVA may last six hours and may occur often (up to six days per week); and (3) some laboratory experiments may require a micro-gravity, micro-acceleration environment. These considerations suggest that a number of "generic operational modes" should be defined and planned during station operations. Example modes might be Normal, Boosting, EVA, Special Experimentation, Power Down, and Power Switching. The coordination of events and operational modes must be integrated into the daily activity schedule and coordinated with the operational control computers.

### 7B.13 Bar, Steakhouse, and Ice Cream Parlor

On the premise that station personnel will reside in orbit for extended periods of time (e.g. 180 days), astronauts will have off-hours time for personal and social activities. With discretionary time available, the station environment should have facilities commonly considered privileged or special. The suggestion of a "steakhouse" or "ice cream parlor" is motivated by the experience with similar facilities granted to North Slope and offshore oil platform employees. Satisfaction of employee needs minimizes development of negative social interactions. More controversial is a minimal "bar," requiring some graceful limits to the rate of alcohol distribution so that alertness and performance are maintained without destroying the crew's sense of personal autonomy.

### 7B.14 Space Stevedor Technology

Space stevedoring is defined as the process of unloading and reloading a shuttle, by direct analogy to ships. Several questions need to be explored. First, what is the best way to establish temporary warehousing (a time-tested procedure) at the dock? (The idea is to warehouse incoming cargo for eventual distribution and to collect cargo for shipment to Earth.) How should cargo be organized and located in the warehouse? Cargo attributes must be tracked and recorded, requiring usable manifests and inventory adjustment knowledge. Another problem is physical manipulation of cargo, involving human, mechanical, and computational tasks as well as specialized cargo-handling tools.

### 7B.15 Sweat Lodge: An Efficent Way to Recycle Potable Water

The sweat lodge is a possible replacement for the space station showers. The lodge conserves water and energy, and sweat can be reclaimed as drinking water. At present, about 5 kg $H_2O$/day/person are allocated for shower purposes. Cleaning action in the humid lodge is from the inside out, much like a sauna; water is secreted by the skin, vaporizes and is removed by vacuum collection. The sweat lodge concept is borrowed directly from the American Indian. It would consolidate groups and their interactions, since several people can be accommodated at one time.

### 7B.16 Laundry

The goal is to produce clean clothing for reasons of personal health and social hygiene. Garments should smell fresh and be appealing after treatment. Laundry must be processed with low-water and low-power consumption; cleaning products must be nonflammable and nontoxic; laundry machines plus cleaning products should occupy minimum storage space and be lightweight; and the entire process should be highly automated, requiring minimum human monitoring.

Possible laundry forms include (1) disposable paper clothing (large space requirements to store disposables for long flights); (2) ultrasound cleaning, as is used to clean jewelry and which appears applicable to soft surfaces (minimal water, hence space/weight, requirements); (3) spray foam (minimal water consumption, but foam must be contained within cleaning unit and must dry before powder can be vacuumed off); (4) conventional soap and water in washing-machine-like process (high water usage, dryer required); and (5) dry cleaning methods (flammable and toxic chemicals may be required).

### 7B.17 Orbital Trauma Facility

The principal goal is to provide prompt intervention as required in trauma cases, in a manner which maximizes the long-term probability of full recovery for the afflicted crewmember while simultaneously minimizing disruption to ongoing space station operations and the cost per traumatic episode. There are three types of trauma which the facility must be prepared to accommodate -- medical, surgical, and psychological.

Medical problems may be acute or chronic. Most acute medical problems should be treatable with drugs. For instance, acute streptococcus infections can be fought with antibiotics. Some chronic medical conditions (such as diabetes) could also be treated onboard, but it is expected that astronauts with more difficult chronic ailments will be weeded out during the crew selection process and not be allowed to fly long-duration missions.

Surgical problems may be elective or acute. In either case, the space station should be equipped with a sophisticated operating theater which can be isolated to maintain sterile conditions. Most routine surgical procedures could be performed on board, including many non-elective operations. Those procedures requiring multiple specialists or highly specialized equipment are impractical for onboard delivery in the first-generation station.

Psychological-emotional trauma can be managed in the short run with psychoactive drugs. A well-stocked pharmacy could probably handle a wide range of such problems until the next scheduled shuttle arrives. Consideration should be given to the need for physical restraint for individuals who constitute a danger to themselves or others.

One final possibility is an EVA medical refuge. Injured personnel, or those with serious life support malfunctions, enter the refuge through an entry hatch. Sealing the hatch from within automatically inflates the bubble and sets off visual and radio beacons. The bubble is then towed back to the station by OTV or (more slowly and from a shorter distance) by MMU-equipped EVA crewmembers.

### 7B.18 Space Suit Maintenance: Automated Valet Service

After EVA astronauts should have available to them a system for automatic spacesuit refurbishment. The system should automatically drain accumulated moisture (e.g., urine, perspiration, spilled drinking fluids), deodorize the moisture collector, and sanitize the suit. Test equipment should verify electronic, mechanical, and communications systems functioning, followed by an airtightness test to check joint and seal integrity and to detect gas/fluid leakage. The goal is to reduce turnaround time from the current 60-72 hours to 15 minutes by largely automating suit checkout. One proviso: Minimizing cleaning/maintenance time should not take precedence over minimizing prebreathing time in suit design -- on the station, a fast start is more important than a fast cleanup afterwards.

### 7B.19 Safe Haven and Emergency Escape Vehicle

The safe haven would be a compact habitation cell, attached to the central base station spine and equipped with basic life support equipment. There, perhaps eight astronauts could survive for up to 30 days while waiting for a rescue shuttle, should some catastrophe disable the main space station.

A somewhat more advanced concept is the emergency escape vehicle, which could provide a safe re-entry to the Earth's atmosphere. The self-propelled craft must be easily and quickly launched, be accessible from the safe haven, and must be capable of floating in case of a water landing. It should be easily maintained, have low space storage and weight requirements, and should carry 24-hour provisions for up to 8 crewmembers. Ultimately it might evolve into either a slightly larger vehicle or into multiple liferafts as crew size grows in the early 21st century.

### 7B.20 Video Space Bike for Exercise and Recreation

A regular program of physical exertion is believed necessary to preserve muscle tone and to limit calcium loss and other negative physiological effects of zero-g. In previous long-duration missions, astronauts have ridden a stationary exercise bicycle (e.g., Skylab). However, a commercial system now exists in which the rider faces a large color video screen upon which natural, roadway, or track scenes are projected. The scene moves across the screen at varying speeds depending on the monitored pedalling pace. Another commercial exercise system is linked to a video arcade game such that the faster the rider pedals, the faster his video space fighter can fly or the more shots it can fire per second. A similar system developed expressly for the space station (using terrestrial or space-oriented themes), in consultation with experienced present-day astronauts, could be of enormous benefit.

### 7B.21 Electronic Catalog Shopping

To help decrease the psychological distance from Earth which astronauts on long-term station assignments might feel, some means of electronic catalog shopping from orbit should be made available. These facilities would permit astronauts to tap into ground-based telemarketing networks and order holiday and birthday gifts for spouses, relatives, and friends. Astronauts could then serve relatively long tours of duty aboard the station and not completely lose touch with important personal, holiday, and special events in the "outside" world.

### 7B.22 References

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# APPENDIX 7C

# SPACE PLATFORM: THE UNMANNED ALTERNATIVE

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A permanently manned space station is a national investment in scientific leadership and economic strength. To support this investment, enormous capital expenditures and operating subsidies will be required. A significant component of these expenses is the high cost of maintaining a habitable environment in orbit. Before the commitment is made to build a manned space station, anticipated missions should be analyzed to determine the extent to which each requires a continuous human presence. If most missions can be performed adequately with only a temporary human presence, then in theory an unmanned space platform supported by the shuttle might provide a sufficient alternative initial capability in space.

This appendix briefly analyzes planned space station missions to determine whether they can be performed by an unmanned space platform utilizing a high degree of telepresence controlled from Earth and supported by shuttle astronauts making bimonthly visits of 20 days each. The platform represents a basic configuration against which manned station performance and costs may be compared.

## 7C.1 Advantages of An Unmanned Platform

An unmanned space platform may provide greater personal and political safety than a manned space station. The crew of a space station has no immediate escape capability as in Apollo or Skylab (MDAC, 1982b), and the death of an American crewman in space would be a major setback. A space platform does not incur the enormous costs necessary to maintain habitability in orbit, as neither environmental control nor life support systems are needed. A simple space platform represents a conservative first step towards achieving a permanent presence in space, and could make use of low-cost, largely off-the-shelf technology from the shuttle and Spacelab programs (MDAC, 1980; TRW, 1981; Priest, 1981).

Both platform and station would be large, flexible structures (MDAC, 1980) experiencing unknown thermal and dynamic stresses. Dynamic disturbances, induced by rotating joints, antenna movements, and solar panel rotations may affect experiments and payload pointing. The precise effects of these stresses on large, flexible space structures are unknown, as such structures cannot be accurately scaled down for neutral buoyancy simulation on Earth (Jean Mayers, Stanford University, personal communication, August 1983). Unknown stresses can be more readily compensated on an unmanned platform than on the first module of a manned space station.

Major scientific missions in space will include astrophysics, solar astronomy, space physics, and planetary and Earth observations (Martin Marietta, 1983). These missions require high pointing accuracy and stability, and none can tolerate contamination. They must be implemented on space platforms removed from man. A recent Stanford University engineering project proposed a flotilla of co-orbiting, unmanned platforms dedicated to scientific missions (Lerman, 1983).

### 7C.1.1 Operations

An initial, coordinating platform can accommodate several payload experiments, each completely occupying at least one Spacelab-type pallet. The platform will have at least three berthing ports for payloads and an additional port for the shuttle. The initial platform with its supporting equipment would be fully operational after one launch by the shuttle. Deployment in orbit, final assembly, and checkout is performed by the shuttle crew using EVA and assisted by the Remote Manipulator System. Experiment pallets are attached during subsequent shuttle visits (MDAC, 1980; TRW, 1981; Priest, 1981; Lerman, 1983).

The initial platform evolves as the nucleus of a growing system with enhanced capabilities. A family of platforms and free flyers maintained in the same orbit would be developed for dedicated or multidisciplinary missions. Other platforms would be deployed in different orbits. The initial platform is modular in design; the addition of extendable arms increases the number of experiment pallets which can be docked, provides a greater payload separation for improved viewing, and allows the accommodation of large facility payloads.

In a free flying mode the platform is tended by the shuttle which makes 7-day visits at 6-month intervals to exchange experiment pallets, resupply

the platform, and to perform routine servicing. The platform could also operate in sortie mode in which the shuttle remains berthed to the platform. In sortie mode the platform supplies electrical power, heat dissipation, attitude control, and other services to the shuttle. Shuttle crewmen could conduct life science and materials processing experiments. The duration of sortie mode would be limited by the supply of consumables needed to sustain the shuttle life support system (TRW, 1981). In the following analysis it is assumed that the unmanned platform is supported by the shuttle in a sortie mode at 2-month intervals with a 20-day sortie duration (the maximum value specified in contractor reports).

### 7C.1.2 System Description

The initial space platform will have a launch weight of over 40,000 lbs (MDAC, 1982a,b; TRW, 1981; Priest, 1981) and will be deployed in LEO at an orbital inclination of 28.5°. A design lifetime of at least 5 years can be extended by on-orbit servicing. The platform will be constructed as a graphite/epoxy space frame because of concentrated design loads and to ensure ready access and simplicity of fabrication (Lerman, 1983).

The platform provides all payloads with electrical power, attitude control and pointing, heat dissipation, communications and high data rate telemetry to the ground through the Tracking and Data Relay Satellite System (TDRSS). The forward section contains solar arrays and a reboost module to compensate for orbit decay. The arrays provide nominal power of at least 12 kW. An upgraded platform to accommodate six or more payload elements should generate at least 25 kW of electrical power.

The central section contains most of the electrical, thermal, attitude control, communications, and data handling subsystems (Priest, 1981). These modular subsystems can be replaced in orbit, thus minimizing reconfiguration, integration, and testing costs. The thermal control subsystem utilizes freon-pumped coolant loop components developed for the shuttle. A thermal control radiator consists of flat panels which are deployable and retractable. The communications subsystem provides for platform and payload control from the ground. Both S-band (1.55-5.2 GHz) and Ku-band (15.35-17.25 GHz) subsystems should be compatible with the TDRSS (Martin, 1978). The S-band subsystem will also be compatible with the Ground Space Tracking and Data Network and with the Orbiter Payload Interrogator. High gain antennas will be mounted on a deployable mast, each utilizing a fixed dish with an electronics package.

### 7C.1.3 Teleoperation Under Ground Control

To an even greater extent than the space station, an unmanned platform requires automation. The ability of a platform to perform its missions is a function of the degree to which its operations are automated. The same technologies needed to automate a space station, namely telepresence (TP), robotics, and artificial intelligence (AI), are necessary to automate an unmanned platform. As in the case of the station, a platform will be largely autonomous from Earth in terms of orbit maintenance, attitude control, and payload support services. However, in contrast to the station, payload elements on an unmanned platform must be under direct, real-time observation and control by people on the ground. TP is the key technology to enable ground personnel to replace astronauts, although this technology may be augmented by shuttle sortie astronauts on EVA who help perform non-routine operations controlled from the shuttle.

In 1991, the earliest projected launch date for either a space station or a space platform, neither robotics nor AI will be sufficiently advanced to be used in orbit (Akin et al., 1983). These are long-term technologies which will contribute to space operations only after 1995. Beginning in 1991, however, TP can enable ground personnel to monitor all platform operations and to control many of them. As TP and higher-level automation technologies become more advanced, a greater number of operations can be controlled from the ground and the frequency and duration of shuttle sorties can be reduced. The major limitations of TP (Akin et al., 1983) in this application are as follows.

First, a very high bandwidth downlink is required to transmit stereo vision signals from the worksite to the operator. The Tracking and Data Relay Satellite System (TDRSS) would have to use a time domain-multiple access (TDMA) system to allow the TP sensors at the worksite to transmit high-speed data bursts using the entire available communications link bandwidth (Martin, 1978). If the bandwidth transmitted by the TDRSS using TDMA is too small to accommodate the TP system, then a pair of dedicated communications satellites with higher frequency transponders could be deployed to control the space platform from the ground. Possibly by 1991 a Ka-band (20-30GHz) communications link, currently being developed using the Advanced Communications Technology Satellite, will be available (Martin Marietta, 1983).

Second, real-time control signals passing between Earth and a TP unit on a platform through TDRSS experience a 0.5-1.0 second time delay in each direction, degrading system performance. The operator cannot see the immediate consequences of his actions or receive prompt force feedback. Techniques of force control are being developed to eliminate the need for immediate force feedback, but compensating for visual feedback delay is a more difficult problem. A network of circum-equatorial ground control stations for communication with the space platform is impractical because the platform would be in the line of sight of a single Earth station for at most 15 minutes. More likely, operators will adopt a move-and-wait strategy in which each move is prefaced by an analysis of the consequences of the last move (Johnsen and Corliss, 1971). On a space platform few emergency situations will arise requiring a human response in less than 0.5 second (Klaus Bieman, MIT, personal communication, August 1983). When such a rare emergency situation does arise -- for example, during a materials processing experiment -- the experiment can be aborted by the TP ground operator. Under emergency conditions a human in space will always be under greater stress than a ground operator, who enjoys the advantages of personal safety and the presence of additional experts at his control site. The expense of permanently maintaining humans in orbit may far exceed the potential value of the rare experiment that is accidently destroyed.

Improved manipulator arms and grippers must be developed to endow TP units with sufficient dexterity to function effectively in a materials

processing laboratory in space. Improved force/torque sensors will enable operators to more effectively monitor the loads applied by manipulator end-effectors. After 1995 more advanced TP may be available with enhanced dexterity and supervisory control, reducing the impact of the time delay problem by enabling a TP unit to execute a sequence of programmed operations semi-autonomously (Pivirotto, 1983; Akin et al., 1983).

## 7C.2. Mission Capabilities of an Unmanned Platform

Mission capabilities for an unmanned platform and a space station compare favorably in the areas of materials processing, communications satellites, life sciences, astronomy, and Earth observations. This provides a basis for a comparative analysis of costs and benefits.

### 7C.2.1 Materials Processing in Space (MPS)

Of all the missions planned for a space station, materials processing is the most critical in terms of future commercial participation. Corporations are reluctant to invest in an MPS laboratory unless they are assured that a human operator will be available at acceptable cost. A human presence in an MPS laboratory is very helpful in the near-term (Martin Marietta, 1983). People can act both as monitor and as controller of experiments, servicing and resupplying the facilities and adjusting the equipment to accommodate new processing sequences. Humans can intervene in response to unanticipated problems, and can change procedures when necessary. The presence of an astronaut will minimize the time needed to conduct experimental research, but the human worker also must take care to avoid contaminating his subject materials or disturbing delicate materials processing experiments by vibration or shock.

Some of the tasks in an MPS laboratory could be accomplished by automation and telepresence. However, in the near-term many desirable experiments could not be performed in this manner. Those tasks which could be performed by automation and telepresence would take more time to complete than if they had been performed by a human crewmember. In the near-term an MPS laboratory relying solely on automation and telepresence will have less capability than one using a human operator.

Consider an MPS laboratory which does not rely solely on TP controlled from the ground. This laboratory cannot be operated at full capability without a human operator. However, the human need not be continuously present, merely continuously available on a part-time basis. Martin Marietta (1983) anticipates MPS laboratory requirements as one crewman for 50% of the workday. In other words, an MPS laboratory which does not rely solely on TP would operate at 100% of its capability, or at 100% efficiency, when staffed by one person working one half time for 360 days per year. If commercial users can accept partial MPS laboratory capability, then a human operator need not be continuously available. Assume for simplicity that the operating efficiency of an MPS laboratory as described above is directly proportional to the number of days per year that a human is available for half-time work. For instance, if personnel are available for half-time work only 120 days per year, the operating efficiency is only 120/360 = 33%. Six shuttle sorties of 20 days each produces an operating efficiency of 33% -- thus, in a given period of time only one-third as many experiments could be completed; or, a given sequence of experiments would require three times longer to perform.

Next, consider an MPS laboratory which relies solely on ground-controlled TP. The major drawback is the >0.5 second time delay following each control movement executed by an operator situated on Earth. Assume arbitrarily that in the near-term an MPS laboratory relying solely on TP takes ten times longer to complete its experiments as one staffed continuously by a man working half-time -- an operating efficiency of 10%. Assume further that a space platform is operated in the sortie mode, with bimonthly shuttle sorties lasting 20 days each, and that human activities in an MPS laboratory cannot be augmented by TP. Then for one-third of a year the MPS laboratory is operated at 100% efficiency solely by a human, and for the remaining two-thirds of a year the MPS laboratory is operated at 10% efficiency solely by TP. The annual operating efficiency of this MPS laboratory is then 1/3(100%) + 2/3(10%) = 40%. If the assumptions are reasonable, then an MPS laboratory operating at 40% efficiency could be provided by an unmanned platform supported by the shuttle in sortie mode. If the cost of operating such an MPS laboratory at 40% efficiency on an unmanned platform is more than 2-3 times lower than its operating cost would be on a permanently manned space station, then the private sector will be likely to invest in MPS on an unmanned platform.

In contrast to MPS research which must be conducted inside an MPS laboratory, commercial MPS development and production hardware will require dedicated, unmanned platforms that are equally well supported by either a space platform or station (Martin Marietta, 1983). Consequently, commercial MPS production facilities supported by a coordinating space platform could operate at 100% efficiency.

### 7C.2.2 Communications Satellites

Communications satellites represent the second most promising area for commercial development of a space station. The three services which could be offered by a space station to the satellite communications industry are to serve as (1) a testing facility for new equipment to be installed in communications satellites, (2) a base for launching communications satellites into geosynchronous orbit, and (3) a base for servicing communications satellites in geosynchronous orbit. None of these demand a permanent human presence in space, and none are needed on a continuous basis. (TP may even be mandatory in geosynchronous orbit because of the radiation hazard to human health.) The latter two services require a reusable, teleoperated orbital transfer vehicle (OTV); the last, in addition, requires a teleoperator maneuvering system (TMS). All three services are equally well provided either by an unmanned platform supported by the shuttle in the sortie mode or by a permanently manned space station.

### 7C.2.3 Life Sciences

The first habitat module for a space station

will contain a health maintenance facility (HMF) staffed by a physician who is continuously available to conduct research on the medical effects of living in space (Martin Marietta, 1983). Since humans are the subject of this research, it cannot be conducted in their absence. A ground-based physician could use TP to monitor and control on-orbit experiments in space medicine, but the presence of a physician in space is necessary to safeguard the health of the crew.

Only during shuttle sorties can HMF research be conducted from an unmanned platform. Since the length of a shuttle sortie is limited to 20 days and its frequency is bimonthly, the long-term effects of space on human health cannot be determined. For this reason the operating efficiency of a human HMF on an unmanned platform in the sortie mode is assumed to be degraded from a maximum possible value of 33% (section 7C.2.2 above), and arbitrarily designated as 10%. If at some future date a habitat module were added to the space platform, then an HMF could be used to study the long-term effects of space on human health.

In the far-term a space station is expected to have a life sciences research module (LSRM) which will contain both a vivarium to support animals and plants and a life sciences laboratory to support experiments on animals and plants. Human-habitable areas on the space station must be environmentally isolated from the animal support and research areas (Martin Marietta, 1983). On an unmanned platform the LSRM would contain an environmental control/life support (ECLS) system. Experiments on animals and plants could be conducted on an unmanned platform via ground-controlled TP. Using the same argument as before (section 7C.2.2), the operating efficiency of an LSRM on an unmanned platform in the sortie mode is estimated at 40%.

### 7C.2.4 Astronomy and Earth Observations

A space station will support scientific missions in Earth observation (best accomplished from a polar orbit) and in astronomy. Astronomy missions include planetary observations, space physics, astrophysics, and solar astronomy. These scientific missions involve delicate instruments with stringent requirements for pointing accuracy, stability, and a contamination-free environment (Lerman, 1983; Martin Marietta, 1983). All instruments must be isolated from people during operation. Regardless of whether a space station or a space platform is deployed, these missions must be implemented on unmanned platforms and free flyers. They probably would be supported equally well by a space station or by a coordinating space platform, and serviced by humans or teleoperators at intervals ranging from 6 months to 2 years.

## 7C.3 Comparison of Costs and Benefits

Three criteria for evaluating any design are performance, cost, and schedule (Mayers, 1983). Using these criteria, an unmanned space platform supported by the shuttle in sortie mode can be compared to a space station. Reports by Martin Marietta (1983) and other contractors specify mission capabilities of a space station, estimate its costs, and define its schedule. For an unmanned platform the mission capabilities used below we assume a high level of TP, automation, and shuttle sortie support. Cost estimates are based on data from a McDonnell Douglas study (MDAC, 1982b) and on comparisons with corresponding elements of the space station, but must be regarded as extremely tentative.

For simplicity, schedules for implementing either an initial space station or an initial space platform are assumed comparable, although contractor reports suggest that a platform could be developed more quickly. Parallel conceptual designs for an initial platform have been completed for Marshall Space Flight Center (MDAC, 1980; TRW, 1981). In 1982 these contractors completed follow-on studies of an expanded space platform (MDAC, 1982a,b). No conceptual designs have been prepared for an initial space station; only studies of needs, attributes, and architectural options have been completed (Martin Marietta, 1983). It is assumed in this analysis that either an initial platform or the first module for a space station could be developed for launch 7 years after receiving authorization to proceed. This is the approximate time needed to develop a new commercial aircraft (Mayers, 1983).

Costs and benefits for a space station and a space platform are forecast for the initial decade in space (1991-2000) in the two tables following. The figures are highly speculative estimates -- an illustrative attempt to quantify and compare future costs and benefits of a space station and a space platform. All costs and benefits are in 1984 $ millions. All benefits are cumulative for the decade 1991-2000. No opportunity cost or rate of return is assigned to invested funds. The entries for the costs and the benefits of a space station, in Tables 7.1 and 7.2, respectively, are based on data in Martin Marietta (1983). A cost of $110 million per shuttle launch is assumed.

In Table 7.1, the years indicated for space station costs are one year later than those given in the Martin Marietta study. Space platform cost figures are constructed by modifying the given station cost estimates as follows. In 1991 the energy module at a cost of $830 million is replaced by an initial space platform at a cost of $240 million, which cost is obtained from a $180 million estimate in 1981 dollars (MDAC, 1982b). The latter value was converted to 1984 dollars by assuming an average annual inflation rate of 10% from 1981 to 1984. In 1992 the $352 million cost of a logistics module is similarly computed from an original $219 million estimate (MDAC, 1982b). Habitat modules are excluded from the space platform in the years 1991, 1993, and 1996. Also excluded in 1993 is a docking tunnel section to connect the habitat modules.

A space station will be visited by the shuttle every 3 months to exchange crews and receive new supplies. A space platform will be visited by the shuttle in sortie mode for 20 days every 2 months. Shuttle astronauts will deliver supplies, repair and replace equipment, exchange payloads, and perform tasks which require a human operator. A human is assumed to require 70 lb. per day of environmental control-life support (ECLS) consumables including oxygen, water, and food (Martin Marietta, 1983). A 4-man shuttle crew thus requires 280 lb. per day, or 5,600 lb. for a 20-day sortie. Six sorties per year at a launch cost of $1,200 per pound yields an annual ECLS cost of $41 million. Since the space platform requires 6 launches per year, two more than the annual number required by a space station, an annual launch cost of $220 million is added. Full shuttle sortie mode has

**TABLE 7.1. SPACE STATION AND SPACE PLATFORM: COST ESTIMATE COMPARISON**

| SPACE STATION | | SPACE PLATFORM | |
|---|---|---|---|
| Year/Element | Costs (in 1984 $ x $10^6$) | Year/Element | Costs (in 1984 $ x $10^6$) |
| **1991:** Energy Module #1 w/Airlock | $ 830 | **1991:** Initial Space Platform w/Energy & Reboost Modules, Extendable Arms | $ 240 |
| Habitat Module #1 | 1,300 | TMS | 30 |
| Teleoperator Maneuvering System (TMS) | 30 | SE&I | 450 |
| Systems Engineering & Integration (SE&I) | 450 | Launch | 125 |
| Launch | 235 | ECLS Consumables for 6 Shuttle Sorties | 41 |
| | | Launches for 5th & 6th Shuttle Sorties | 220 |
| **1992:** Logistics Module w/Propellant Storage | 425 | **1992:** Logistics Module (Consumables Stores) | 352 |
| Payload Pallets (Astron., Earth obs., EOS) | 95 | Payload Pallets (Astron., Earth obs., EOS) | 95 |
| Manned Maneuvering Unit (MMU)/ Remote Manipulator System (RMS) | 30 | MMU/RMS | 30 |
| Materials Processing Laboratory | 235 | Materials Processing Laboratory | 235 |
| SE&I | 150 | SE&I | 150 |
| Operations | 150 | Operations* | 150 |
| Launch | 240 | Launch | 240 |
| **1993:** Habitat Module #2 | 630 | **1993:** Energy Module #2 | 240 |
| Docking Tunnel Section for Habitats | 130 | OTV | 50 |
| Energy Module #2 | 395 | Cryogenic Storage & Transfer for OTV | 145 |
| Orbital Transfer Vehicle (OTV) | 50 | Second TMS for OTV | 30 |
| Cryogenic Storage & Transfer for OTV | 145 | SE&I | 265 |
| Second TMS for OTV | 30 | Operations* | 220 |
| SE&I | 265 | Launch | 235 |
| Operations | 220 | | |
| Launch | 455 | | |
| **1994:** Hangar for OTV | 245 | **1994:** Hangar for OTV | 245 |
| Science Platform #1 (Solar/Terrestr. Obs.) | 485 | Science Platform #1 (Solar/Terrestr. Obs.) | 485 |
| Materials Processing Platform #1 | 170 | Materials Processing Platform #1 | 170 |
| SE&I | 50 | SE&I | 50 |
| Operations | 220 | Operations* | 220 |
| Launch | 330 | Launch | 330 |
| **1995:** Science Platform #2 (Astro/Solar Phys) | 120 | **1995:** Science Platform #2 (Astro/Solar Phys) | 120 |
| SE&I | 30 | SE&I | 30 |
| Operations | 220 | Operations* | 220 |
| Launch | 110 | Launch | 110 |
| **1996:** Habitat Module #3 | 630 | **1996:** Life Sciences Research Laboratory | 170 |
| Life Sciences Research Laboratory | 170 | SE&I | 25 |
| SE&I | 25 | Operations* | 285 |
| Operations | 285 | Launch | 55 |
| Launch | 165 | | |
| **1997:** Earth Observ. Platform (Polar Orbit) | 170 | **1997:** Earth Observ. Platform (Polar Orbit) | 170 |
| SE&I | 15 | SE&I | 15 |
| Operations | 285 | Operations* | 285 |
| Launch | 110 | Launch | 110 |
| **1998:** Materials Processing Platform #2 | 120 | **1998:** Materials Processing Platform #2 | 120 |
| OTV Upgrade | 50 | OTV Upgrade | 50 |
| Science Platform #3 (Solar Obs/Space Phys) | 120 | Science Platform #3 (Solar Obs/Space Phys) | 120 |
| SE&I | 10 | SE&I | 10 |
| Operations | 285 | Operations* | 285 |
| Launch | 275 | Launch | 275 |
| **1999:** Operations | 290 | **1999:** Operations* | 290 |
| **2000:** Science Platform #4 (Solar Terrestr. Observ./Space Physics--Geosynch. Orbit) | 120 | **2000:** Science Platform #4 | 120 |
| Operations | 285 | Operations* | 285 |
| Launch | 110 | Launch | 110 |
| | | * 1992-2000: plus ECLS ($41M/yr) & Sorties ($220M/yr), for 9 years | 2,349 |
| **TOTAL** | $ 11,990 | **TOTAL** | $ 10,652 |

**TABLE 7.2. SPACE STATION AND SPACE PLATFORM: ECONOMIC BENEFITS ESTIMATE COMPARISON**

| SPACE STATION | | SPACE PLATFORM | |
|---|---|---|---|
| Benefit | Value of Benefit (in 1984 $ x $10^6$) | Benefit | Value of Benefit (in 1984 $ x $10^6$) |
| A. Missions Based on Space Station | | A. Missions Based on Coordinating Platform | |
| 1. Space Physics | $ 85 | 1. Space Physics | $ 85 |
| 2. Materials Processing Research | 340 | 2. Materials Processing Research (340) x (0.4) = | 136 |
| B. Missions Based on Co-Orbiting Platforms | | B. Missions Based on Co-Orbiting Platforms | |
| 3. Astronomy | 340 | 3. Astronomy | 340 |
| 4. Space and Solar Physics | 1,280 | 4. Space and Solar Physics | 1,280 |
| 5. Materials Processing for Commercial Development and Production | 1,020 | 5. Materials Processing for Commercial Development and Production (1,020) x (0.4) = | 408 |
| C. Mission Based on Polar Orbit Platform | | C. Mission Based on Polar Orbit Platform | |
| 6. Earth Observation | 510 | 6. Earth Observation | 510 |
| D. Payload Delivery (Including Communications Satellites) | | D. Payload Delivery | |
| 7. Delivery to Low-Earth Orbit (LEO) | 2,200 | 7. Delivery to LEO | 2,200 |
| 8. Delivery to Geosynchronous Orbit (GEO) | 6,400 | 8. Delivery to GEO | 6,400 |
| E. Spacecraft Servicing (Including Communications Satellites) | | E. Spacecraft Servicing | |
| 9. Servicing in LEO | 2,600 | 9. Servicing in LEO | 2,600 |
| 10. Servicing in GEO | 400 | 10. Servicing in GEO | 400 |
| **TOTAL** | $ 15,175 | **TOTAL** | $ 14,359 |

been assumed for the entire decade, 1991-2000, although advanced TP, anticipated after 1995, doubtless will enable the frequency and duration of shuttle missions to be significantly reduced. To simplify the analysis, systems engineering and integration costs are assumed equal for both station and platform.

Economic benefits of a space station (Table 7.2) are computed in Martin Marietta (1983), which converts mission capabilities to economic benefits by calculating the number of dedicated shuttle flights needed to implement these missions in the absence of a space station, then multiplying that number by $110 million per launch. (No economic benefits are identified by Martin Marietta for life sciences, presumably because, in their opinion, life science experiments cannot be conducted in space solely by dedicated shuttle flights.)

Table 7.2 also estimates the economic benefits of a space platform. With the exception of materials processing research and production, all the remaining benefits of a space platform are identical to those for a space station, because, in this analysis, these benefits are based on identical mission capabilities for both structures. Since a space platform, supported by the shuttle in sortie mode, is assumed to have only 40% of the capability of a space station to conduct MPS research, the economic benefits of materials processing research on a space platform are only 40% of those benefits on a space station.

From this analysis, based on the costs and benefits for a space station forecast by Martin Marietta (1983), and on the mission capabilities and configuration for a space platform described in the earlier discussion, both station and platform produce economic benefits greater than their respective costs. The additional benefit of $816 million in MPS research and production provided by a space station is exceeded by the space station's apparent additional cost of $1,338 million. Given the huge uncertainties inherent in these figures, it is difficult to draw any definite conclusions. However, it is clear that certain features of an unmanned space platform are worthy of further detailed consideration.

## 7C.4 References

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# CHAPTER 8

# CONCLUSIONS AND RECOMMENDATIONS

Summarized for the Group by

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The following general conclusions are suggested by the results of the present study:

1. Machines will not replace humans in space. Rather, they will free us for more productive endeavors. People and machines in space will demonstrate new types of interactions and will thrive, not just survive. Humans and machines must be viewed as an integral system from the first stages of conceptualization and design.

2. Artificial intelligence systems will not have a major impact on the initial space station design for the early 1990s. There are expert systems that can be employed in specific areas but it will take at least another 5-10 years before highly autonomous intelligent machines become available. An evolutionary station should be designed with this future possibility in mind.

3. Two areas of human-machine interaction appear most promising: (a) Using computers for monitoring with humans serving in a supervisory capacity, and (b) direct interaction in the form of teleoperation and telepresence. No major technological breakthroughs are necessary to develop effective teleoperation systems. These systems eliminate the near-term need for extensive intelligent AI systems, and the development of superior end-effectors will provide exceptional physical capability. Furthermore, as artificial intelligence systems emerge, the advances which have been made in teleoperator systems can be used to create more efficient and effective robots.

4. Sophisticated monitoring systems can be developed to sharply reduce ground personnel requirements. However, use of these systems will not necessarily increase ground/space autonomy because monitor computers will be located on the ground so they can be improved and developed as technology advances. Later, though, most of the human control will shift to the space station.

5. Ultimately, the station is the gateway to space colonization and the forerunner of permanent space colonies. It is a launching platform to other planets and a stepping stone to the stars.

We recommend the following to NASA:

1. Major effort and funding should go into the development of manned EVA, teleoperator/telepresence and robot systems. NASA should develop EVA suits, tools, and capabilities for near-term use; invest in telepresence and AI now for the near- and mid-term future; and invest in robotics for mid- and long-term utilization.

2. Using the latest technology, high-level monitoring systems should be established on the ground with onboard microcomputers maintaining the normal operation of many station systems and taking over many routine decisions formerly made by humans. Astronauts must retain ultimate authority, making the highest-level decisions of which machines are yet incapable. Databases should be developed with eventual AI uses in mind, and be readily accessible by all users. One or more computer networks should be employed aboard the space station, enabling critical functions to be separated from scientific and other uses. Every effort should be made to take advantage of the capabilities of commercial systems, particularly in the areas of computer hardware and software development, natural languages and expert systems.

3. To counteract the psychological and social negatives of living and working in a highly automated, relatively isolated artificial environment, the space station should be designed from the outset with due regard to extra-terrestrial setting factors, communications factors, and organizational factors. Interdisciplinary teams should address problems of work and setting design for human-machine interaction. The station is best viewed as a facility, not as a flight. NASA should encourage an up-to-date examination of issues and findings in social sciences research of possible relevance both to space station organizational and physical design and to a long-term human presence in space.

# GLOSSARY

Contributions by

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AI (ARTIFICIAL INTELLIGENCE)

ALGORITHM (see also HEURISTIC)
A procedure for accomplishing a given result by proceeding on a logical step-by-step basis. Computer programs and N/C routines for machine tools are developed in this way. A method of attacking a problem which is assured of success. An ordered sequence of steps followed in order to solve a problem or execute a procedure. A strong method in the sense of a method guaranteed to yield certain results for certain problems but applicable only to a narrow class of problems.

ALPHANUMERIC
Text or data consisting of both alphabetic and numerical characters.

ANALOG (see also DIGITAL)
Computers of this type are designed to control continuous process operations such as flows, temperatures, or other infinitely variable-type operations. Digital computers process only discrete digital data.

ANALOG COMPUTER (see also DIGITAL COMPUTER)
A computer capable of handling non-digital data only, usually in a time-dependent manner.

ARAMIS (AUTOMATION, ROBOTICS, AND MACHINE INTELLIGENCE SYSTEMS)

ARC (NASA/AMES RESEARCH CENTER)

ARCHITECTURE, COMPUTER
The design of a computer. Usually, but not always, refers to hardware.

ARTIFICIAL INTELLIGENCE (see also KNOWLEDGE ENGINEERING)
A field of computer science concerned with understanding the principles and building working models of intelligent behavior, with developing general principles for symbolic reasoning and problem solving by computer, and with constructing computers which exhibit behavior that would normally be regarded as requiring human intelligence.

AUTOMATED WORK ENVIRONMENT
A work environment in which a maximum number of computer- and robotic-based aids are available for the performance of work, including word or data processing, expert systems, decision support systems, CAD/CAM systems, communications, database and information retrieval systems, and a software library.

AUTOMATIC
Functioning in a predefined manner with a minimum of reprogrammability; possessing only limited process information closure.

AUTOMATIC MACHINES
These machines perform a predetermined operation or sequence without human interaction. This category includes all automatic machinery, from an air conditioner to a time clock.

AUTOMATIC PROGRAMMER AND PROGRAM TESTER
This program, given a high-level description of a programming task, creates a computer algorithm to accomplish the task. This algorithm is written in a prespecified language (e.g., Fortran, Lisp, etc.). In the near-term, the high-level task description is a moderately structured task-oriented language, either from humans or from another program. More advanced technology will be able to operate on task descriptions in English. The program is also capable of reviewing existing software and finding errors in programming logic and syntax. Eventually these systems should be able to analyze existing software and verify that it is capable of performing a given function. This could include checking that a newly created piece of software is compatible with the existing system (e.g., verifying that a software patch will not cause trouble in a spacecraft software system).

AUTOMATION (see also AUTONOMY)
The replacement of manual labor with machine labor. The application of artificial devices and machines to tasks which would otherwise involve human labor or intellect.



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AUTONOMIC NERVOUS SYSTEM
The part of the human nervous system that regulates organs controlled by smooth muscles.

AUTONOMOUS
Functioning independently of other components or systems; self-governing or self-controlling; possessing virtually complete information closure in normal operation. (See also AUTONOMY)

AUTONOMY (see also AUTOMATION)
The degree to which a system operates independently of outside control; functioning independently of other components or systems; self-governing or self-controlling; possessing virtually complete information closure in normal operation. (See Chapter 1 and Appendix 6B.)

BANDWIDTH
Rate of data/information transmission or processing, measured in bits/second.

BASE
A core of modules including facilities for docking, control and human habitation.

BIT (see also INFORMATION)
A binary digit of either 0 or 1; the smallest unit of information. In computer science, a memory cell storing either a 1 or a 0.

BLACKBOARD
A data structure for holding knowledge on which a number of independent processes operate. Sometimes the blackboard is just a globally accessible database; other times it holds knowledge about the order in which processes should be activated, given the current state of knowledge in the system.

BOOTSTRAP
A technique for loading the first few instructions of a computer program into active memory and then using them to bring in the rest of the routine.

BOOTSTRAPPING
Using a crude measure or procedure to derive a better one.

BUFFER STORAGE
A place for storing information in either a computer or a control unit so that it is immediately available for action once the previous instructions have been completed. Buffers eliminate the need to wait for information to be transferred from a slower bulk storage medium into active memory.

BYTE
A series of computer binary digits organized to represent an alphanumeric symbol; sometimes called a "word" of memory; 4-, 8-, and 16-bit bytes are common in computing.

CAD (COMPUTER-AIDED DESIGN) (see also CAT, CAM and CASE)
The use of computers to aid in product design and development. A technique for automating the design of systems. CAD systems range from simple automated drafting machines to complex units which can analyze and predict the impact of a change of one or more components upon the entire design.

CAM (COMPUTER-AIDED MANUFACTURING)
The use of computers to assist in any or all phases of manufacturing. Numeric Control (N/C) is one form of CAM.

CARTESIAN COORDINATES
A system of two or three mutually perpendicular axes along which any point may be located in terms of distance and direction from any other point.

CASE (COMPUTER-AIDED SYSTEMS ENGINEERING)
The use of computers in all phases of design, development, operations and documentation.

CAT (COMPUTER-AIDED TESTING)
The use of computers to aid in the testing of manufactured output.

CENTRAL NERVOUS SYSTEM
Neural cells located within the spinal cord and brain.

CHIP
Small piece of semiconductor material upon which electronic components and subassemblies are formed. Integrated circuits, LSI and VLSI are made on chips.

CIRCADIAN RHYTHM
A cyclically-occurring human biological or psychological event, typically with a period of about 24 hours.

CLOSED-LOOP SYSTEM
A system whereby signals from a control unit are acted upon by the machine effector or teleoperator, and a monitoring unit then returns the acted-upon signals for comparison; operates using feedback from errors, thus achieving some level of self-correction; opposite of OPEN-LOOP SYSTEM.

CLOSURE
Exists when system function or output exceeds system structure and input requirements. Closure may involve quality, quantity, or throughput rate, and may apply to mass (parts, materials), energy (power, collectors), or information (assembly operations, repairs).

COBOCOL (COMMON BUSINESS-ORIENTED COMMUNICATION LANGUAGE)
A high-level language standard for communicating transactions, requests, queries, etc. between computers in the business community. COBOCOL should have sufficient expressiveness to handle communications such as "What are the price and delivery conditions for 10K No. 3 pencils?" There are network standards at the physical level and at the level of bitstreams, but not at the level of messages. COBOCOL is a communications standard at the level of messages.

COGNITION
Programmed models which approximate the behavior of natural cognition, in the context of robotic and artificial intelligence systems. The process of knowing, perceiving, and recognizing; most generally, thinking.

COMMAND (see also CONTROL)
A discrete event resulting in the activation of a device, or starting or terminating a sequence of actions. Command may also carry the connotation of a high-level instruction.

COMPATIBILITY
The degree to which tapes, languages, and programming can be interchanged among various computer and computer-controlled systems.

COMPUTER
A machine whose work output consists of manipulating information rather than physical objects.

COMPUTER MODELING AND SIMULATION
An interactive computer-based modeling and simulation system. The computer maintains a database containing a geometric and/or functional model of the system being simulated. A computer-aided-design system is a limited example of such a system. The simulation can be run in accelerated time to predict outcomes of spacecraft procedures prior to actual functions.

COMPUTER VISION (see VISION)

CONTEXTUAL LEARNING
The assimilation of meaning to a new item from the surrounding context.

CONTROL (see also COMMAND)
A continuous set of instructions for maintaining the stability or integrity of a system. Control also has a connotation of low-level instructions.

COST-EFFECTIVE
Economical in terms of the tangible benefits produced by money spent.

CPU (CENTRAL PROCESSING UNIT)
The basic memory or logic center of a computer that includes the circuits controlling the processing and execution of instructions.

CRT (CATHODE RAY TUBE)
Common term for computer console video display screen. An electronic vacuum tube containing a screen on which graphics or alphanumeric information may be displayed.

DAI (DISTRIBUTED AI)
Artificial intelligence systems designed to run on more than a single processor at a given time. Problems given to DAI systems may be broken up into subproblems each of which is solved on an independent processor.

DATA (see also KNOWLEDGE and INFORMATION)
Symbols and wave forms often gathered during observations.

DATA HIDING
Keeping the values and identifying names of data in one program module separate and distinct from those in other modules. When data is completely hidden, both the name and the value of the data cannot be discovered by processes within another module.

DATA MANAGEMENT
In the broadest sense, data management includes all the essential elements of the data collection, organization, storage, and dissemination process. However, current usage in computer science has narrowed the definition to focus on the computer-based processes that store previously gathered and encoded data, provide a storage organization for that data, and can retrieve specified data items.

DDCU (DISTRIBUTED DIGITAL CONTROL UNIT)

DECISION SUPPORT SYSTEM
A computer-based tool to assist in planning, in analyzing decision alternatives, and in monitoring the progress of activities.

DEDICATED COMPUTER
A computer devoted exclusively to a single application.

DEDUCTIVE TECHNIQUES (THEOREM PROVING)
The study and development of the deductive process, using mathematical languages (predicate logic). A basic problem-solving technology, closely related to automatic programming. The chief difference between the two is that automatic programming constructs a path to a given goal, while theorem-proving techniques verify that the desired results are produced by a proposed path. Theorem proving involves a network structure of definitely-true if-then statements. The theorem prover compares a new hypothesis to this structure, attempting to disprove the hypothesis; if the theorem prover cannot disprove it, the hypothesis is called true.

DEGREES OF FREEDOM (DOF)
The state of a mechanism can be described by specifying the current value of each variable parameter (each degree of mechanical freedom), particularly rotating or sliding elements, of robot systems.

DFRC (NASA/DRYDEN FLIGHT RESEARCH CENTER)

DIGITAL (see also ANALOG)
Information and values are expressed in discrete terms. In a digital computer such terms are generated by a combination of binary on/off or positive/negative signals, as distinguished from analog wherein a fluctuating signal strength determines the fluctuations of values.

DIGITAL COMPUTER (see also ANALOG COMPUTER)
A machine capable of handling discrete data items. Digital computer calculations are generally time independent.

DIGITIZE
The process of converting a scaled, but non-mathematical, image into digital data.

DISK
A random-access data storage component of a computer system.

DOC (DEPARTMENT OF COMMERCE)

DOD (DEPARTMENT OF DEFENSE)

DOE (DEPARTMENT OF ENERGY)

DOF (see DEGREES OF FREEDOM)

DOMAIN, PROBLEM (see DOMAIN, SUBJECT)

DOMAIN, SUBJECT
A closely defined and bounded topic area. For example -- human nutritional needs in space.

DOS (DISK OPERATING SYSTEM)

DUMP
The removal of all or part of the contents of a computer storage medium such as memory or disk and its reproduction in some other medium such as hard copy printout, tapes or cards.

ECLSS (ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM)

ELEMENT
Any module, platform or free-flyer which is dependent upon the space station system for its long-term operation. In computer architecture, a single member of a distributed processing system. Also, a single member of a matrix or array.

END-EFFECTOR (see MANIPULATOR and ROBOT)

ENTITY MATRIX
The matrix which characterizes the major players in the space station as men and machines along one axis and as ground-based and space-based along the other.

EPROM (ERASEABLE PROM)

ET (EXTERNAL TANK)

EVA (EXTRA VEHICULAR ACTIVITY) (see also IVA)

EXPERT CONSULTING SYSTEMS (see also EXPERT SYSTEM)
Systems that provide users with "expert" conclusions about specialized subject areas. These systems operate on relational databases, consisting of well-specified representations of information relevant to the problem and of "rules" describing relationships between pieces of the database. These rules are typically if-then relationships (e.g., if component A fails, then component B will measure 5 volts in the circuit). Existing medical diagnosis expert systems (e.g., MYCIN and EMYCIN) compare input symptoms to their relational databases and compute probabilities of various potential diagnoses. They can request specific information to improve their deductions. Such systems currently have diagnostic abilities equivalent to a first year intern.

EXPERT SYSTEM (see also EXPERT CONSULTING SYSTEMS)
An artificially intelligent program designed to provide advice on matters which would otherwise require consultation with human experts. A computer program which uses human expertise in a limited subject domain that has been extracted from the human and then placed into a "knowledge base" which is separate from the program that uses the knowledge base to resolve a problem in the knowledge domain; computer systems that embody knowledge including inexact, heuristic and subjective knowledge; the results of knowledge engineering.

EXPERT SYSTEM WITH HUMAN SUPERVISION
Given an extensive database comprised of consistent, logical models ("representations") of information known to be true, an expert system employs "production rules" to determine the viability of plausible inferences based on a given situation. For example, the system can receive inputs describing the situation, and use "common-sense" production rules to compute the probabilities that certain statements are true or false. In some cases, the production rules can be explicit and the probabilities may then be certainties; on the other hand, some situations may only provide partial or inaccurate data, and the system then evaluates the deficits and discrepancies in the data as part of the calculation of probabilities. Then the human supervisor, equipped with the likelihood of various options and inferences as to possible ramifications, makes a determination and initiates action.

EXTRA-TERRESTRIAL
Originating or existing outside the Earth.

FAIL-OPERATIONAL
When component of system fails, system remains operational. System survival is not jeopardized.

FAIL-SAFE
When component of a system fails, system survival is not jeopardized.

FEEDBACK
Information returned from the output of a machine or process intended for use as input in subsequent operations or for purposes of automatic control.

FIRST-ORDER (PREDICATE) LOGIC (see also LOGIC)
A system of logic in which the terms are restricted to standing for individuals only (as opposed to sets) but with the proper mechanisms necessary to capture formally the ideas of an individual, a function, a relation, quantification and inference.

FREE-FLYER
A free-flying unmanned satellite which is serviced by or otherwise dependent upon the space station system.

GEO (GEOSYNCHRONOUS or GEOSTATIONARY EARTH ORBIT, see also HEO and LEO)
An orbit of the earth at altitude 22,300 miles in the plane of the equator. A satellite in geosynchronous orbit is fixed with respect to an observer on the Earth.

GSFC (NASA/GODDARD SPACE FLIGHT CENTER)

HALO ORBITS (see LAGRANGIAN ORBITS)

HARD VACUUM
Extremely high vacuum (usually $< 10^{-9}$ mm Hg).

HARDWARE, COMPUTER
The physical computer.

HARDWIRED
Computer or computer-controlled system which functions by means of fixed and committed circuitry; reprogramming is possible only by altering the nature of or interconnections among physical components.

HAWTHORNE EFFECT
The effect on subjects' performance attributable to their knowledge that they are serving as experimental subjects or being treated in a special manner.

HEAT SINK
A place or device for the absorption or dissipation of unwanted heat.

HEO (HIGH EARTH ORBIT) (see also LEO and GEO)

HEURISTIC (see also ALGORITHM)
A "shortcut" method for solving a problem that may or may not work. A heuristic computer program is one which begins with only an approximate method of solving a problem within the context of some goal, and then uses feedback from the effects of the solution to improve its own performance. A rule-of-thumb, trick, or hint used to solve a problem. A weak method in the sense of a method not guaranteed to find a solution if one exists but possibly applicable to a wider variety of problems.

HEURISTICS (see also ALGORITHM)
The informal, judgmental knowledge within an application area that constitutes the "rules of good judgment" in the field. Heuristics also encompass the knowledge of how to solve problems efficiently and effectively, how to plan steps in solving a complex problem, how to improve performance, and so forth.

HLLV (HEAVY LIFT LAUNCH VEHICLE)

HUD (HEAD-UP DISPLAY)

HUMANE
Civilizing, refining, humanizing; having or encouraging the best qualities of humankind.

IC (see INTEGRATED CIRCUIT)

ICAM (INTEGRATED COMPUTER-AIDED MANUFACTURING)

INFERENCE TECHNIQUE
A methodology for reasoning about information in knowledge representation, and for drawing conclusions from that knowledge.

INFORMATION (see also KNOWLEDGE and DATA)
Data given meaning by a context structure. In an information-theoretic sense, information is defined to be $\log_2$ of the cardinality of a set of possibilities. Information differs from DATA and KNOWLEDGE. The amount of information in the result of a coin toss is exactly one bit. That information becomes DATA if it is used in some procedure, such as deciding who sits in the back seat. It becomes KNOWLEDGE if it is assigned a meaning, such as the meaning of the result of a coin toss.

INTEGER PROGRAMMING
An algorithmic process which seeks to minimize (or maximize) a result expressed as an integer value subject to algebraically stated constraints.

INTEGRATED CIRCUITS (ICs)
A very small single structure assembly of electronic components containing many circuits and functions on a chip.

INTELLIGENT MACHINES
These are programmable computing machines whose programs contain explicit representations for the assumptions and conclusions of the problem, as well as the rules used and the ways in which they were applied. Such explicit data structures can give the user confidence that the program will reach any conclusions it ought to reach, within its domain of knowledge. Intelligence is not a "yes or no" quality; a program may deserve to be considered intelligent only in a certain range of thought. Example: a program which analyses electrical circuits by solving a large system of equations is merely automatic or programmable, but one which knows about various laws such as Ohm's law and applies them as appropriate to the circuit diagram has intelligence in that particular domain. An intelligent program may use the same information about the particular problem as a nonintelligent one would use, but the information is explicitly labeled in the intelligent program.

INTERFACE
The medium by which two separate elements of a computer system are joined to permit mutual interaction.

I/O (INPUT/OUTPUT) DEVICE
Input or output equipment or programming, used to communicate with a computer or control system.

IPAD
Developmental software package for computer-aided aircraft design; computer science research program at LARC.

IVA (INTERNAL VEHICULAR ACTIVITY) (see also EVA)

JPL (NASA/JET PROPULSION LABORATORY)

JSC (NASA/JOHNSON SPACE CENTER)

KNOWLEDGE (see also DATA and INFORMATION)
Data given meaning by a context structure.

KNOWLEDGE BASE
A base of information encoded in a knowledge representation for a particular application.

KNOWLEDGE BUS
A communication medium for passing knowledge in a standard format (such as first-order logic) among the components of a distributed AI system.

KNOWLEDGE ENGINEERING (see also ARTIFICIAL INTELLIGENCE)
The engineering discipline whereby knowledge is integrated into computer systems in order to solve complex problems normally requiring a high level of human expertise.

KNOWLEDGE REPRESENTATION
A formalism for representing facts and rules about a subject or specialty.

KR (KNOWLEDGE OF RESULTS)

KSC (NASA/KENNEDY SPACE CENTER)

L1,L2,L3,L4,L5 (see LAGRANGIAN ORBITS)

LAGRANGIAN ORBITS
In the classical three-body problem, small objects placed at one of the five Lagrangian points in the plane of revolution are in dynamical equilibrium, and two of these, the triangular points L4 and L5, are stable. The true Earth-Moon system represents a four-body problem because of the significant gravitational influence of the Sun. L4 and L5 themselves are unstable, but large, stable libration orbits exist around them, synchronized with the synodic month. Orbits around L1 and L2, called HALO ORBITS, are dynamically unstable and can only be maintained via stationkeeping.

LANGUAGE, FORMAL
A precisely defined symbolic communication process developed by humans to serve particular purposes. Syntax and semantics are invariant. First-order logic is a formal language.

LANGUAGE, NATURAL
An informal symbolic communication process developed in parallel during the course of human evolution. Syntax and semantics are flexible and variably defined. English is a natural language.

LARC (NASA/LANGLEY RESEARCH CENTER)

LARGE-SCALE INTEGRATION (see LSI)

LEARNING
Learning may occur by (1) being told or rote memorization, (2) examples and counterexamples, or (3) hypothesis (theory) formation.

LEARNING CURVE
A record of improved performance over trials from which learning may be inferred.

LEARNING EXPERT SYSTEM WITH INTERNAL SIMULATION
Same as other expert systems, but the "learning" aspect adds the ability to evaluate the accuracy of former predictions, and the ability to modify the database and the production rules to improve future predictions to give "better" directives.

LEO (LOW EARTH ORBIT) (see also HEO and GEO)
The range of minimum orbital altitudes, reaching from the edge of the atmosphere (the limit where an unpowered body can complete at least one full orbit without suffering total orbital decay) up to an altitude of several hundred miles.

LISP (LIST PROCESSING LANGUAGE)
The lingua franca of artificial intelligence research today; a computer language invented by John McCarthy in 1958 with very simple syntax and the unique feature that no distinction is made between programs and data.

LOGIC (see also FIRST-ORDER LOGIC)
That branch of mathematics and philosophy dedicated to the formal study of meaning and inference. A logic is a formal system consisting of symbols, rules for manipulating the symbols, and rules for assigning meaning to those symbols.

LRC (NASA/LEWIS RESEARCH CENTER)

LSI (LARGE-SCALE INTEGRATION)
The organization of many integrated circuits on a single very small substrate; the basis of microcomputers and minicomputer logic systems.

MACHINE
Most generally, a physical device that can be used to perform work. Machines include can openers, automobiles, computers, and sewing machines. In computer science the jargon term "machine" most often refers to a digital computer.

MANIPULATOR
A mechanical device used for handling, alignment and positioning tasks.

MANIPULATOR SYSTEMS
A generic term for any mechanical device which a robot uses to directly manipulate its environment.

MICROGRAVITY
Gravity in LEO caused by tidal forces, measuring approximately one-millionth of the terrestrial surface gravity, or a micro-g.

MMU (MANNED MANEUVERING UNIT)

MODULE
An attached space station element which provides a unique or common function for system operations.

MORALE
A positive group attitude toward perseverence in work.

MOTIVE SYSTEMS
A generic term for the mechanisms used to convey a robot around its environment.

MPS (MATERIALS PROCESSING IN SPACE)

MSFC (NASA/MARSHALL SPACE FLIGHT CENTER)

NASA (NATIONAL AERONAUTICS AND SPACE ADMINISTRATION)

N/C (NUMERICAL CONTROL) MACHINE TOOL
A mill, lathe, or other production machine driven by computer-generated instructions for manufacturing, read from a tape or other input medium, which the machine follows to complete a given task.

NEEDS (NASA END-TO-END DATA SYSTEM)

NOISE
Background of stimulation in which signal is embedded; unwanted signals.

NSF (NATIONAL SCIENCE FOUNDATION)

NTM (NON-TERRESTRIAL MANUFACTURING)

OAST (NASA HEADQUARTERS/OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY)

OFFLINE OPERATION
Peripheral equipment operating independently of a central computer, to conserve expensive online central computer time.

OMS (ORBITAL MANEUVERING SYSTEM)

OPEN-LOOP SYSTEM
A system which generates output signals but relies upon the integrity of the system to execute them, without feedback for monitoring or comparison purposes. Open-loop systems ignore error signals and operate on the assumption that no errors occur. Opposite of CLOSED-LOOP SYSTEM.

OPERATIONS OPTIMIZATION PROGRAM
This is a computer program using a dynamic model of available resources and mission objectives to determine optimal scheduling and optimal resource allocation. It can then command resource distribution at the appropriate times. This program would use iterative mathematical techniques and a binary decision tree to select optimum values for scheduling and resource allocation based on consideration of cost, time and resource levels.

OTV (ORBITAL TRANSFER VEHICLE)

PERFORMANCE
Recordable, overt behavior; what the organism actually does; the database for inferences about knowledge, experience, and learning.

PLATFORM
An unmanned, orbiting multi-use structure capable of supplying limited utilities to changeable payloads and dependent upon the space station system for its long-term operation.

PRODUCTION RULES
A widely-used knowledge representation in which knowledge is formalized into "rules" containing an "if" part and a "then" part (also called a condition and an action). The knowledge represented by the production rule is applicable to a line of reasoning if the "if" part of the rule is satisfied; consequently, the "then" part can be concluded or its problem-solving action taken.

PROGRAM
Instructions for carrying out a particular set of calculations, by a computer.

PROGRAMMABLE MACHINES
These are automatic machines which are also reprogrammable. Programmable machines are a subset of automatic machines, special in that they can be reprogrammed, either by a human or by another system. A numerically-controlled milling machine is an example of a programmable machine; it can be programmed by a human operator locally, or it can be programmed by a computer, as in a CAM system.

PROGRAM MODULARITY
A modular program is composed of separate and distinct program modules.

PROGRAM MODULE
A subpart of a program that has only one exit and one entrance. A subprogram (subroutine, procedure, package, function) is the preferred way of delineating a module. Data transfer in a modular subprogram should only occur through the parameter list.

PROGRAMS, "DUMB"
Programs that are written in the belief that the demands of the problem are fully understood and can be completely described in the program.

PROGRAMS, "SMART"
Programs that either (a) can deal with ill-defined situations, (b) are capable of learning, or (c) utilize a knowledge base to resolve problems.

PROLOG
A programming language based on first-order logic. Prolog is gaining popularity today and widespread attention due to its selection as the core language for Japan's Fifth Generation Computer Project.

PROM (PROGRAMMABLE ROM) (see also RAM, ROM, EPROM)
Can be programmed only by special routines; once programmed with permanent data, it becomes a ROM or Read-Only Memory.

PS (POWER SYSTEMS)

PUMA (PROGRAMMABLE UNIVERSAL MANIPULATOR FOR ASSEMBLY)
One of a class of robotic manipulator devices ("robot arm"), manufactured by Unimation, Inc.

QWERTY
Refers to the first six letters on standard typewriter keyboard; more generally, refers to standard keyboard itself.

RAM (RANDOM ACCESS MEMORY)
Memory to which information may be read and to which information may be written at any time (access time effectively independent of data location).

R&D (RESEARCH AND DEVELOPMENT)

REAL-TIME
The ability of a computer to function and control processes as those processes actually occur.

RMS (REMOTE MANIPULATOR SYSTEM)
A six-degree-of-freedom five-link manipulator manufactured by SPAR Aerospace of Canada and deployed from the space shuttle cargo bay.

ROBOT
A reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks. A programmable device for manipulating the environment in versatile ways.

ROM (READ-ONLY MEMORY) (see also RAM, PROM, EPROM)
Memory from which information may be read but to which cannot be written.

ROSS (REMOTE ORBITAL SERVICING SYSTEM)

RULES (see PRODUCTION RULES)

SEMANTICS
The meaning of a language statement.

SENSOR
A device which responds to physical stimulus and transmits a resultant signal containing information about the stimulus to a controller or operator.

SETI (SEARCH FOR EXTRA-TERRESTRIAL INTELLIGENCE)

SMF (SPACE MANUFACTURING FACILITY)

SOFTWARE, COMPUTER
Computer programs.

SOFTWARE ENGINEERING
A discipline that seeks to make programs easier to construct, test, and modify. Key concepts include PROGRAM MODULARITY and DATA HIDING.

SOFTWARE VERIFICATION
The process of formally ascertaining that a program will do what it is supposed to do. A high level of software verification is the attempt to prove programs "correct."

SPACE STATION
Collection of physical structures in space, to assist in performing work in space, possibly to permit habitation of space by man and to establish a work environment there. A totality of manned and unmanned Earth-orbiting interdependent elements.

SRS (SELF-REPLICATING SYSTEM)
A system capable of complete manufacture of a physical copy of the original system, by the original system.

ST (SPACE TELESCOPE)

STS (SPACE TRANSPORTATION SYSTEM)
The space shuttle.

SUPPORT
Ground- or space-based operations and equipment which interact with and assist the space station.

SYNTAX
The form- or rule-specified pattern of a language statement.

TASK DOMAINS
Application areas for knowledge systems such as analysis of oil well drilling problems or identification of computer system failures.

TELEFACTOR (see TELEOPERATOR)

TELEOPERATION
Remote electronic control of electromechanical systems.

TELEOPERATOR
Remote-controlled master-slave manipulator (telefactor) or tool, permitting the separation of the source of control and the effectors of action; remote operation. A mechanical device for following, displaying, or amplifying the motions of the human body (hands, legs, head) to perform some useful task.

TELEPRESENCE
Teleoperation with maximum sensory feedback to the operator, providing a feeling of "being there" thus allowing greater precision and reliability in performance; remote presence.

THEOREM-PROVING PROGRAM
A theorem-proving program takes an assertion (the theorem) and verifies that it is true under all possible conditions. For example, if the assertion is a mathematical equation including variables, the program verifies the truth of the equation for all possible values of the variables. The assertion is input into the program as a set of specific if-then statements (this is called FIRST-ORDER LOGIC). The program first negates the assertion, i.e., it considers the opposite of what is to be proved. The intent is to prove that this opposite is false, and therefore the assertion must be true. Having formed the negation, the program examines it according to "rules of inference", which are logical statements (e.g., if-then and if-and-only-if statements) which are guaranteed to be true. These rules of inference are used to break up the negation of the assertion into a series of simpler statements (called "interpretations"), reducing the negation's if-then statements into a collection of "and" and "or" statements. These are then systematically checked by the program, looking for contradictions. If contradictions occur in all the cases, using all the rules of inference that the program knows, then it concludes that the negation of the assertion is false. Therefore the assertion is true, and the theorem is proved.

TMS (TELEOPERATOR MANEUVERING SYSTEM)

USER-FRIENDLY
Simple enough for a human being to use, when the user knows little or nothing about software or other low-level system functional details. Describes methods and technologies that make it easier for people to use a machine. Within the context of computers, it usually implies that interaction with the computer is in a natural or pseudo-natural language.

VISION
The process of acquiring meaningful knowledge from images. In the sense of computer vision, the automatic transformation of optical data into higher-level representations such as shape, texture, geometric and relational models.

VLSI (VERY LARGE SYSTEM INTEGRATION)
Electronic microchips with self-contained processor, memory, and I/O.

WALDO
An anthropomorphic teleoperator providing physical magnification of human capabilities.

WFC (NASA/WALLOPS FLIGHT CENTER)

WORKLOAD
In general, a performance level, whether physical or information processing, required during a fixed time interval. There is no universally accepted definition or metric of mental workload, a theoretical concept closely related to operator stress and effort, the combination of occupational demands placed on the human operator which requires some action. Operational definitions based on behavioral and physiological workload measures have been more frequently used.

WORLD MODEL
An information structure built up in the memory of a computer or robot, based on both initialization and heuristic interaction with the environment. A knowledge representation of a particular subject domain that may be used to draw logical inferences.

ZERO-G (see MICROGRAVITY)