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SPACE APPLICATIONS OF AUTOMATION, ROBOTICS AND MACHINE INTELLIGENCE SYSTEMS (ARAMIS)
VOLUME 1: EXECUTIVE SUMMARY

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16. ABSTRACT

This study explores potential applications of automation, robotics, and machine intelligence systems (ARAMIS) to space activities, and to their related ground support functions, in the years 1985-2000, so that NASA may make informed decisions on which aspects of ARAMIS to develop. The study first identifies the specific tasks which will be required by future space projects. It then defines ARAMIS options which are candidates for those space project tasks, and evaluates the relative merits of these options. Finally, the study identifies promising applications of ARAMIS, and recommends specific areas for further research.

The ARAMIS options defined and researched by the study group span the range from fully human to fully machine, including a number of intermediate options (e.g., humans assisted by computers, and various levels of teleoperation). By including this spectrum, the study searches for the optimum mix of humans and machines for space project tasks.

This is Volume I of a four-volume set, the fourth volume consisting of two documents, CR-162082, and an appendix, CR-162083.

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The example also identifies some fundamental technologies (in double boxes) which enhance some capabilities, and lists the capabilities in other technology trees which benefit from prior development of the computer architecture capabilities. The development of the Onboard Dedicated Microprocessor, in particular, enhances the later R&D of a wide variety of capabilities.

1.2.6 Evaluation of Candidate Capabilities

After defining the candidate ARAMIS capabilities for each space project task, the research team also evaluated the relative merits of the ARAMIS options in fulfilling each task. This evaluation used seven indices of performance, called "decision criteria":

Decision Criteria

1) Time to Complete the Task
2) Maintenance
3) Nonrecurring Cost
4) Recurring Cost
5) Failure-Proneness
6) Useful Life
7) Developmental Risk

The evaluation procedure centered on the production of "Decision Criteria Comparison Charts", one chart for each of the 69 space project tasks. An example of such a chart is shown in Table 1.2. This is the chart for Position and Connect New Component; a brief description of the task is included. The

ARAMIS will reduce the cost of certain space tasks and of related ground support functions. In addition, there are some applications of ARAMIS required by safety considerations (e.g. in working in high-radiation orbits) and by non-interference requirements (e.g. in operating extremely delicate zero-gravity materials processing equipment). Also, the emergence of larger and more complex spacecraft and space activities suggests that ARAMIS will be desirable to handle routine or repetitive operations (e.g. production of structural beams for large space antennas).

The cost of automating all space activities, however, would be prohibitive. The human being's extreme flexibility and ingenuity in dealing with partial information or novel situations could only be entirely replaced by ARAMIS at what, in many cases, may be an unwarranted cost. In the opinion of the study group, for each task in space, there is an optimum mix of humans and machines which will yield best performance at minimum cost.

This study explores potential applications of automation, robotics, and machine intelligence systems to space activities, and to their related ground support functions, in the years 1985-2000, so that NASA may make informed decisions on which aspects of ARAMIS to develop. The study first identifies the specific tasks which will be required by future space projects. It then defines ARAMIS options which are candidates for those space project tasks, and evaluates the relative merits of these options. Finally, the study identifies promising applications of ARAMIS, and recommends specific areas for further research.

The study addresses selected space and ground activities, starting with the preparation of spacecraft at Kennedy Space Center prior to launch, and including the deployment of spacecraft and their checkout in orbit, routine spacecraft operations in space and the related support operations on the ground, and occasional operations in space such as spacecraft maintenance, repair, modification, retrieval, or disposal.

The study looks at the application of ARAMIS from a general point of view, to develop information which will apply to a wide range of space missions. Therefore each of the tasks required by future space projects is examined by itself, outside the context of any specific space mission. It is expected that later case studies will consider individual projects in greater detail; Phase II of this study includes such case studies, as described at the end of this document.

The ARAMIS options defined and researched by the study group span the range from fully human to fully machine, including a number of intermediate options (e.g. humans assisted by computers, and various levels of teleoperation). By including this spectrum, the study searches for the optimum mix of humans and machines for space project tasks.

1.1.3 This Document and The Final Report

This document is the executive summary of the final report for Phase I of the ARAMIS study. It includes: a brief review of the study method; a description of the promising applications of ARAMIS identified by the study; conclusions, and recommendations for further research; and a preview of Phase II, which will concentrate on "telepresence" (defined in Section 1.5).

There are three other volumes in this final report:

ARAMIS Phase I Final Report
Volume 1 - Executive Summary
Volume 2 - Space Projects Overview
Volume 3 - ARAMIS Overview
Volume 4 - Application of ARAMIS Capabilities to Space Project Functional Elements

Volume 4 is the pivotal volume of the report, in that it presents the relationships between space project tasks and ARAMIS options. It therefore includes a detailed description of the study method and presents the final results of the study. For the convenience of the reader, Volume 4 is in two bindings: "Volume 4" and "Volume 4 (Supplement): Appendix 4.E".

Volume 2 presents the tasks required by future space projects. Volume 3 discussses ARAMIS in general, describes the ARAMIS options defined by the study group, and maps out logical sequences of development of ARAMIS for space applications.

1.2 BRIEF REVIEW OF STUDY METHOD

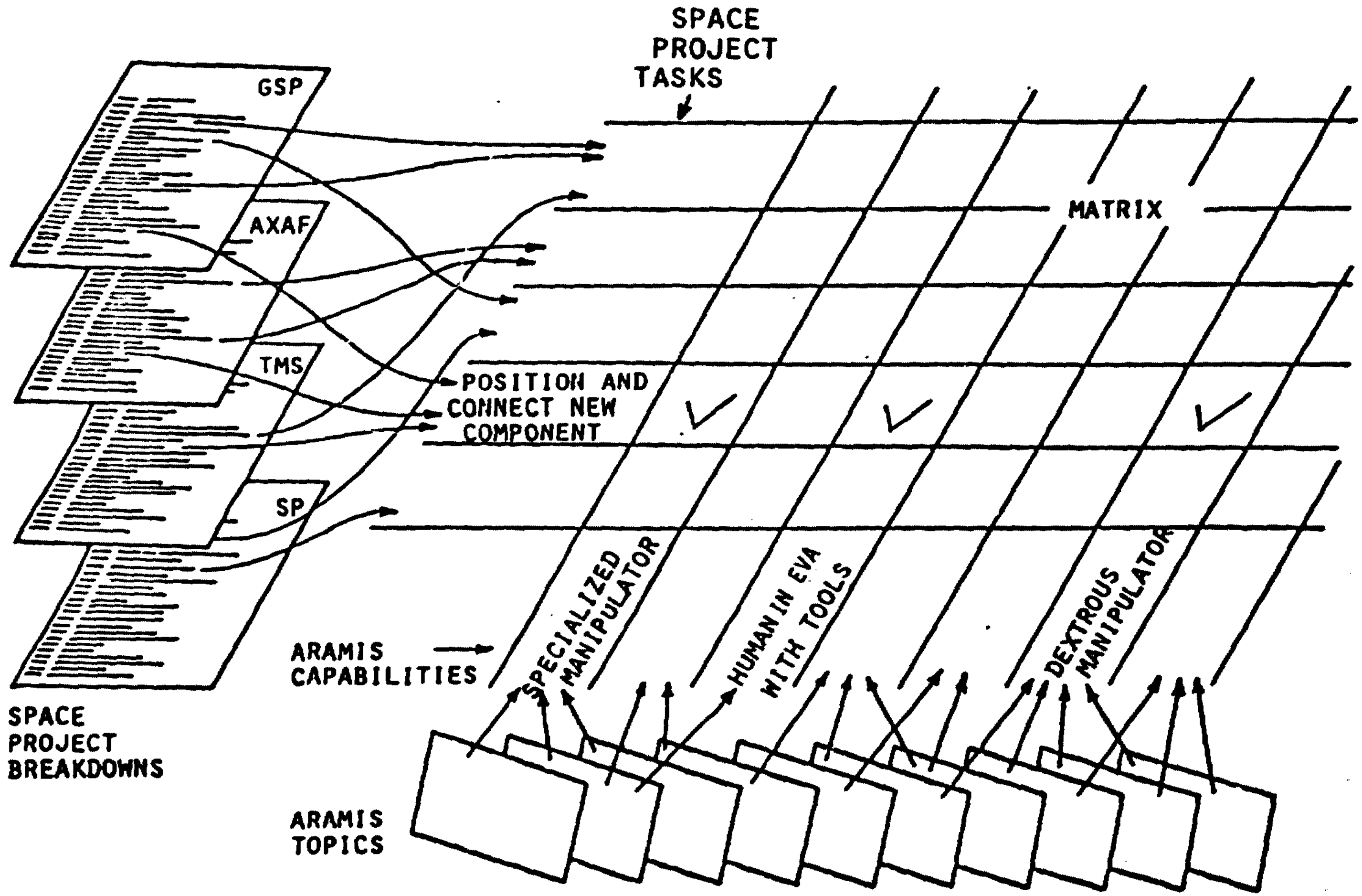
1.2.1 Overview of Method

The overall ARAMIS study method is illustrated in schematic form in Figure 1.1. The method concentrates on the production of a matrix relating space project tasks to ARAMIS "capabilities". The example in the figure shows that the space project task "Position and Connect New Component" can be satisfied by any of three ARAMIS "capabilities": a specialized manipulator specifically designed for this task, a human in a pressure suit with appropriate assembly tools, or a dextrous manipulator versatile enough to do many other tasks as well. Note that each ARAMIS capability by itself can satisfy the space project task.

1.2.2 Space Project Tasks

As illustrated in the figure, space project tasks are identified from space project "breakdowns". Four space projects were selected for this study: the Geostationary Platform (GSP), a communications relay satellite in geosynchronous orbit; the Advanced Xray Astrophysics Facility (AXAF), an Xray telescope spacecraft; the Teleoperator Maneuvering System (TMS), a multipurpose free-flying satellite tender; and the Space Platform (SP), a versatile platform for scientific and space applications research. These space projects were selected because they span the range of space activities expected in the years 1985-2000:

FIGURE 1.1: ARAMIS STUDY METHOD: SPACE PROJECT TASK/ARAMIS CAPABILITY MATRIX



NOTE: EACH CHECKMARK ACTUALLY CONSISTS OF A SERIES OF DECISION CRITERIA VALUES, AND OF COMMENTS ON SPECIAL ASPECTS OF THAT ARAMIS APPLICATION communications, astronomy, satellite servicing and support, and science and applications development.

Each space project was then broken down into five succesively finer levels. At the most detailed level are small tasks (e.g. Track Nearby Objects, Adjust Currents and Voltages, Position and Connect New Component) required by the space projects. The research team selected 69 of these space project tasks for detailed study (they were called "generic functional elements" or "GFE's" in the study). For clarity, the 69 tasks were organized into 9 types:

Types of Space Project Tasks

A. Power Handling
B. Checkout
C. Mechanical Actuation
D. Data Handling and Communication
E. Monitoring and Control
F. Computation
G. Decision and Planning
H. Fault Diagnosis and Handling
I. Sensing

Because the 69 tasks came from breakdowns of four diverse space projects, and because they were selected to span the 9 types listed above, they cover the spectrum of tasks which NASA's projects are expected to require in the next twenty years.

To develop the space project breakdowns, and to handle the large amounts of data involved in this study, the research team found it essential to develop a series of computer programs and files. Details of these are presented in Volume 4 of this report.

1.2.3 Organization of ARAMIS

Also illustrated in Figure 1.1 are ARAMIS "topics". To clarify access to, and presentation of, information on ARAMIS, the research team developed a classification of the whole field of Automation, Robotics, and Machine Intelligence Systems into 6 general "areas" and 28 more specific "topics". These are listed in Table 1.1. There is considerable overlap between areas and between topics, a natural result of the active interaction of technologies in rapid development. This classification was useful because it clarified the study group's understanding of the field of ARAMIS, and because experts on individual topics could be identified for consultation.

1.2.4 Definition of ARAMIS Capabilities

To define the ARAMIS "capabilities" which were candidates to perform space project tasks, the research team considered each of the 69 tasks in turn. Based on the background knowledge and classification of ARAMIS developed by the study, the researchers then defined possible candidate ARAMIS capabilities for each task. As an example, the simple illustration in Figure 1.1 showed three capabilities defined as candidates for the task "Position and Connect New Component". The actual study was more specific, de-

TABLE 1.1: LIST OF ARAMIS "AREAS" AND "TOPICS"

(6 Areas, 28 Topics)

MACHINERY

1. Automatic Machines
2. Programmable Machines
3. Intelligent Machines
4. Manipulators
5. Self-Replication

SENSORS

6. Range & Relative Motion Sensors
7. Directional & Pointing Sensors
8. Tactile Sensors
9. Force & Torque Sensors
10. Imaging Sensors
11. Machine Vision Techniques
12. Other Sensors (Thermal, Chemical, Radiation, etc.)

HUMAN-MACHINE

13. Human-Machine Interfaces
14. Human Augmentation & Tools
15. Teleoperation Techniques
16. Computer-Aided Design

DATA HANDLING

17. Data Transmission Technology
18. Data Storage and Retrieval
19. Data & Command Coding
20. Data Manipulation

COMPUTER INTELLIGENCE

21. Scheduling & Planning
22. Automatic Programming
23. Expert Consulting Systems
24. Deductive Techniques (Theorem Proving)
25. Computer Architecture

FAULT DETECTION & HANDLING

26. Reliability & Fault Tolerance
27. Status Monitoring & Failure Diagnosis
28. Reconfiguration & Fault Recovery

fining eight candidate capabilities for this task:

Candidate Capabilities Defined for one Space Project Task

Task: POSITION AND CONNECT NEW COMPONENT

- DEDICATED MANIPULATOR UNDER COMPUTER CONTROL
- COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR
- COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK
- COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK
- HUMAN IN EVA WITH TOOLS
- SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL
- DEXTROUS MANIPULATOR UNDER HUMAN CONTROL
- TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

Many capabilities had multiple applications, i.e. they were candidates for several space project tasks. Altogether 78 ARAMIS capabilities were defined by the study group. Each of these capabilities was defined and described in an ARAMIS Capability General Information Form, developed by the research team; these forms are included in Volume 3 of this report.

1.2.5 Favorable Sequences of ARAMIS Development

The early development of some ARAMIS capabilities enhances the later R&D of other capabilities. In other words, there is a favorable order in development, starting with simple concepts and building up to more complex options. The research team identified which capabilities enhanced other capabilities, and developed a graphical representation of these favorable sequences of development, called a "technology tree". As it turns out, almost all of the 78 capabilities defined in the study are interrelated in this fashion. This large and complex technology tree was therefore broken into eight simpler trees, with interconnections between the trees. One of these trees is shown in Figure 1.2. The eight technology trees are presented in Volume 3 of this report.

The example shows the favorable sequence of development of those capabilities associated with ARAMIS topic number 25: Computer Architecture. The tree is read from top to bottom, and indicates that the early development of Deterministic Computer Program on Ground (i.e. computer programs in current languages such as BASIC and FORTRAN) enhances the later R&D of space-rated computer programs. This in turn supports the R&D of dedicated microprocessors (i.e. special-purpose computer chips such as those used in personal computers and videogames), which would be used to run computer programs on spacecraft. Dedicated microprocessors can be grouped and organized into more powerful and versatile microprocessor hierarchies. Finally, all of the above-mentioned capabilities contribute to the R&D of space-rated adaptive control systems (i.e. computer programs to control complex spacecraft functions, capable of modifying their own programming to respond to major changes in the spacecraft; these would probably be run on microprocessor hierarchies).

FIGURE 1.2: ARAMIS TECHNOLOGY TREE (NO. 1 OF 8)

(TOPIC 25)

COMPUTER PROGRAMMING TECHNIQUES

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25.4 DETERMINISTIC COMPUTER PROGRAM ON GROUND

- (A) to 14.2 Human on Ground with Computer Assistance
- (B) to 16.1 Computer Modeling and Simulation
- (C) to 27.3 Equipment Function Test via Telemetry

25.3 ONBOARD DETERMINISTIC COMPUTER PROGRAM

- (D) to 3.1 Automated Docking Mechanism
- (E) to 7.1 Dead Reckoning From Stored Model
- (F) to 21.2 Operations Optimization Program

COMPUTER MEMORY DEVELOPMENT → 25.1

SPACE-RATED INTEGRATED CIRCUITS → 25.1

25.1 ONBOARD DEDICATED MICROPROCESSOR

- (G) to 2.2 Dedicated Manipulator under Computer Control
- (H) to 6.1 Optical Scanner (Passive Cooperative Target)
- (I) to 6.2 Proximity Sensors
- (J) to 6.4 Radar (Active Target)
- (K) to 6.5 Onboard Navigation and Telemetry
- (L) to 8.1 Tactile Sensors
- (M) to 13.2 Human Eyesight via Graphic Display
- (N) to 13.7 3-D Display
- (O) to 27.5 Equipment Data Checks by Onsite Human
- (P) to 27.7 Internal Acoustic Scanning

25.2 ONBOARD MICROPROCESSOR HIERARCHY

- (Q) to 4.1 Computer-Controlled Specialized Compliant Manipulator
- (R) to 11.2 Imaging (Nonstereo) with Machine Processing
- (S) to 15.3 Teleoperator Maneuvering System with Manipulator Kit
- (T) to 18.12 Electron Beam Memory
- (U) to 27.1 Equipment Function Test by Onboard Computer
- (V) to 27.4 Equipment Data Checks by Onboard Computer

25.5 ONBOARD ADAPTIVE CONTROL SYSTEM

- (W) to 15.2 Dextrous Manipulator under Human Control
- (X) to 23.2 Learning Expert System with Internal Simulation

The example also identifies some fundamental technologies (in double boxes) which enhance some capabilities, and lists the capabilities in other technology trees which benefit from prior development of the computer architecture capabilities. The development of the Onboard Dedicated Microprocessor, in particular, enhances the later R&D of a wide variety of capabilities.

1.2.6 Evaluation of Candidate Capabilities

After defining the candidate ARAMIS capabilities for each space project task, the research team also evaluated the relative merits of the ARAMIS options in fulfilling each task. This evaluation used seven indices of performance, called "decision criteria":

Decision Criteria

1) Time to Complete the Task
2) Maintenance
3) Nonrecurring Cost
4) Recurring Cost
5) Failure-Proneness
6) Useful Life
7) Developmental Risk

The evaluation procedure centered on the production of "Decision Criteria Comparison Charts", one chart for each of the 69 space project tasks. An example of such a chart is shown in Table 1.2. This is the chart for Position and Connect New Component; a brief description of the task is included. The

TABLE 1.2: DECISION CRITERIA COMPARISON CHART

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.

CANDIDATE ARAMIS CAPABILITIES:

DECISION CRITERIA

	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	3	
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	

chart also lists the eight candidate ARAMIS Capabilities for the task.

The relative merits of those eight options were evaluated by rating their decision criteria on 1-to-5 scales, with 1 representing favorable performance, and 5 unfavorable. First, one capability was selected as "current technology" (C.T.), i.e. this was the option that would currently be used to perform this particular task. The C.T. capability received preset decision criteria values (3, 3, 2, 3, 3, 3, 1 across its row), to serve as a baseline for comparison. In the example, the Human in Extra-Vehicular Activity with Tools was so selected. The decision criteria values of the other capabilities were then estimated <u>relative</u> to this baseline. For example, the Dedicated Manipulator under Computer Control received a value of 1 for time, indicating that it is somewhat faster than the Computer-Controlled Dextrous Manipulator with Force Feedback (which received a 2), and significantly faster than the human in a pressure suit (who received the baseline value of 3).

Since the estimation of these relative values is subjective, the research team supplemented these numbers with ARAMIS Capability Application Forms. One such form is presented in Table 1.3. This form describes the application of the Computer-Controlled Dextrous Manipulator with Force Feedback to the specific task Position and Connect New Component. It repeats the appropriate row of decision criteria values from the Comparison Chart, but follows each number with commentary and, when available, information

TABLE 1.3: ARAMIS CAPABILITY APPLICATION FORM

CAPABILITY NAME: Computer Controlled Dextrous Manipulator With Force Feedback
CODE NUMBER: 4.2 DATE: 6/15/82 NAMES: Paige/Ferreira/Kurtzman
GENERIC FUNCTIONAL ELEMENT NUMBER AND NAME: g73 Position and Connect New Component

DECISION CRITERIA (1 TO 5 SCALES; CURRENT TECH.=3 UNLESS NOTED)

TIME TO COMPLETE FUNCTIONAL ELEMENT (1 SHORT, 5 LONG): 2
REMARKS AND DATA SOURCES: The dextrous manipulator requires less time than a Human in EVA with Tools since it doesn't involve human safety, does not require suiting time, and can optimize motions to the mechanical limit of the hardware.

MAINTENANCE (1 LITTLE, 5 LOTS): 2
REMARKS AND DATA SOURCES: Maintenance would be low since the only parts likely to need service are the mechanical parts. The software and sensors would be very reliable (Minsky).

NONRECURRING COST (1 LOW, 5 HIGH; CURRENT TECH.=2): 4
REMARKS AND DATA SOURCES: This cost is high since no system has yet been developed which incorporates the abilities of this manipulator. Some of the R&D will probably be done commercially.

RECURRING COST (1 LOW, 5 HIGH): 2
REMARKS AND DATA SOURCES: This capability was judged below current technology in recurring costs as it does not necessitate the support of a human. This capability may cost slightly more than a dedicated manipulator since the end-effector would require more maintenance.

FAILURE-PRONENESS (1 LOW, 5 HIGH): 4
REMARKS AND DATA SOURCES: The failure-proneness is higher than that of a human (who can correct problems after they occur) since the programming is neither adaptive or intelligent.

USEFUL LIFE (1 LONG, 5 SHORT): 2
REMARKS AND DATA SOURCES: The dextrous manipulator has a useful life which is longer than the more obsolescent dedicated manipulator. Eventually it should be replaced by manipulators with vision. Its useful life is judged longer than current technology as it is deemed more desirable to have an autonomous system than use valuable human-in-space time.

DEVELOPMENTAL RISK (1 LOW, 5 HIGH; CURRENT TECH.=1): 4
REMARKS AND DATA SOURCES: This is high since there is currently no manipulator that can be called dextrous, and to advance to computer control would also be a large step.

OTHER REMARKS AND SPECIAL ASPECTS: This manipulator has the advantage of being adaptable to a number of tasks. The system could probably be built with a modular design, so that a vision capability could easily be added as it comes online. The current technology capability is Human in EVA with Tools.

sources. It also includes remarks on special aspects of this application. The 69 Decision Criteria Comparison Charts and the 465 associated ARAMIS Capability Application Forms are included in Volume 4 (Supplement) of the final report.

1.2.7 Selection of Promising Applications of ARAMIS

The research team identified promising applications of ARAMIS by reviewing two bodies of information: the decision criteria values and the technology trees. A capability was judged promising if it had received favorable decision criteria values in its applications to tasks, and/or it significantly enhanced the development of other useful capabilities in the technology trees.

The decision criteria values were reviewed through the calculation of "average sums" of values for each candidate capability. First, the space project tasks were separated according to the 9 task types listed above (in section 1.2.2). For example, there are eight tasks of the "mechanical actuation" type. Next, the research team considered all of the ARAMIS capabilities which were candidates to perform those eight mechanical actuation tasks, and computed the average sums shown in Table 1.4.

This table shows that fifteen capabilities are candidates for the eight mechanical actuation tasks. The right-handmost column identifies the number of tasks for which each capability is a candidate. For example, the Automated Docking Mechanism is a candidate for only one task, the Onboard Deployment/Retraction Actuator is a candidate for five tasks, and so on. The average sums (all criteria) shown in the first column were calculated in

TABLE 1.4: AVFRAGE SUMS OF DECISION CRITERIA VALUES: MECHANICAL ACTUATION

ARAMIS CAPABILITIES: **AVERAGE SUMS:**

ARAMIS CAPABILITIES	ALL CRITERIA	WITHOUT TIME	WITHOUT MAINTENANCE	WITHOUT NONRECURRING COST	WITHOUT RECURRING COST	WITHOUT FAILURE-PRONENESS	WITHOUT USEFUL LIFE	WITHOUT DEVELOPMENTAL RISK	NUMBER OF OCCURENCES
AUTOMATED DOCKING MECHANISM	15	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	16	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	21.86	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	22.86	19.86	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.

a simple manner: the seven decision criteria values received by the capability in each of its applications were added together; then these totals were averaged together. For example, the Computer-Controlled Dextrous Manipulator with Force Feedback received values 2, 2, 4, 2, 4, 2, 4 in the Comparison Chart in Table 1.2, 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 1.4. Since the capabilities are ordered according to their average sums (all criteria) in the Table, 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. For example, the Automated Docking Mechanism 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-proness rating is due to the severity of any failures).

It should be noted that this evaluation procedure is subjective, both in the estimation of decision criteria values and in their review. In particular, in the summing and averaging of decision criteria values, the procedure assumes equal importances of all seven decision criteria: the time to complete the task is as important an input into the average sum as the failure-proneness of the capability. In other words, there are no weightings applied to the decision criteria values. In specific space missions, however, this equivalence might not be the case. For example, for a task which is done once every three years as part of spacecraft maintenance, the time required may not be an important factor; but the failure-proneness of the device doing the task may be an important aspect. Therefore some more detailed case studies are needed to make final decisions on the most favorable use of ARAMIS for specific space missions.

In general, the study group emphasizes that no overall method, such as this study's, can replace the engineering judgment of the Space Project Engineer. It is not possible to develop an all-encompassing system to select the best ARAMIS Capabilities for the tasks in any space project. What this study can do is to spread out the ARAMIS options for the Project Engineers to review, to present background information and data sources on the options, and to display the study group's opinion on the potential advantages, disadvantages and relative merits of the options. The final decision on the most appropriate capability for each task, however, rests with the Project Engineer, since this decision involves constraints and requirements specific to the particular space project. The study output presents information to support that decision process, and suggests a systematic approach to the choice; the input data can be refined and updated, the evaluations reviewed one at a time, and various weightings tried on the criteria values, to improve the decision.

1.3 RESULTS: PROMISING APPLICATIONS OF ARAMIS

1.3.1 Organization of Results

The research team identified promising ARAMIS capabilities, based on their decision criteria values, the average sums of those values, and the favorable sequences of ARAMIS development. The selection was done by types of tasks. For example, certain capabilities are considered promising for power handling tasks; others are favorable for mechanical actuation; and so on.

The following sections present the promising ARAMIS capabilities (underlined) identified by the study group for each of the nine types of tasks listed on page 1.7. These capabilities are favorable in the general sense, in that the decision criteria were weighted equally in the evaluation. They are therefore worthy of further study and development, but their applicability to particular space missions should be reviewed through specific case studies leading to accurate weightings on the decision criteria.

1.3.2 Power Handling

For overall power system control, the Onboard Adaptive Control System, implemented on an Onboard Microprocessor Hierarchy, offers the advantages of speed, resistance to failure, and ease of modification. Adaptive control systems are computer programs capable of modifying their own programming to respond to major changes in the spacecraft, such as degradation of components and changing demands made upon a spacecraft power system. Microprocessor hierarchies are networks of microprocessor chips (such as the chips in personal computers and videogames), which can exchange data and computer programs between each other, as needed. The development of the Onboard Adaptive Control System also enhances later R&D of sophisticated manipulators, and of a fully autonomous Learning Expert System. The R&D of the Onboard Microprocessor Hierarchy supports later R&D of manipulators, imaging sensors with computer processing of data, failure diagnosis by onboard systems, and the Teleoperator Maneuvering System.

For checkout and monitoring of power systems, Equipment Function Test by Onboard Computer and Equipment Data Checks by Onboard Computer appear favorable, since they can routinely handle large amounts of data without the costs of telemetry or human supervision. A function test involves sending commands to the spacecraft components, requesting actions by those devices, then observing the resulting data from the components to determine the state of health of the system. Data checks only look at the normally available data to judge the status of the components. The Equipment Function Test by Onboard Computer enhances later development of Fault Tolerant Software.

If the power system to be managed is simple, then the traditional Automatic Switching Systems are favored because of low costs. They should also be considered as a backup mode to the more sophisticated options. Automatic Switching Systems is one of the technologies which contribute to manipulator development.

In general, the emphasis in power handling should be on onboard and automated systems. As power systems technology becomes more complex, the costs of telemetry and human supervision will become excessive.

1.3.3 Checkout

The Equipment Data Checks by Onboard Computer and Equipment Function Test by Onboard Computer are promising options for 5 and 7 tasks, respectively, due to these capabilities' low recurring costs and autonomous abilities. One interesting note is that these two capabilities were favored both for checkout in space and for payload checkout on the ground, prior to launch. There are advantages to having the same checkout system in both places, so that data prior to and after launch can be compared.

There are also several checkout tasks that are particularly well handled by specific capabilities. For the checkout of interfaces between the Space Platform and its payloads, the Onboard Dedicated Microprocessor and Onboard Microprocessor Hierarchy are favorable options. A dedicated microprocessor is a computer chip similar to those in personal computers and videogames. A microprocessor hierarchy is a network of such chips. As shown in Figure 1.2, these capabilities enhance the development of a wide variety of other capabilities, including manipulators, human-machine interfaces, sensors, failure detection and diagnosis systems, and the Teleoperator Maneuvering System.

For mission sequence simulation, either prior to launch as part of spacecraft verification, or after launch to support mission decisions or failure diagnosis, Computer Modeling and Simulation was preferred. The study group felt that this capability would be particularly useful if implemented end-to-end, i.e. from the original mission definition, through spacecraft design, manufacture, test, integration, launch, on-orbit checkout, normal operations, spacecraft modifications, and fault diagnosis and handling. Having such a capability would also improve communication between mission supervisors, and reduce documentation requirements. This capability also enhances the development of manipulators (and the training of their operators) and the development of expert systems.

1.3.4 Mechanical Actuation

For the specific task of docking, the Automated Docking Mechanism seemed more promising than other options, due to its low maintenance and recurring cost. Such a system is apparently in use by the Soviet Union. It should be noted, however, that this capability benefits from prior development of the other docking options.

For simple mechanical actuations (e.g. deployments, component motions), the traditional Onboard Deployment/Retraction Actuator was favored, due to its low maintenance, costs, and developmental risk. In addition, this capability enhances the development of manipulators. However, if the task is complex (e.g. deployment of large surfaces, delicate motions of components), these actuators are impractical.

For many mechanical actuation functions, five capabilities (each of which applies to 7 or 8 tasks) are close together in their evaluations: Human in EVA with Tools, Dedicated Manipulator under Human Control, Teleoperator Maneuvering System with Manipulator Kit, and Dextrous Manipulator under Human Control. This indicates that, without weightings on the decision criteria values, these mechanical actuation options are comparable in overall merits. It is the constraints and figures of merit of specific space projects which will make one or the other of these five candidates most favorable. Since these capabilities span the range of telepresence, Phase II of this study will clarify these issues. It is expected that the use of telepresence will be desirable for work in locations either hazardous to humans (e.g. high-radiation orbits) or expensive to reach (e.g. geostationary orbit), and that it will be less expensive than other options in other tasks as well. However, the optimum mix of humans and machines in such applications is not yet clear. More detailed case studies will identify the most favorable human and machine functions.

The R&D of simple automatic manipulators and human-controlled manipulators supports the development of more dextrous human-controlled manipulators, culminating in the TMS with Manipulator Kit. These manipulators also enhance the development of sophisticated autonomous manipulators.

1.3.5 Data Handling and Communication

Most of the capabilities that apply to data handling and communications are candidates for only one or two of those tasks. Of those with three or four potential applications, the Onboard

Microprocessor Hierarchy and the Onboard Dedicated Microprocessor are promising options for data-taking and data-processing functions. The Onboard Deterministic Computer Program, with four potential applications and a rating close to the microprocessors, would probably be implemented on a microprocessor or microprocessor hierarchy. A deterministic computer program is written in an "algorithmic" language, such as the current BASIC and FORTRAN languages: the program runs a series of preset instructions, and cannot modify itself. As mentioned above, the development of microprocessors enhances a wide variety of other capabilities.

The other promising options have single applications. For long-term data storage on the ground, Microform on Ground (i.e. microfiche or microfilm) is favored because of its low non-recurring and recurring costs (virtually no maintenance is required).

For long-term data storage in space, Electrically Alterable Read-Only Memory (a version of current computer memory chips: it stores data which is normally only read by the computer; on occasion, the memory can be rewritten if needed) and Optical Disc (a computer memory version of the current videodiscs) are promising options, because of low maintenance (hence low recurring cost) and high reliability.

For short-term data storage in space, Random Access Memory (the memory used by most current computers to run programs) and Magnetic Bubble Memory (potentially more compact and reliable) are favored, due to low maintenance, R&D cost, and developmental risk.

In general, computer memory development supports the R&D of the Onboard Dedicated Microprocessor, the Onboard Microprocessor Hierarchy, imaging sensors with computer processing, and human/ machine interfaces (e.g. graphic displays and computer-generated audio).

For communication between humans and computers, the promising options are Computer-Generated Audio (the generation of sounds or speech by the computer to give information to the human) and Human Eyesight via Graphic Display (the display of text, drawings, or visual cues to the human on a screen), particularly in those situations when more traditional methods are cumbersome (e.g. during work in a pressure suit, docking, or manipulator control). In general, the development of human/machine communication is an important prerequisite to successful telepresence applications.

To maintain communications links, Fault Tolerant Software is promising, due to low maintenance and high reliability. Fault tolerant computer programs recover from failures, either from damage to the computer equipment or from faulty programming, by finding methods to operate around the problem.

1.3.6 Monitoring and Control

For monitoring of spacecraft components and procedures in general, a promising option is Equipment Data Checks by Onboard Computer, because it doesn't incur the costs of telemetry or human supervision. The onboard computer in this capability might be an Onboard Dedicated Microprocessor or an Onboard Microprocessor Hierarchy, both of which also receive favorable ratings.

For thermal subsystem control, the promising options are the Operations Optimization Program and the Onboard Adaptive Control System. The operations optimization computer program uses operations research techniques (such as linear and dynamic programming, and variations of these) to compute schedules of operations and control commands for best performance. These two capabilities showed comparable promise in their application to the related power handling task Adjust Currents and Voltages. Both capabilities are low-maintenance options, not prone to failures. In addition, the Onboard Adaptive Control System enhances the R&D of dextrous manipulators, and both contribute to the development of expert systems.

If the monitoring and control tasks are simple, then the traditional Automatic Switching Systems are favored due to low costs. They should also be considered as a backup mode for the more sophisticated options. Automatic Switching Systems contribute to manipulator development.

In general, the more favorable options are automated, since the large volumes of routine monitoring and control data in complex spacecraft will make human evaluation too expensive.

1.3.7 Computation

For 5 of the computation tasks the Onboard Microprocessor Hierarchy is a promising option, due to its reliability, versatility, and low recurring cost. Also promising are the Onboard Dedicated Microprocessor and Deterministic Computer Program on Ground, which have overall ratings close behind the microprocessor hierarchy. The development of space-qualified microprocessors enhances the R&D of a variety of capabilities. The Deterministic Computer Program on Ground has the advantage of low recurring cost, since it does not require in-space maintenance of hardware.

For logical operations and evaluations, the Expert System with Human Supervision and the Learning Expert System with Internal Simulation show some promise. Expert systems are complex computer programs, which use relational data bases to reach conclusions from partial data. A relational data base consists of a body of information on a particular topic, and of a set of rules explaining relationships between pieces of information. For example, expert systems currently in development for medical diagnosis include a data base of possible human symptoms and ailments, and a set of rules expressing the relationships between symptoms and ailments. Given a patient's symptoms, the expert system computes probabilities of various possible diagnoses; it can also request specific additional information to improve its diagnosis. Such systems currently have the proficiency of a first-year intern.

Expert systems can be developed for a wide variety of applications. Current systems require human supervision, to update the data base and to evaluate the system's responses. Eventually a learning expert system may be developed, which would improve its own data base by operating a simulation of a spacecraft, trying solutions to a problem until it found a workable answer, and remembering the cause-and-effects involved.

In general, expert systems can handle multi-variable decision tasks rapidly and reliably. As satellites become more complex, expert systems may become a necessity, to sift through all of the interrelated status data from a spacecraft, and to formulate appropriate responses to spacecraft conditions.

For the single task Apply Compensating Forces (e.g. for spacecraft structure control), the Onboard Adaptive Control System is a promising option, due to its low maintenance, high reliability, and versatility. The development of this capability benefits the R&D of dextrous manipulators and of learning expert systems.

1.3.8 Decision and Planning

For optimal scheduling and consumables allocation, the Operations Optimization Program is a promising option, because of its low cost and developmental risk, and high reliability. This capability also supports the development of expert systems.

To support decisions on mission status and procedures, Computer Modeling and Simulation is useful, particularly if implemented end-to-end, i.e. from the original mission definition, through spacecraft design and manufacture, to the operation of the spacecraft in orbit.

For many of the simpler decision and planning functions, the Onboard Deterministic Computer Program and the Deterministic Computer Program on Ground are adequate, with the advantage of low recurring costs (no direct human supervision is required). Complex decisions requiring qualitative evaluations are left to more sophisticated software or humans.

The use of Onsite Human Judgment is favorable in two tasks: the the evaluation of system performance, because of the human's versatility and low failure-proneness; and for the piloting of spacecraft around objects, because of the human's rapid evaluation of three-dimensional data and rapid definition of responses to trouble.

1.3.9 Fault Diagnosis and Handling

To identify problems, Equipment Data Checks by Onboard Computer, Equipment Function Test by Onboard Computer, and Equipment Data Checks via Telemetry are promising options. The development of the Equipment Function Test by Onboard Computer also contributes to the development of Fault Tolerant Software. Also useful is the Deterministic Computer Program on Ground, which in this application is an on-ground equivalent to the data checks and function test by onboard computer.

To recover from failures, Fault Tolerant Software is favored, because it operates rapidly and autonomously, with low recurring costs. The use of this capability is limited to those problems that can be modeled in software, and whose solutions can be programmed in advance. The development of Fault Tolerant Software contributes to the R&D of a Learning Expert System with Internal Simulation.

For diagnosis of more complex problems and development of solutions, the Expert System with Human Supervision is a promising option. In this application the expert system is similar to the medical diagnosis systems currently in development (see

Section 1.3.7 above).

The study group feels that 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 such failure modes and effects becomes combinatorially enormous. At the same time, on-orbit repair systems are becoming available, such as the Shuttle, the Teleoperator Maneuvering System, or repair teleoperators onboard 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, including the relationships between components (particularly the effects of component failures on other components) into the relational data base 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 help in (or perform) failure diagnosis, suggest potential solutions, and verify that the proposed solutions will cure the problems. The repair systems can then implement those solutions. When the spacecraft designers become confident that the failure diagnosis expert system has a sufficient data base to perform the services described above, then the spacecraft can be cleared for manufacture.

The Human on Ground with Computer Assistance shows some versatility: it applies to 5 tasks. For the definition of corrections to faulty computer programs, the human can be favorably aided by an Automatic Programmer and Program Tester, which accepts high-level (e.g. english-language) descriptions of what the program is supposed to do, then writes the computer code and checks it in a simulation of the spacecraft software. For the identification of faulty software and the definition of correction algorithms, Computer Modeling and Simulation is another favorable option to aid the human.

1.3.10 Sensing

For all four sensing tasks, the Optical Scanner (Passive Cooperative Target) had very favorable decision criteria values, in comparison to other candidates. In addition, the development of the optical scanner enhances the R&D of the Automated Docking Mechanism and of the Teleoperator Maneuvering System. The optical scanner requires that the target cooperate by displaying passive laser reflectors in known locations. The system scans the reflectors with a laser beam and computes their positions, thus deducing the location and orientation of the components to which the reflectors are attached. The high speed, reliability, and low cost of such a system (e.g. the PATS military version) make it a promising option. The laser reflectors can also carry identification codes (such as bar codes read by similar laser scanners in supermarkets). This suggests that all spacecraft components could be tagged with identifying reflectors in known locations, so that an optical scanner could locate and recognize them. The position information would then be used either directly by a computer, or by a human through the medium of a computer-generated graphic display.

The closest competitor to the Optical Scanner is Radar (Active Target), which has advantages in power consumption and range (at long ranges, the laser power required by the Optical Scanner can pose a safety hazard), but which requires an active transponder on the target. This capability also supports the development of the Automated Docking Mechanism and of the Teleoperator Maneuvering System.

Other sensing options (e.g. Onboard Navigation and Telemetry, Tactile Sensors, various human eyesight options) have specialized uses, and their respective merits depend strongly on the specific details of the applications.

1.4 CONCLUSIONS AND RECOMMENDATIONS

1.4.1 Conclusions

These are the principal conclusions drawn by the research team, at the end of Phase I of the ARAMIS study:

1) Automation, Robotics, and Machine Intelligence Systems can be applied to a wide variety of NASA activities, both in space and on the ground.

2) In most cases, ARAMIS will not replace humans; it is more likely to be used to make the existing workforce more productive. This increase in productivity will be required to meet the higher workloads projected for the next fifteen years (e.g. Shuttle launch rates of 25 to 40 per year).

3) Case design studies and experimental work are needed to focus on the study information in the context of specific space projects. This is particularly true for telepresence applications, because the optimum mix of the human operators and of the several technologies involved is not yet clear.

4) Potential applications of ARAMIS to payload handling and launch vehicle operations at Kennedy Space Center require more specific study, for two reasons:

a) KSC requires many parallel, interrelated functions under strict timelines. Therefore applications of ARAMIS to one task may affect many others. Such relationships were beyond the scope of our more general study.

b) Payload handling at KSC is one of the principal interfaces between NASA and the spacecraft builder. The division of functions between NASA and the spacecraft builder is not yet clear, particularly in the context of the new Space Transportation System.

5) Space-qualified microprocessors will play a critical role in ARAMIS applications to spacecraft functions. Low weight, low power consumption, and large computational capability make current microprocessor chips a fundamental enabling technology for a wide variety of space activities.

1.4.2 Recommendations

Based on the information developed in Phase I of the ARAMIS study, the research team makes the following principal recommendations:

1) There should be more study on telepresence, for application to routine functions, servicing, failure diagnosis, repair, and construction of spacecraft. This should include:

   a) case design studies to develop quantitative estimates of the relative merits of options.

b) experimental work, because design studies alone cannot fully evaluate the benefits and drawbacks of this multi-technology area.

c) development of simulation facilities to aid in the development of operational telepresence systems.

In all of the above objectives, the concept of supervisory control (the sharing of control between the human operator and a computer) deserves special attention.

[Telepresence is discussed further in the next section.]

2) There should be more study of computer expert systems, for support of spacecraft decision functions. This should include:

a) analyses of potential applications of expert systems in general, since their abilities are not yet fully known.

b) a study of the specific application of expert systems to the problems of spacecraft failure diagnosis and handling.

c) an evaluation of the requirements in putting an expert system on a spacecraft or space platform.

As spacecraft complexity increases, it becomes almost impossible to consider all possible failures in advance. The expert system may be the best method to deal with spacecraft failures, both during design and operation.

3) There should be more specific study of ARAMIS applications to payload handling and launch vehicle operations at Kennedy Space Center, including:

a) a review of ARAMIS potential in helping payload handling functions, with attention to the respective roles of NASA and the spacecraft builder.

b) analyses of the flow of Space Transportation System processing and refurbishment between flights, to identify likely areas of ARAMIS application.

c) an evaluation of machine intelligence options to support the launch operations during countdown.

4) There should be studies and developmental work on space-qualified microprocessors for spacecraft applications, including:

a) a review of specific potential applications.

b) an analysis of the relative merits of space-rating microprocessor chips versus flying redundant sets of chips as delivered by commercial manufacturers.

c) analyses of the tradeoffs between developing dedicated chips for specific applications, or using commercial-variety chips and developing specialized computer programs for them.

NASA should develop an in-house capability to devise, design, debug, produce, test, and space-rate microprocessor chips for spacecraft. (If space-rating is not required, the production could be commercial.) Computer-aided design systems for chips, which transfer the new chip designs to special facilities for rapid manufacture, are in use today (e.g. at the MIT Artificial Intelligence Laboratory).

5) **A central clearinghouse for information on ARAMIS would be a benefit to NASA, to improve transfer of information both within NASA and between the ARAMIS community and NASA. An interactive computer network (modeled after DARPA's ARPANET) should also be considered. Links to the ARPANET should be established, as a means of access to ARAMIS research. The major conferences on ARAMIS now include tutorials on the state-of-the-art and technical displays, and should there-ore receive more attention from potential users.**

6) 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 super-visors, and reduce documentation costs. As the study group found in its own data management system, important objectives are that each individual user should have access to all the data, and that paper should become secondary to the computer as a communication medium.

7) The ARAMIS technologies are currently in rapid development, and the optimum mix of humans and machines will change in character and degree as both human support and machine technologies evolve. Therefore, general updates on the overall state-of-the-art and potential of ARAMIS for space

applications should be performed every four years, so that NASA can make informed decisions on which ARAMIS options to develop.

1.5 PREVIEW OF FOLLOW-ON WORK: TELEPRESENCE

1.5.1 Definition of Telepresence

The second phase of this study concentrates on the more specific subject of telepresence and its potential uses in space activities. Telepresence is defined by the character and degree of communication between the operator and the remote worksite: at the worksite, the manipulators have the dexterity to allow the operator to perform normal human functions; at the control station, the operator receives sensory feedback to provide a feeling of actual presence at the worksite.

In other words, telepresence starts with the ingredients of current master-slave manipulators: a control station with one or two master arms; a remote worksite with one or two slave arms, geometrically similar to the master arms; and feedback (usually video, sometimes also force) to let the operator perceive what is happening at the worksite. However, telepresence requires a greater degree of dexterity and feedback than current tele-operators. The systems in use today (e.g. in the nuclear power industry) usually have two-finger claw grabbers as end-effectors, and therefore do not give the operator a feeling of natural manipulation, even in simple tasks. Similarly, the usual video feedback (from one or two cameras) does not provide depth or parallax perception, or peripheral vision; some do not have enough resolution to show sharp details in the workscene. To achieve telepresence, current systems may need to be upgraded to include stereovision, movable points of view, high-resolution zones of focus and low-resolution peripheral vision, sense of touch, force, and thermal and audio feedbacks. Which types and degrees of feedback are required depends on the specific task to be done; it is therefore easier to achieve telepresence in a simple, low-tolerance task than in a complex, delicate one. The defining criterion is that the interaction between operator and worksite must give the operator a comfortable impression of being there.

1.5.2 Phase II of this Study

Phase II of this study will begin with a review of NASA program plans involving development or use of telepresence, such as remote spacecraft servicing and space structure construction. Also included will be an analysis of present state-of-the-art and future potential of technologies and facilities contributing to telepresence, within NASA and in the U.S. in general.

The study group will then select some representative projects for detailed case design studies of the application of telepresence in space. Candidates for study are the Advanced X-ray Astrophysics Facility (which would be studied as a telepresence counterpart to the astronaut-serviced Space Telescope), the Teleoperator Maneuvering System, and the Space Platform.

Some of the fundamental issues in telepresence, to be addressed by Phase II, are listed in Table 1.5, in the form of currently unresolved questions.

TABLE 1.5: SOME ISSUES IN TELEPRESENCE DEVELOPMENT

End-Effector Design:

1) Are non-anthropomorphic end-effectors (e.g. interchangeable end-effectors including specialized tools) sufficient for some tasks?

2) For those tasks which are best done by hands, should the hands have five, four, or fewer fingers?

3) Should fingers include force feedback, tactile feedback (imaging, force, or slip), thermal feedback?

Teleoperator Design:

1) Should telepresence devices be free-flying or fixed-base?

2) What loads will a telepresence manipulator encounter, and what strength will it require?

3) What is the tradeoff between teleoperator capability (e.g. its degree of telepresence) and cost?

4) To what extent can a computer in the control loop (supervisory control) help achieve telepresence?

Human Factors:

1) If the worksite manipulators are larger than human arms, how will the operator adapt to the unusual dynamics and scale effects?

2) In dealing with transmission time delays between operator and worksite, what are the limitations and alternatives to predictive displays?

3) What cues does the operator need to determine the orientations and velocities of objects (including the telepresence devices) in space?

4) What are the "presence" requirements (visual field, tactile fidelity) to make the operator feel comfortably onsite?

5) To what extent can ground-based simulations be used to validate telepresence concepts for use in space?