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SPACE APPLICATIONS OF AUTOMATION, ROBOTICS AND MACHINE INTELLIGENCE SYSTEMS (ARAMIS) VOLUME 3: ARAMIS OVERVIEW

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Phase 1, Final Report

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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 III of a four-volume set, the fourth volume consisting of two documents: CR-162082 and CR-162083 (an appendix).

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VOLUME 3: ARAMIS OVERVIEW

3.1 INTRODUCTION

3.1.1 Contractual Background of Study

On June 10, 1981, NASA Marshall Space Flight Center (MSFC) awarded a twelve month contract (NAS8-34381) to the Space Systems Laboratory and the Artificial Intelligence Laboratory of the Massachusetts Intstitute of Technology, for a study entitled "Space Applications of Automation, Robotics, and Machine Intelligence Systems (ARAMIS)", Phase I. The Space Systems Laboratory is part of the M.I.T. Department of Aeronautics and Astronautics; the Artificial Intelligence Laboratory is one of M.I.T.'s interdepartmental laboratories. Work on the contract began on June 10, 1981, with a termination date for Phase I on June 9, 1982.

Following discussions between M.I.T. and NASA MSFC, the contract was expanded to include several additional tasks specifically concerned with structural assembly in space. This "structural assembly expansion" to the contract started on October 27, 1981, with a termination date also on June 9, 1982.

At NASA's request, separate progress reports were produced for the original contract tasks (called the "main study") and for the structural assembly expansion. Separate final reports were also prepared, though some sections are identical in both.

This document is the final report for Phase I of the ARAMIS

main study. The final report for the structural assembly expansion of this study is entitled "Automated Techniques for Large Space Structures" (also contract number NAS8-34381).

The NASA MSFC Contracting Officer's Representative is Georg F. von Tiesenhausen (205-453-2789). The M.I.T. Principal Investigators are Professor Rene H. Miller (617-253-2263) and Professor Marvin L. Minsky (617-253-5864). The M.I.T. Study Manager is David B.S. Smith (617-253-2298).

3.1.2 Organization of the Final Report

Volume 1 of the final report is the Executive Summary. Volumes 2, 3, and 4 are roughly chronological, in the sense that the data and results presented were developed in that order by the study.

Volume 2: Space Projects Overview describes the space project breakdowns, which are used to identify tasks ("functional elements") which will be required by future space projects.

Volume 3: ARAMIS Overview gathers together the information specifically related to automation, robotics, and machine intelligence systems (ARAMIS). The volume starts with a general discussion of ARAMIS and the organization of this field into "topics." It then presents General Information Forms on ARAMIS "capabilities" which are candidates to perform space project tasks.

Volume 4: Application of ARAMIS Capabilities to Space Project Functional Elements is the pivotal volume in the report,

since it deals with the relationships between the space project tasks and the ARAMIS capabilities. Specifically, in Volume 4, the list of tasks generated in Volume 2, and the background knowledge on ARAMIS presented in Volume 3, are combined to define "candidate ARAMIS capabilities" for each task. Volume 4 then presents the evaluation of the relative merits of the various candidates to perform the space project tasks, and the selection of the promising options suggested for further study.

Thus Volumes 2 and 3 serve to some extent as preparatory material and appendices to Volume 4, which contains most of the complexities of the research effort. Therefore a complete description of the study's objectives and method is included in Volume 4, while partial synopses of the study method appear in Volumes 2 and 3, specifically explaining the production of the data in those volumes.

The study recipient who wishes to apply the results of this study to a new space project will principally use Volume 4, referring to Volume 2 to check further on the definition of a space project task, and referring to Volume 3 for descriptions of suggested candidate ARAMIS capabilities. In addition, Volume 3 is intended as a general introduction to the field of ARAMIS and to its complex jargon.

3.1.3 Partial Synopsis of Study Method: ARAMIS Classification

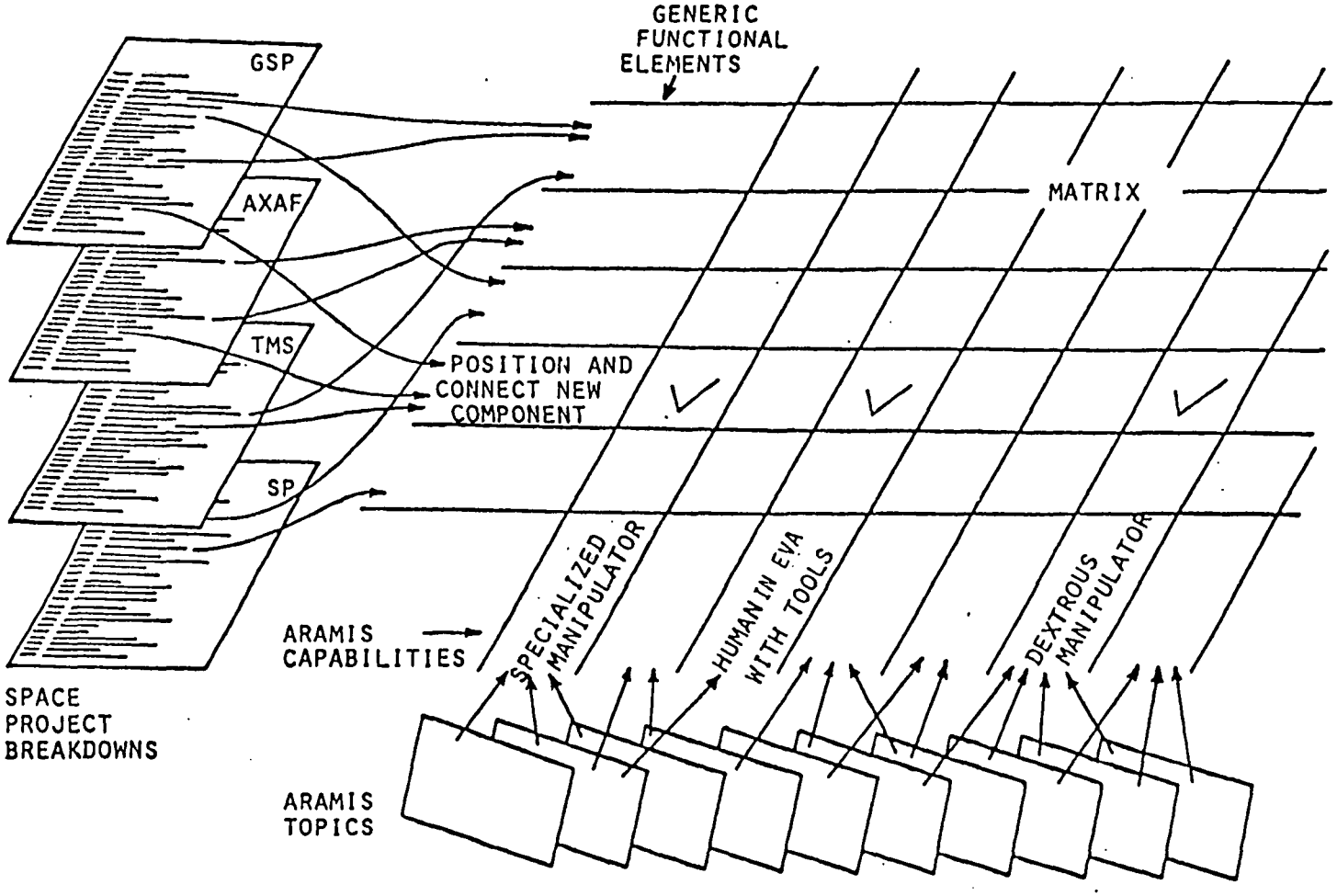
The overall ARAMIS study method is illustrated in schematic form in Figure 3.1. The method concentrates on the production of a matrix relating space project tasks (called "generic functional elements"; on the vertical axis in the figure) to pieces of ARAMIS (called "ARAMIS capabilities"; on the horizontal axis in the figure). The example in the figure shows that the generic functional element "Position and Connect New Component" can be satisfied by any of three ARAMIS capabilities: Specialized Manipulator, Human in EVA with Tools, or Dextrous Manipulator. Note that each ARAMIS capability by itself can satisfy the generic functional element.

As illustrated in the figure, the generic functional elements (GFE's) are generated from the space project breakdowns. The breakdown procedure and the collection of the generic functional elements are described in Volume 2: Space Projects Overview.

The ARAMIS capabilities are generated by considering each generic functional element in turn, and defining pieces of ARAMIS capable of satisfying the element. These definitions are based on the general background knowledge and organization of ARAMIS developed by this study.

A general discussion of automation, robotics, and machine intelligence systems is presented in Section 3.2. The method used by this study to organize the field of ARAMIS is discussed in Section 3.3. The procedure for definition and research of ARAMIS capabilities is described in Section 3.4. This includes discussion of the descriptions of capabilities in General Information Forms, and of the definition of favorable sequences

FIGURE 3.1: ARAMIS STUDY METHOD: GENERIC FUNCTIONAL ELEMENT/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

of ARAMIS development ("technology trees").

The checkmarks on the matrix grid in the figure are for schematic presentation only. In actuality, each checkmark consists of values of seven decision criteria, with commentary and data sources, on the potential application of that ARAMIS capability to that generic functional element. These criteria are defined and discussed in Section 4.6 (Volume 4).

The ARAMIS study uses a specialized nomenclature, partly adopted from NASA and partly defined specifically for this study. Table 3.1 defines this nomenclature, as well as some acronyms.

Most of the data management functions required by the study method were implemented on a computer, for ease of access and display of the information. The use of the computer in the ARAMIS study is discussed in Appendix 4.F (Volume 4).

TABLE 3.1: ARAMIS STUDY NOMENCLATURE

ARAMIS - Automation, Robotics, and Machine Intelligence Systems

FUNCTIONAL ELEMENT - A small piece of a space project (examples: Open Access Panel, Open Supply Valve), which can be satisfied by a single ARAMIS capability.

GENERIC FUNCTIONAL ELEMENT LIST (GFE LIST) - A list of all the functional elements in the four space project breakdowns; a functional element already collected from a previous breakdown is not listed again.

ARAMIS TOPIC - A part of the overall field of ARAMIS (e.g. Manipulators, Machine Vision Techniques, Computer Architecture); the study group identified 28 such topics (with considerable overlap between topics) which collectively cover ARAMIS.

ARAMIS CAPABILITY - A piece of ARAMIS (hardware and/or software) which can by itself satisfy a generic functional element; each capability only involves a small (manageable) part of the wide field of ARAMIS.

DECISION CRITERIA - Indices of the performance of an ARAMIS capability applied to a generic functional element; these indices are evaluated for each candidate ARAMIS capability applied to each generic functional element.

TECHNOLOGY TREES - Favorable sequences of ARAMIS development; i.e. early R&D of certain capabilities enhances later R&D of other capabilities (e.g. prior R&D of tactile sensors and microactuators benefits the development of a dextrous manipulator).

CRITICAL ELEMENT/CAPABILITY (E/C) PAIR - An application of an ARAMIS capability to a generic functional element, for which: the decision criteria values are favorable; and/or the capabilities are important in technology trees. This is therefore a promising application of ARAMIS.

GSP - Geostationary Platform

AXAF - Advanced Xray Astrophysics Facility

TMS - Teleoperator Maneuvering System

SP - Space Platform

3.2 GENERAL DISCUSSION OF ARAMIS

3.2.1 General Comments

Automation, Robotics, and Machine Intelligence Systems are not a single technology, but rather a field of interrelated technologies. These range from simple to complex, from human to machine, and from hardware to software. Examples of human-related ARAMIS research are the development of mechanical fingers and tactile sensors, the study of the mechanisms and processes in human vision, and fundamental research on the process of human thought. Other ARAMIS technologies involve the development of machines, for the purpose of optimizing their non-human abilities: large-scale exact memory recall, rapid numerical computation, response to changes at electronic speeds, precise repeatability, absence of maintenance, and resistance to adverse environments.

Many of the potentially profitable ARAMIS developments involve the interaction between technologies. For example, one approach to machine vision involves a three-way marriage of optics, integrated circuits, and hierarchical processing software. Thus a classification scheme for ARAMIS, although desirable for clarity, is difficult to produce, as discussed in the next section.

Some of the advanced ARAMIS technologies are potentially high risk, high-yield concepts. For example, it is not yet clear how difficult it will be to produce a computer able to understand conversational human speech (computers can now understand single words and preprogrammed phrases, and can produce

speech). However, if such a system is developed, its applications are likely to be numerous, and some will be revolutionary, allowing real-time, conversational requests for data and analyses, from machines with enormous memories and very fast computation abilities.

Because ARAMIS is made up of diverse technologies, and because many ARAMIS concepts are on the forefront of knowledge, it is seldom that one finds a concensus in the "ARAMIS community" on major issues. For example, there are many discussions on optimum design of manipulators: one side favors dedicated manipulators controlled by simple software, in preset and precise worksite geometries; another side prefers versatile manipulators with flexible or adaptive control, in unconstrained worksites. There are also differences of opinion on the relative merits of humans and computers to provide that flexible or adaptive control. Part of that uncertainty is due to a lack of quantitative knowledge on human abilities, and to the difficulty in defining useful figures of merit for comparisons. For example, a desirable figure of merit for structural assembly in space would be "accurately assembled kilogram per safe person-hour", which poses problems in measurement.

For the last few years, this country has suffered from a gap between advanced research on ARAMIS and the use of ARAMIS on the production line. In some cases, this gap was filled by Japan, and U.S. industries found themselves purchasing Japanese ARAMIS hardware and techniques (or ARAMIS-manufactured products), which had been developed from U.S. ARAMIS research. Fortunately, the

gap in this country is closing, both through increased communication between research organizations and industrial users, and through the formation of numerous small companies (e.g. Automatrix, Machine Intelligence Corp., Apple Computer) specifically for the purpose of developing commercial applications of recent ARAMIS research (their engineering sections are typically filled by recent university graduates). The current upsurge in the market for industrial manipulators is also boosting old and new robotics firms (e.g. Unimation, Cincinnati Milacron, IRI), which are turning to new research to improve their competitive edge.

The study group, after literature review and a number of consultations, identifies six major thrusts in current ARAMIS research and applications:

1) Industrial programmable machines, particularly manipulators, for use on production lines. One aspect relevant to space applications is the current attempt to lighten and shrink industrial devices by using active control techniques to achieve close positioning, rather than the traditional structural bulk. To the knowledge of the study group, however, this development of manipulators includes very little work on teleoperation, i.e. on manipulators under human control. The principal current application of teleoperators is in the nuclear industry; their master-slave devices have remained virtually unchanged for the last ten years.

2) Machine vision, also for use on production lines, to recognize parts for sorting and handling, or to identify defects. Commercial systems tend to use simple optical sensing (e.g. planes of laser light) and recognize objects by comparing what they see to computer models.

3) Natural language understanding and speech, to improve communication between humans and computers. Machines can produce speech, but can only understand it in limited fashion (e.g. pre-programmed words and phrases, from a particular human). The goal of this research is to let the machine receive human speech and convert it to computer code which is compatible with its programming.

4) Knowledge engineering, which is the application of computers, particularly computer data bases, to current problems. This includes relatively simple concepts,such as library data bases (which will soon be privately accessible over phone lines) and the educational computer systems currently used in elementary schools. Knowledge engineering also includes higher-level concepts such as computer-aided-design, and relational data bases capable of inferences from partial data (called "expert systems").

5) Cognition, the fundamental issue of how intelligence works. This includes research into the process of learning (how data is accepted, sorted, classified, stored, retrieved, and used in logical evaluation), and into techniques of problem-solving (how a potential solution to a problem is generated from the available data, and evaluated by rational means). Some research projects in this fundamental area explore human cognition; others consider the potential of machine cognition, outside the human context.

6) Computer architecture, both in hardware and software. This ranges from the very large, very fast numerical computers (e.g. the CRAY machines), through intermediate concepts such as large-array parallel processors, to applications of micro-

processor chips to smaller tasks. The latter includes development of larger chips, chip-design systems, and applications to personal computers and videogames. In general, this research selects hardware and software options appropriate in scale and complexity to the tasks to be done (e.g. CRAY machines for simulations of global weather, large-array parallel processors for computational fluid dynamics modeling of turbulent flow, microprocessors and microprocessor hierarchies for manipulator position feedback evaluation and manipulator control).

These six general thrusts include most of the current ARAMIS work. A more detailed and comprehensive classification of ARAMIS was developed by the study group; it is presented in Section 3.3.1.

3.2.2 Issues in Classification of ARAMIS

The study group decided to apply a classification scheme to the field of ARAMIS for three reasons:

1) to make data accession and classification manageable. Trying to find library information on general areas of ARAMIS (e.g. sensing, computers) would produce large quantities of data, most of it irrelevant.

2) to define categories on which individual experts could be consulted. With sufficiently specific definitions of the subjects of interest, individual experts could be identified; a more general expert (e.g., on computers) seldom had the specific information needed by the study group.

3) to provide a framework to transfer information to the study recipient. The classification system simplifies the task of describing the ARAMIS technologies and their interrelationships.

However, there are some difficulties inherent in any current attempt to organize the field of Automation, Robotics, and Machine Intelligence Systems. First, there is no consistent nomenclature across ARAMIS. Different research groups define common-usage terms differently (e.g. "robot" means an industrial programmable manipulator to some, and a fully autonomous decision-making unit to others), and similar concepts are labeled differently from one laboratory to the next. The study group side-stepped some of these problems by avoiding the use of certain ambiguous terms, such as "robot" and "artificial intelligence".

Second, there have been virtually no previous attempts at comprehensive classification schemes for ARAMIS. The reason for this, given to the study group in consultations, is that the overall field is too young to have been so organized - which is seen by some as a boon, since such a process of classification can stifle creative mixing between the emerging branches of the field. In many cases, clear-cut distinctions between sections of ARAMIS are not yet possible, and the rationale for grouping pieces of ARAMIS into clusters is not yet evident. For example, it is difficult to draw a clear distinction between automatic programmers and natural language interfaces; both accept high-level (e.g. English-language) inputs and communicate them to a computer. Some classification schemes for parts of ARAMIS exist (e.g. the

classification developed by Dr. Ewald Heer in Ref. 3.1), but in general the organizations doing ARAMIS research each have their own classification schemes, not compatible with each other.

Third, at the time that the study group attempted to organize ARAMIS, there were apparently no comprehensive directories of ARAMIS research. There were some data bases, including NASA's own RECON computer base, which listed some sections of ARAMIS, but the study group could not find a field-wide catalog of ARAMIS literature. Neither was there a catalog of organizations or individuals doing research on the various aspects of ARAMIS. In fact, the "ARAMIS community" is, by its own admission, very oral: to find out who is working on a particular subject, the study group would ask someone in the field, who suggested another contact, and so on, until the needed expert had been located. The most prevalent communication medium between ARAMIS researchers appears to be the ARPANET computer network, but that does not include industrial users of the technology.

However, the study group knows of two general directories of ARAMIS which were prepared concurrently with this study, for the benefit of aerospace users. The first, prepared by Dr. William Gevarter (Ref. 3.2), covers ARAMIS world-wide, concentrating on U.S. research and on Japanese efforts. The second, produced for the European Space Agency (Ref. 3.3), concentrates on European work on ARAMIS.

In addition, the field of ARAMIS is organizing itself, and the publications and conferences are becoming more informative and comprehensive. Section 3.3.2 discusses some useful sources of information on ARAMIS, and introduces this study's biblio-

graphy (in Appendix 3.B).

The study group first attempted a "branching-tree" type of classification on the whole of ARAMIS. The intention was to break down ARAMIS into succesively finer levels, until the lowest level would contain all the desired categories. For example, ARAMIS could be first broken down into the general areas of sensing, computation, actuation, and communication; then each area could be further broken down, and so on.

After some work on the concept, however, the study group concluded that the branching-tree type of breakdown tended to confuse the organization of ARAMIS rather than clarify it. ARAMIS can be broken down in a variety of ways, each of which contains information useful to the reader; a too-specific breakdown method obscures instructive relationships between pieces of ARAMIS. For example, a useful classification for sensors distinguishes between proprioceptive sensors (which sense only within the device, e.g. joint position sensors in a manipulator) and exteroceptive sensors (which sense the outside environment, e.g. laser ranging systems); but too much attention to this distinction obscures the fact that some sensors can serve as both simultaneously, e.g. a camera watching both the position of a manipulator (proprioceptive) and the target being reached for (exteroceptive).

For these reasons, the study group chose a more versatile classification scheme for ARAMIS, breaking the field down into 6 general areas and 28 topics, with overlaps between areas and between topics. These areas and topics are discussed in

Section 3.3.1.

3.2.3 Human and Machine

One important aspect of the organization of ARAMIS for space applications is the issue of the respective roles of humans and machines. Guideline (2) in Section 4.2.3 (Volume 4) assumes that each space project task has an optimum in terms of ARAMIS, and that different tasks will have different optima. In the opinion of the study group, this optimum includes the optimum mix of humans and machines.

The research team believes that the mix of humans and machines is one of the significant variables in the design of spacecraft hardware and mission procedures. Rather than a competition between human and machine options, the issue is the definition of the most appropriate roles for humans and for machines, so that their partnerships will yield the best performance of project tasks.

Therefore this study includes human options wherever appropriate, to cover the range from fully human to autonomous machines. The classification of ARAMIS (described in the next section) includes several categories with various levels of human involvement, including Human Augmentation and Tools, Human-Machine Interfaces, and Teleoperation Techniques. Later in this study, Direct Human Eyesight is considered as an option for some sensing tasks, and the Human in EVA with Tools is an option for a variety of functions. Although some earlier studies

have compared human and machine options for specific space projects (including the ESA study in Ref. 3.4), this study takes the more general view that humans (and systems including humans) are part of the spectrum of available ARAMIS options.

3.3 CLASSIFICATION OF ARAMIS

3.3.1 System Used in this Study: ARAMIS Topics

Keeping in mind the issues discussed in the previous two sections, the study group developed a flexible classification scheme for ARAMIS, breaking the field down into 28 "topics". There is considerable overlap between topics, a natural (and probably desirable) result of the active interaction of technologies in rapid development. Fortunately for clarity, these topics can be grouped into 6 general "areas", again with considerable overlap between areas. The topics and areas are listed in Table 3.2. In addition, brief definitions of the 28 topics are presented in Appendix 3.A: ARAMIS Topics and their Definitions.

The topics were defined through literature review (e.g. Ref. 3.1), and refined through consultations with Dr. William B. Gevarter (National Bureau of Standards) and Dr. Ewald Heer (Jet Propulsion Laboratory). These topics are useful in that looking up one topic yields a manageable amount of information, and experts on individual topics can be found for consultation.

The study group tried to make the list of ARAMIS topics comprehensive, i.e. the 28 topics collectively cover the whole field of ARAMIS. Some of the topics are therefore very advanced, possibly beyond the scope of the study (e.g. Self-Replication, not likely to be available before 1995). Some topics, such as Deductive Techniques (Theorem Proving) and Reconfiguration and

TABLE 3.2: 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

Fault Recovery, are in technological infancy: they have not had significant commercial applications to date. Their contributions may therefore be limited in the next few years, but may become much more significant as these technologies mature. This list of topics was defined to inform the study recipient about the subjects of current work in ARAMIS; it is also intended to show the potential directions of R&D in this field. These topics were also used to assign code numbers to ARAMIS capabilities, as described in Section 3.4.1.

3.3.2 Useful Sources of Information

The study group has come across several useful sources of information on ARAMIS in general and on some specific ARAMIS topics.

As mentioned earlier, the ARAMIS researchers appear to communicate primarily through the computer network ARPANET, or by word-of-mouth. One of the more productive methods of access to ARAMIS research information is to become a recognized user on the ARPANET. This has three principal benefits:

1) The user has access to a wide variety of research reports, including status reports on current studies, which are only available from the ARPANET files. In fact, some of these reports may never exist on paper, since they are created, distributed, and read (on video terminals) as computer files; the ARPANET resists attempts at printouts by low-level users, for security reasons, but will display a large variety of files on request.

2) The user can set up a selective mailbox, indicating which keywords (from a large and varied menu) are of special personal

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interest. The network will then automatically notify the user of any new reports filed under those keywords. Thus the mail-box collects the latest network inputs of particular interest to the user.

3) The user can have long-distance discussions with other ARPANET users, either in a conversational mode or by exchanging blocks of text. This allows rapid responses to questions or reviews of new ideas. A large amount of discussion is handled in this fashion on the ARPANET every day, and other users can observe the exchanges without participating. A user can also request help on a particular topic, and the network will try to identify other users with that specialty.

To enter the word-of-mouth information circuit, there are several major conferences each year which attract the foremost researchers. These conferences have recently (i.e. in the last year) become more comprehensive and informative, partly by the inclusion of tutorials on the state of the art (usually presented by very knowledgeable sources) and of technical displays by hardware and software producers. The latter addition has also set up a forum for direct interaction between the advanced research side of ARAMIS, usually pursued in universities and research institutes, and the commercial application side, typically handled by industry.

Particularly worth noting are the International Joint Conferences on Artificial Intelligence (the IJCAI in 1981 was held in Vancouver, B.C., Canada) and the American Association for Artificial Intelligence conferences (the AAAI-82 conference

in August 1982 is in Pittsburgh, Pennsylvania). In general, the American Association for Artificial Intelligence (AAAI, 445 Burgess Drive, Menlo Park, CA 94025; (415) 328-3123) is emerging as the most active organization dealing with advanced ARAMIS research in the U.S..

There are also a number of conferences and workshops on commercial development of ARAMIS, particularly on industrial programmable machines. Many of these gatherings are sponsored by Robotics International of the Society of Manufacturing Engineers (SME). Also recommended is their magazine, Robotics Today (One SME Drive, P.O. Box 930, Dearborn, MI 48128; (313) 271-1500), published in cooperation with the Robot Institute of America. The magazine concentrates on hardware, and includes schedules of upcoming workshops, new product descriptions, and reviews of literature. Subscribing to the magazine also puts the recipient on some useful mailing lists.

Another magazine of potential interest is Robotics Age (Robotics Age Subscriptions, P.O. Box 358, Peterborough, NH 03458; (603) 924-7136), which also discusses hardware but includes articles on machine intelligence as well. Reviews of new products and literature are also included.

A number of newsletters, magazines, and journals are appearing (ranging from the Bache robotics newsletter for investors to quarterly journals on robotics research) but the study group has not reviewed these. There are also several hardware directories now available (e.g. the Robotics Industry Directory, P.O. Box 725, La Canada, CA 91011; (213) 352-7937), but the study group has not reviewed these either.

The literature reviewed by the study group is listed in Appendix 3.B: ARAMIS Bibliography. Entries are organized according to the 28 topics presented in Table 3.2. Since there is overlap between topics, a number of listings are repeated under several headings. In addition, there is a section of the bibliography organized according to the 9 types of generic functional elements which are defined by this study: power handling, checkout, mechanical actuation, data handling and communication, monitoring and control, computation, decision and planning, fault diagnosis and handling, and sensing. This section of the bibliography presents literature on those types of space project tasks; much of this information is in NASA studies.

[The definition process for generic functional elements (GFE's) is described in Section 3.13 and in Volume 2 of this report. The use of the 9 types of GFE's is described in Section 4.4.1 of Volume 4.]

Besides the information sources discussed above, the study group found much of the literature through catalogs in several MIT libraries, from references and bibliographies in other documents, and from consultations with researchers throughout the U.S.. NASA studies were accessed through the Scientific and Technical Aerospace Reports catalogs in the MIT Aeronautics and Astronautics Library, from a NASA RECON database search (initiated from the KSC library during a visit by study group members), and from the large amounts of support documentation provided by the MSFC technical monitor.

In addition, the study manager reviewed the 1981 NASA Research and Technology Objectives and Plans (RTOP) Summary, and found 18 items of interest to the study group. Not all of these proposed

studies are funded, but the RTOP's were used to identify who was working on ARAMIS-related research within NASA.

3.4 ARAMIS CAPABILITIES

3.4.1 Method of Definition

As described in Section 4.4 (Volume 4), the 330 GFE's in the Generic Functional Element List were reduced to 69 GFE's selected for detailed study. To define candidate capabilities for each of the 69 GFE's, the study group experimented with two methods.

The first involved the production of an exhaustive list of ARAMIS capabilities, based on the background knowledge of ARAMIS developed by the study. The intent was to select appropriate ARAMIS capabilities from this list, to fill out the study matrix. However, there was no guarantee that all of the relevant ARAMIS capabilities would be in the list. Also, the level of detail was very uneven within the list: some items seemed large and complex enough to fulfill whole space project activities or even sequences; while other items were so small in scope that several would have to be combined to apply to a GFE. Therefore the study group rejected this approach. The attempt was instructive, however, because it acquainted the study group with the scope and variety of options within the field of ARAMIS.

The study group therefore devised a simple and pragmatic method to define ARAMIS capabilities. In team brainstorm

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sessions, the generic functional elements were considered one at a time. For each GFE, based on the background knowledge and the ARAMIS topics developed by the study, the research team defined candidate ARAMIS capabilities. Additional literature search, consultation, and conceptual design were done, as needed, to ensure that all potential candidate capabilities to perform each GFE were identified. Each ARAMIS capability was assigned to two (or more) team members for detailed study.

As an example of this process, Table 3.3 shows the candidate ARAMIS capabilities defined for GFE g73 Position and Connect New Component. Eight capabilities were defined as candidates for this GFE.

This example illustrates several aspects of the definition process. Each candidate capability in the example can satisfy, by itself, the generic functional element. This locks together the levels of detail of GFE's and ARAMIS capabilities, thus keeping the production and presentation of the study matrix straightforward.

TABLE 3.3: CANDIDATE ARAMIS CAPABILITIES DEFINED FOR ONE GENERIC FUNCTIONAL ELEMENT

g73 POSITION AND CONNECT NEW COMPONENT	
2.2	DEDICATED MANIPULATOR UNDER COMPUTER CONTROL
4.1	COMPUTER-CONTROLLED SPECIALIZED COMPLIANT MANIPULATOR
4.2	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH FORCE FEEDBACK
4.3	COMPUTER-CONTROLLED DEXTROUS MANIPULATOR WITH VISION AND FORCE FEEDBACK
14.3	HUMAN IN EVA WITH TOOLS
15.1	SPECIALIZED MANIPULATOR UNDER HUMAN CONTROL
15.2	DEXTROUS MANIPULATOR UNDER HUMAN CONTROL
15.3	TELEOPERATOR MANEUVERING SYSTEM WITH MANIPULATOR KIT

Another issue is the possible interpolation or hybridization between capabilities. In the example above, one could define a combination of the Human in EVA with Tools and the Specialized Manipulator under Human Control (the Shuttle RMS) to perform the GFE. In general, one could form intermediate capabilities or partnerships between many pairs of capabilities in the matrix. The study group decided to limit the candidates to those capabilities significantly different from each other, leaving interpolations between capabilities to the study recipient. This kept the number of candidate capabilities manageable. Also, such interpolations are usually suggested by circumstances specific to a space project, and thus beyond the scope of this more general study.

In a number of instances, the research team considered the issue of the time dependence of capabilities. For example, it is expected that a machine vision system in 1995 will be substantially better than in 1985; therefore the applicability of such a capability would depend on the date of use. Since Phase I of this study does not concern itself with space mission launch dates, the study group dealt with this issue in two ways. In most cases, if a capability could be brought online in 1985 at the earliest (following an orderly development program), then it was defined as it would appear in 1985. For those cases where significant time variations in capabilities were expected, near-term and far-term versions were presented as separate capabilities. In the example in Table 3.3 above, the Computer-Controlled Dextrous Manipulator with Force Feedback is a far-term descendant of the current industrial Dedicated Manipulator under

Computer Control.

The example also illustrates the human-to-machine span considered by this study, since the candidate capabilities range from a human in a pressure suit to a fully autonomous manipulator. This wide range is in keeping with the study group's philosophy that the human-to-machine range is one of the variables to be studied: the optimum mix of humans and machines will fall somewhere in this range (including, possibly, at one of the endpoints).

The study matrix, listing the candidate ARAMIS capabilities defined for each of the 69 GFE's selected for detailed study, is presented in Appendix 4.D (Volume 4).

To simplify access to, and presentation of, the ARAMIS capabilities, they were grouped by ARAMIS topics (see Section 3.3.1) and assigned numbers accordingly. These assignments were necessarily artitrary, since many capabilities could be associated with several topics (e.g. Dextrous Manipulator under Human Control, which could be classified under Manipulators, Human-Machine Interfaces, or Teleoperation Techniques). The study group assigned each capability to the topic which seemed to describe the technical challenge in the capability most accurately (e.g. the Dextrous Manipulator under Human Control was classified under Teleoperation Techniques, because of the difficulties in closing the multi-media sensory-motor loop). One result of this procedure was that several ARAMIS topics do not have any specific capabilities listed under them. In the case of topic 5 (Self-Replication), no capabilities were defined with that attribute. In the other cases

(9. Force and Torque Sensors; 12. Other Sensors; 20. Data Manipulation; 28. Reconfiguration and Fault Recovery), those capabilities which might have been associated with these topics were deemed more closely related to other, overlapping topics.

The ARAMIS capability code numbers were assigned by taking the ARAMIS topic numbers (as listed in Table 3.2 above) and adding sequential numbers to them. Thus 14.2 Dextrous Manipulator under Human Control is the second capability listed under topic 14: Teleoperation Techniques.

The study group wishes to emphasize the distinction between ARAMIS topics and ARAMIS capabilities. The topics were broken down from the overall field of ARAMIS, and have a considerable amount of overlap between each other. The capabilities are specific pieces of ARAMIS, defined as candidates to fulfill specific generic functional elements. After their definition, the capabilities were arbitrarily associated with topics, for the convenience of the study researchers and recipients. Thus the process of classification of ARAMIS was separate from the process of definition of ARAMIS capabilities.

3.4.2 Production of ARAMIS Capability General Information Forms

A substantial part of the study effort was devoted to the further description of the defined ARAMIS capabilities. This information is presented through the medium of ARAMIS Capability General Information Forms (one for each of the 78 capabilities defined by the study group). An example of such a Form is shown

in Table 3.4. All of the 78 forms are presented in Appendix 3.C: ARAMIS Capability General Information Forms.

As shown in the example, each General Information Form contains: the name of the capability; the capability's code number; the date on which the Form was filled out; the names of the researchers contributing to the Form; a definition of the capability; identification of individuals and organizations working on the concept; estimates of the dates on which the capability will reach various technology levels; remarks and (when available) data sources on the technology levels; estimates (when available) of R&D costs between technology levels; remarks and data sources on those cost estimates; remarks on any special aspects of the capability; identification of which other capabilities should be developed prior to this one, to enhance its R&D; and a list of the code numbers of the GFE's to which the capability applies.

The technology levels used in the Form are from the 7-level scale used by NASA OAST's Space Systems Technology Model. These levels are defined in Table 3.5. On this scale, a capability at level 6 or 7 is available to the spacecraft designer at the technology cutoff date. These levels are straightforward in their application to hardware development. In software development, however, levels 4 and 5 may be included in level 3: in many cases, the first analytical test of software design requires an all-up test of the software, equivalent to a "bread-

TABLE 3.4:

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Computer-Controlled Dextrous Manipulator with Force Feedback

CODE NUMBER: 4.2 DATE: 6/28/82 NAME(S): Kurtzman/Paige/Ferreira

DESCRIPTION OF CAPABILITY: A multipurpose multifingered manipulator, under computer control, and capable of operating under various geometries. The system would be reprogrammable and would use input from force-feedback sensors for final guidance and motion control.

WHO IS WORKING ON IT AND WHERE: Ewald Heer and Antal Bejczy (JPL); Marvin Minsky (MIT AI Lab); Dan Whitney (Draper Labs); Victor Sheinman (Automatix, Burlington, MA); Tom Williams (DEC, Maynard, MA).

TECHNOLOGY LEVELS:	LEVEL1:	Now	LEVEL2:	Now	LEVEL3:	Now
LEVEL4:	Now	LEVEL5:	1986	LEVEL6:	1986	LEVEL7:	1989

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Present and future levels were provided by Marvin Minsky. The intermediate levels were computed by interpolation based on the background of the study group.

R&D COST ESTIMATES BETWEEN LEVELS;	1-2:	N/A		2-3:	N/A		
3-4:	N/A	4-5:	$10-20 Million	5-6:	N/A	6-7:	$2.5 Million

REMARKS AND DATA SOURCES ON COST ESTIMATES: Dan Whitney suggested a figure of $10-20 million to develop the whole system to level 6. Cost to go from level 6 to level 7 was estimated at $2.5 million by extrapolating from a figure of $1 million to space rate a dedicated manipulator under computer control (Robert F. Goeke, MIT Center for Space Research).

REMARKS ON SPECIAL ASPECTS: None

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 4.1 Computer-Controlled Specialized Compliant Manipulator; 15.2 Dextrous Manipulator under Human Control; 19.1 A/D Converter.

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g67, g73, g134, g148, g177.

TABLE 3.5: TECHNOLOGY READINESS LEVELS

(from the May 1980 NASA OAST Space Systems Technology Model)

Level 1	Basic Principles Observed and Reported
Level 2	Conceptual Design Formulated
Level 3	Conceptual Design Tested Analytically or Experimentally
Level 4	Critical Function/Characteristic Demonstration
Level 5	Component/Breadboard Tested in Relevant Environment
Level 6	Prototype/Engineering Model Tested in Relevant Environment
Level 7	Engineering Model Tested in Space

board test in a relevant environment" for hardware. Thus, for a number of the software-intensive ARAMIS capabilities, several intermediate technology levels are reached concurrently. Similarly, it can be difficult to pinpoint R&D costs for such intermediate levels. The abbreviation "N/A" indicates either "not applicable" or "not available" in the Forms.

The General Information Forms present the information which was available to this general study. More detailed research, such as the case studies planned for Phase II of this study, could fill out such forms in greater depth, and improve time and cost estimates. The format of these Forms was devised to be useable in more detailed studies.

The General Information Forms were filled out through literature search, consultation, and conceptual design. They were developed and stored as computer files, and printed out camera-ready for Appendix 3.C. The use of the computer in this study is described in Appendix 4.F (Volume 4).

3.4.3 Favorable Sequences of R&D: Technology Trees

As mentioned above, for each ARAMIS capability, the General Information Form includes a list of those capabilities from whose earlier development this capability would benefit. In other words, the prior development of the listed capabilities enhances the R&D of the capability named at the top of the Form. In some cases, the list can include some fundamental technologies (e.g. Computer Programming Techniques, Computer Memory Development) which also contribute to the R&D effort.

These lists of desirable prior R&D collectively form "technology trees", favorable sequences of development of ARAMIS capabilities. The technology trees suggest an evolutionary flow of R&D, in which early research on simple or fundamental capabilities contributes to the later development of more complex options.

The study group spent some time developing a straightforward format for the display of Technology Trees. As it turns out, the R&D of almost all of the 78 capabilities is interrelated, and these capabilities also benefit from 12 fundamental technologies. The study group therefore separated the overall tree into 8 more

specific Technology Trees, with interconnections between the trees. One of these 8 Technology Trees is presented in Figure 3.2.

This example illustrates a number of rules used in the display of the Trees:

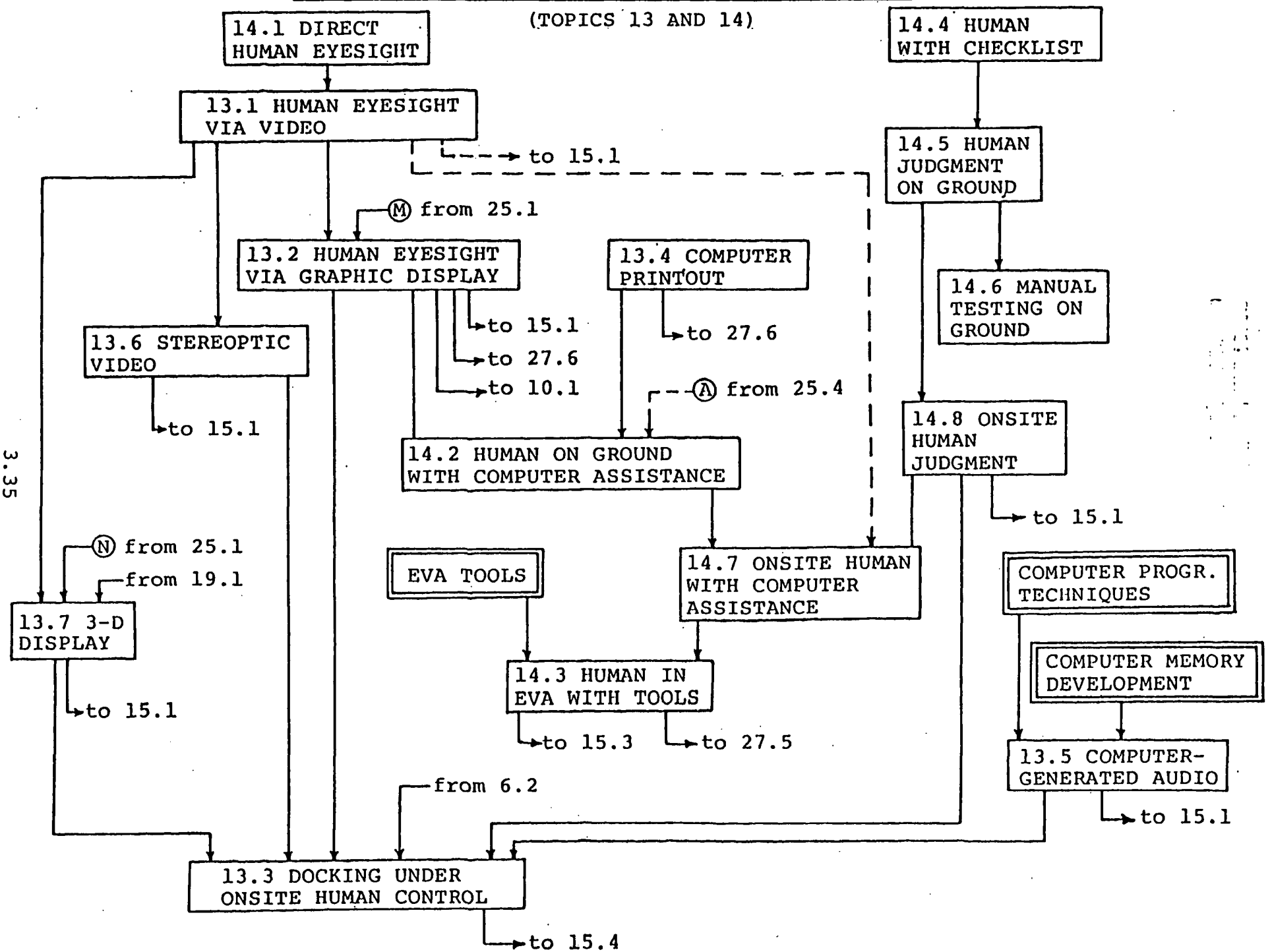
1) The Trees are presented as flowcharts, to be read from top to bottom (i.e. the development of the capabilities and technologies at the top of the figure enhances the R&D of the capabilities lower down).

2) Each capability is displayed in a single box, and appears only once in all the Trees. The fundamental technologies, however, are displayed in double boxes, and can appear in several Trees; for example, Computer Programming Techniques appears in several other Trees, besides the one in the example.

3) A direct enhancement of a capability's R&D by the prior development of a capability or technology is indicated by a solid arrow between them. However, capabilities are also considered to benefit from items further up the trees. For example, 14.2 Human on Ground with Computer Assistance benefits directly from earlier R&D of 13.4 Computer Printout and of 13.2 Human Eyesight via Graphic Display. However the Human on Ground with Computer Assistance, through 13.2, also benefits from development of 13.1 Human Eyesight via Video and 25.1 Onboard Dedicated Microprocessor (from another Tree), and so on up the Trees. The capabilities or technologies up those trees are said to be "available" to 14.2 Human on Ground with Computer Assistance. [See Section 3.4.1 for a description of the capability code numbers.]

FIGURE 3.2: ARAMIS TECHNOLOGY TREE (NO. 3 of 8)

(TOPICS 13 AND 14)



4) Although a capability may have several strings of capabilities and technologies "available" to it in the Trees, not all of these are necessarily useful to the capability's R&D in a particular application. For example, some applications of Human on Ground with Computer Assistance would not benefit from earlier R&D of 13.2 Human Eyesight via Graphic Display, but might benefit from Human Eyesight via Video, available through 13.2. Therefore some engineering judgement is needed in evaluating the actual contributions of other capabilities or technologies. As another example, Human on Ground with Computer Assistance benefits from the software development behind 25.1 Onboard Dedicated Microprocessor, not from the development of the space-rated microprocessor itself.

5) In those cases where one of the "available" capabilities several levels up the Tree is particularly relevant, this is indicated by a dashed arrow. In the example, 14.7 Onsite Human with Computer Assitance benefits from 13.1 Human Eyesight via Video, through 14.2 and 13.2. However, 13.1 is considered to contribute significantly to the R&D of 14.7, and therefore a dashed arrow emphasizes the connection.

The study group found that the clearest separation of the 8 Technology Trees came from clustering ARAMIS topics into individual trees. In the example, topics 13 (Human-Machine Interfaces) and 14 (Human Augmentation and Tools) are closely interrelated, and are therefore displayed together in one Tree. In general, clustering by topics minimizes the numbers of interconnections between the Trees, simplifying the overall presentation.

In the ARAMIS Capability General Information Forms presented in Appendix 3.C, the lists of capabilities and technologies which enhance the Form's capability include only those capabilities directly connected to the capability in the Trees. In other words, only those capabilities which send solid or dashed arrows downward to the Form's capability in the figures, are listed in the General Information Forms.

The technology tree information developed by the study group contributes to the selection of promising applications of ARAMIS, as described in Section 4.7 (Volume 4).

The 8 Technology Trees are displayed in Appendix 3.D: Technology Trees.

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APPENDIX 3.A:

ARAMIS TOPICS AND THEIR DEFINITIONS

3.A.1 Notes on this Appendix

As described in Section 3.3.1, the study group organized the field of ARAMIS into 28 "topics". There is considerable overlap between topics. For clarity of presentation, these topics were grouped into 6 general "areas", again with considerable overlap between areas. Table 3.A.1 lists these areas and topics.

This appendix presents brief definitions of the 28 topics, including examples as needed. The listing of topics and definitions follows.

TABLE 3.A.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

ARAMIS TOPICS DEFINITIONS

MACHINERY

1) AUTOMATIC MACHINES

Definition: 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.

2) PROGRAMMABLE MACHINES

Definition: 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.

3) INTELLIGENT MACHINES

Definition: These are programmable 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 system which solves electical 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 exact same information about the particular problem as a nonintelligent one would use, but the information is explicitly labeled in the intelligent program. For example, an intelligent circuit-understander might have a datum saying "The voltage at point A is 5 volts", whereas a nonintelligent one would have a number 5 stored in a location which only the program's author knows represents the voltage at point A.

4) MANIPULATORS

Definition: Mechanical devices used for handling, alignment, and positioning tasks.

Manipulators include general-purpose and dedicated devices. Dedicated manipulators are used for a specific task. Examples include sensor-aiming devices and docking grapples. General-purpose manipulators are those intended for a wide range of uses.

5) SELF-REPLICATION

Definition: The ability of a system to produce functional duplicates of itself.

A lunar mining facility would have as a part of its output the products necessary to duplicate itself. Its manipulator systems could assemble duplicates and provide them with operating instructions.

6) RANGE AND RELATIVE MOTION SENSORS

Definition: Sensors that measure the distance to an object and its velocity and acceleration relative to the sensor.

Range sensors include radars, proximity detectors, sonars, and laser rangers.

7) DIRECTIONAL AND POINTING SENSORS

Definition: Sensors that determine the direction of an object in the sensor's reference frame.

These include star-trackers, horizon sensors, and radio direction finders.

8) TACTILE SENSORS

Definition: Sensors that respond to touch or physical contact.

These include "whiskers" and silicone rubber tactile sensors. The former sense contact at their tips. The latter operate on the principle that applied pressure increases contact area, decreasing the electrical resistance, and providing proportional sensing.

9) FORCE AND TORQUE SENSORS

Definition: These sensors measure forces and torques.

Force sensors include strain gages (used with material of known properties), conductive silicone rubber (see Tactile Sensors), and pressure sensors. Torque sensors may incorporate force sensors in the proper geometric relationship, or may sense torque directly.

10) IMAGING SENSORS

Definition: These sensors return a two-dimensional information pattern, forming an image.

Imaging sensors may be electromagnetic like television or radar, and may operate at many wavelengths. Other imaging sensors include tactile arrays which return an image of the pressure distribution in the sensor. Sonar is another imaging sensor.

11) MACHINE VISION TECHNIQUES

Definition: Techniques for the extraction of information from images.

This includes: shape analysis (determination of an object's dimensions and characteristics); depth perception (ability to determine distances perpendicular to the vision plane); lighting/shadow analysis (detection of reflections, illumination sources, and shadows in an image); motion sensing (detection and imaging of moving objects); pattern recognition (ability to correleate a given set of points with a previously defined configuration); image decomposition (the process of breaking down a large image); image representation (the identification and characterization of a pattern from a line arrangment); and labeling (assignment and association of an object to a given tag).

12) OTHER SENSORS

Definition: This is the miscellaneous category.

It includes thermal sensors, radiation sensors, chemical analysers, electric and magnetic field sensors, and acoustic detectors.

HUMAN-MACHINE

13) MAN-MACHINE INTERFACES

Definition: The system which converts information from a remote system to a form understandable by the human operator, and converts the operator's commands into information for the remote system's components or actuators.

This interface contains displays, operator controls, a communications subsytem, and control subsystem. Displays are the devices which convert information from the remote devices to a form the human operator can interpret. Operator controls are the devices which convert commands from the operator to information for transmission to the remote system. The communications subsystem transmits the command and sensory information between the remote system and the operator. The control subsystem coordinates all the sections. The control subsytem may be entirely within the operator (as in a master-slave manipulator system with force-feedback), or may involve additional hardware and software (e.g. a computer in the loop to compute manipulator joint positions, or to position sensors according to manipulator motions). If the computer takes over some operator functions and performs them under occasional human scrutiny, this is called supervisory control.

14) HUMAN AUGMENTATION AND TOOLS

Definition: Devices and techniques that assist and augment humans in the performance of a task.

Any method of extending human capabilities may be considered a tool or augmentation. These include passive tools like a screwdriver and active ones like a maneuvering unit. Teleoperation may also be considered as a tool, but is often thought of separately.

15) TELEOPERATION TECHNIQUES

Definition: These are the systems and techniques used to teleoperate a remote device. A teleoperator always has a human in the control loop, although the human need not have total control. The prefix "tele" describes the ability of this man-machine system to project man's senses and abilities across distances and through physical barriers.

These techniques determine the hierarchy of control in a teleoperated system. Supervisory control is one teleoperation technique; force-feedback is another.

16) COMPUTER-AIDED-DESIGN

Definition: 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.

DATA HANDLING

17) DATA TRANSMISSION TECHNOLOGY

Definition: The technology by which data is transmitted from one point to another.

This includes acoustic couplings, radio links, microwave beams, laser links, and fiber optic links.

18) DATA STORAGE AND RETRIEVAL

Definition: The hardware and software used for storage and retrieval of information in advanced data storage systems. This can include the modeling and usage of "common sense" (facts outside the subject domain).

Intelligent access to data bases is necessary to handle large amounts of information. Facts are derived from information, which in turn is composed of data. The deduction of requested facts is complicated by the human use of "common sense" in database requests. For example, a LANDSAT data retrieval system might be asked to find and retrieve images recorded at some given subject domain--say, Columbus, Ohio in August 1979. This request would be simple to meet, but inclusion of common knowledge in the request (i.e., omit images that show only cloud cover), may be beyond the capabilities of elementary database-retrieval systems.

19) DATA AND COMMAND CODING

Definition: The technique of encoding and decoding information for transmission or manipulation.

This includes data compression and encryption schemes, error checking and correcting codes, and data conversion from one form to another (such as analog to digital conversion).

20) DATA MANIPULATION

Definition: A process which operates on and alters a set of data.

This includes: data filtering and enhancement, to improve the accuracy of the input stream; preliminary operations on the input stream, such as classifying the input data into a spectrum; onboard evaluations such as comparision to a world model and identification of anomalous data. In general, these are operations to enhance or select information in the data. They may include large-scale computation, e.g. the numerical processing of a LANDSAT image.

COMPUTER INTELLIGENCE

21) SCHEDULING AND PLANNING

Definition: Scheduling and planning problems involve finding and specifying optimal or best case schedules (combinations).

Automated scheduling and planning systems find workable schedules while trying to avoid "combinatorial explosion" (i.e. attempting to minimize the increase in problem difficulty with growing problem size). An example of a scheduling combinatorial explosion could be satellite data access to ground receiving stations: given widely-varying orbital characteristics for each satellite, the regular scheduling of needed satellite access to ground stations may become difficult or impossible as the number of satellites using the stations increases.

22) AUTOMATIC PROGRAMMING

Definition: Takes a very "high level" (natural-like) description of a program's objectives and produces a program from it.

This category, related to problem solving and the proving of theorems, concerns the theory and design of "super compilers"; that is, programs which write programs to produce specified results.

23) EXPERT CONSULTING SYSTEMS

Definition: Systems that provide users with "expert" conclusions about specialized subject areas.

These systems operate on relational data bases, consisting of well-specified representations of information relevant to the problem and of "rules" describing relationships between pieces of the data base. 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 at Stanford AI) compare input symptoms to their relational data bases, and compute probabilities of various potential diagnosies. They can request specific information to improve their deductions. Such systems currently have diagnostic abilities equivalent to a first-year intern.

24) DEDUCTIVE TECHNIQUES (THEOREM PROVING)

Definition: 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.

25) COMPUTER ARCHITECTURE

Definition: The design of processor hierarchies and configurations, both in hardware and software.

An example of this is a control system with a central computer commanding several microprocessors, each of which controls some individual element or subsystem of the whole. Another example is parallel processors sharing a task and resources.

FAULT DETECTION & HANDLING

26) RELIABILITY AND FAULT TOLERANCE

Definition: The part of the design and operation of a system concerned with overall lifetime, failure rate, and resistance of the total system to failure once a component has failed.

High reliability is always desirable, but it must be traded-off against cost. Also, intelligent systems, which can self-repair or "vote" between redundant components, may permit use of cheaper, less reliable parts than non-intelligent systems. Fault tolerant systems may not require active (intelligent) response to a failure.

27) STATUS MONITORING AND FAILURE DIAGNOSIS

Definition: Monitoring system conditions and modeling system status to diagnose failures and detect potential failures.

For example, a spacecraft with a sudden power loss must determine the type and cause of the problem. It must first check that there was an actual power loss and not a sensor failure or software error. Then it must decide if it is a failed solar array, a short in a power bus, or a failed power conditioning unit.

28) RECONFIGURATION AND FAULT RECOVERY

Definition: Changing the system configuration to allow for maintenance or a change of operating modes, or to recover from hardware or software failures.

For example, a satellite with a failed attitude control system and a large pointing error would shut down all nonessential systems to conserve power. Then it would use the backup attitude control system to reorient the spacecraft. With the spacecraft's solar arrays once again receiving power, the spacecraft could reactivate the systems which were shut down and resume normal operations.

APPENDIX 3.B:
ARAMIS BIBLIOGRAPHY

3.B.1 Notes on this Appendix

This appendix presents some of the literature found useful by the study group. Other data sources appear in ARAMIS Capability General Information Forms (Appendix 3.C) and Application Forms (Appendix 4.E in Volume 4), and in references listed at the end of each volume of this report. Other useful sources of information are discussed in Section 3.3.2.

For ease of accession, this bibliography is presented in two major sections. The first section, called "ARAMIS Bibliography", is organized according to the 6 "areas" and 28 "topics" defined by the study group to classify the field of ARAMIS. These areas and topics are listed in Table 3.B.1. Because there are overlaps between topics, and because some sources deal with several topics, a number of listings appear several times, under different topics. The reader may also be referred to other related topics for data sources.

The second major section, called "Bibliography (organized by GFE type)", is organized according to the 9 types of GFE's defined in Section 4.4.1 (Volume 4):

A) Power Handling
B) Checkout
C) Mechanical Actuation
D) Data Handling and Communication
E) Monitoring and Control

TABLE 3.B.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

F) Computation
G) Decision and Planning
H) Fault Diagnosis and Handling
I) Sensing

Here also, there are overlaps between types of GFE's, and therefore some listings appear under several different headings. Some types of GFE's correspond closely to ARAMIS topics or areas (e.g. C. Mechanical Actuation with the area of Machinery), and the reader may then be referred to those areas and topics for data sources.

The two major sections of the bibliography, on Automation, Robotics, and Machine Intelligence Systems, follow.

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APPENDIX 3.C:
ARAMIS CAPABILITY GENERAL INFORMATION FORMS

3.C.1 Notes on this Appendix

This appendix presents 78 ARAMIS Capability General Information Forms, each of which describes one of the ARAMIS capabilities defined by the study group. Each General Information Form contains: the name of the capability; the capability's code number; the date on which the Form was filled out; the names of the researchers contributing to the Form; a definition of the capability; identification of individuals and organizations working on the concept; estimates of the dates on which the capability will reach various technology levels; remarks and (when available) data sources on the technology levels; estimates (when available) or R&D costs between technology levels; remarks and data sources on those cost estimates; remarks on any special aspects of the capability; identification of which other capabilities should be developed prior to this one, to enhance its R&D; and a list of the code numbers of the GFE's to which the capability applies.

As described in Section 3.4.1, the ARAMIS capabilities were grouped by topics and numbered accordingly. These assignments were necessarily arbitrary, since many capabilities could be associated with several topics. In each case, the study group selected the topic which described the technical challenge in the capability most accurately. For example, Dextrous Manipulator under Human Control was classified under topic 14: Teleoperation

Techniques; as the second capability listed under that topic, it received the number 14.2. One result of this procedure was that several ARAMIS topics (nos. 5, 9, 12, 20, and 28) do not have any capabilities listed under them; other topics were deemed more appropriate. For the convenience of the reader, the ARAMIS topics and their numbers are listed in Table 3.C.1.

The technology levels used in the Form are from the 7-level scale used by NASA OAST's Space Systems Technology Model. These levels are defined in Table 3.C.2. On this scale, a capability

TABLE 3.C.2: TECHNOLOGY READINESS LEVELS

(from the May 1980 NASA OAST Space Systems Technology Model)

Level 1	Basic Principles Observed and Reported
Level 2	Conceptual Design Formulated
Level 3	Conceptual Design Tested Analytically or Experimentally
Level 4	Critical Function/Characteristic Demonstration
Level 5	Component/Breadboard Tested in Relevant Environment
Level 6	Prototype/Engineering Model Tested in Relevant Environment
Level 7	Engineering Model Tested in Space

at level 6 or 7 is available to the spacecraft designer at the technology cutoff date. These levels are straightforward in their application to hardware development. In software development, however, levels 4 and 5 may be included in level 3; in many

TABLE 3.C.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

cases, the first analytical test of software design requires an all-up test of the software, equivalent to a "breadboard test in a relevant environment" for hardware. Thus, for a number of the software-intensive ARAMIS capabilities, several intermediate technology levels are reached concurrently. Similarly, it can be difficult to pinpoint R&D costs for such intermediate levels. The abbreviation "N/A" indicates either "not applicable" or "not available" in the Forms.

The 78 ARAMIS Capability General Information Forms follow, in the order of the capability code numbers. [Note: there are no capabilities 1.4 and 1.5 in the listing; although originally defined, they were later found unnecessary.]

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Stored Energy Deployment Device

CODE NUMBER: 1.1 DATE: 6/4/82 NAME(S): Thiel/Katz

DESCRIPTION OF CAPABILITY: A device that deploys or extends an object or array using energy stored in an elastic medium.

WHO IS WORKING ON IT AND WHERE: This type of device has been used by virtually all spacecraft manufacturers. Various studies can be found under the heading of large space structures, but much of this work uses motors rather than energy storage devices.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: NOW LEVEL5: NOW LEVEL6: NOW LEVEL7: NOW

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: None

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: Although the technology is developed, individual units are still expensive beause each one is unique to each particular spacecraft design.

REMARKS ON SPECIAL ASPECTS: Limited to reasonably small arrays due to mechanical limitations. Has limited growth potential beyond present uses (Harold Bush, LaRC).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Shape Memory Alloys

CODE NUMBER: 1.2 DATE: 6/29/82 NAME(S): Kurtzman/Katz

DESCRIPTION OF CAPABILITY: Metals that can be plastically deformed at one temperature and completely recover their original shape upon being raised above a certain higher temperature are used to make spacecraft antennae which can be reduced (compacted) to a small volume and then expanded to their desired shape upon heating.

WHO IS WORKING ON IT AND WHERE: David Goldstein, U.S. Navy Surface Weapons Laboratory; Martin Marietta (Denver); Goodyear Aerospace; Aerojet General; G. B. Brook, Fulmer Research Institute Ltd. (Stokes-Poge, England); D. G. Powley, British Aircraft Corporation Ltd.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: N/A LEVEL6: See below LEVEL7: See below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The Goodyear Aerospace Corporation has built a demonstration antenna to illustrate the function of the shape memory material (See L. McDonald Schetky, "Shape-Memory Alloys," Scientific American, Volume 241, Number 5, November 1979). It would probably take 6 months to design and test a small antenna, and 2 years to expand the methodology to large antennas (L. McDonald Schetky, Technical Director, Metallurgy, International Cooper Research Association, Inc., 708 Third Avenue, New York, New York 10017 (212) 697-9355).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: Not available 6-7: Not available

REMARKS AND DATA SOURCES ON COST ESTIMATES: None.

REMARKS ON SPECIAL ASPECTS: Shape-memory alloys have also been used to make a latching device which rapidly and reliably triggers the release of spacecraft instrument booms. In this capacity, the shape memory alloy functions as part of an Onboard Deployment/Retraction Actuator, and hence is not part of this capability. See "The Design and Testing of a Memory Metal Actuated Boom Release Mechanism" by D.G. Powley and G.B. Brook.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None.

CAPABILITY APPLIES TO (GFE NUMBERS): g27

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Inflatable Structure

CODE NUMBER: 1.3 DATE: 6/24/82 NAME(S): Marra

DESCRIPTION OF CAPABILITY: Balloon-like structures are inflated with gas. The object to be deployed may be attached to the inflatable structure or be inflatable itself.

WHO IS WORKING ON IT AND WHERE: See below

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: see below LEVEL6: see below LEVEL7: see below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: All the necessary technology is currently avaiable. No one is currently trying to develop such a system. If work should begin, it would not take long for the system to be developed. Work would be done using space-rated equipment. (Vought Corporation Systems Division; George Sarver, M.I.T., Space Systems Laboratory)

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: see below 6-7: see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Cost estimates were not available to the study group. Costs are dependent on the nature of the application.

REMARKS ON SPECIAL ASPECTS: In order to make large inflatable structures feasible a system must be developed to keep then in constant repair. One proposition is the development of free flying robots inside the inflatable structure. Such robots would have the capability of detecting and repairing leaks by themselves. Such robots would not be very hard to develop (George Sarver, M.I.T. Space Systems Lab).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Space-Rated Polymers

CAPABILITY APPLIES TO (GFE NUMBERS): g27

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Automatic Switching Systems

CODE NUMBER: 1.6 DATE: 6/15/82 NAME(S): Thiel/Marra

DESCRIPTION OF CAPABILITY: Automatic switching systems are devices which are capable of decision making and control operations, but only on a limited scale. They may be as simple as a thermostat or as complicated as an attitude control system. The difference between a very complicated Automatic Switching System and a computer is the ability of the computer to be reprogrammed. The Automatic Switching Sytem is a hardwired device and its programming cannot be changed.

WHO IS WORKING ON IT AND WHERE: Any spacecraft manufacturer uses several devices of this kind on virtually every spacecraft so any spacecraft company maintains the capability to produce Automatic Switching Systems of various levels of complexity.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: NOW LEVEL5: NOW LEVEL6: NOW LEVEL7: NOW

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: These devices are a well developed technology. Future technology advances will make more sophisticated Automatic Switching Systems possible, but they will probably be made obsolescent by computers.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: The technology for these systems is available as off-the-shelf hardware, but it usually has to be custom made for each spacecraft type.

REMARKS ON SPECIAL ASPECTS: Limited capability due to limits imposed by hardwired devices and lack of reprogrammability.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None

CAPABILITY APPLIES TO (GFE NUMBERS): g83, g87, g150, g239, g240, g241

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Onboard Deployment/Retraction Actuator

CODE NUMBER: 2.1 DATE: 6/21/82 NAME(S): Marra/Paige

DESCRIPTION OF CAPABILITY: Dedicated mechanical system which is directly attached to the deployable member. The Actuator can deploy and retract the member many times throughout the mission. Examples of such actuators include extendable booms and motor driven winches.

WHO IS WORKING ON IT AND WHERE: William B. Palmer, TRW Defense and Space Group; Charles R. Griffin, Goddard Space Flight Center; Robert L. James Jr, Langley Research Center.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: William B. Palmer (TRW); Charles R. Griffin (NASA, GSFC).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: The Onboard Deployment/Retraction Actuator is a dedicated device. That is, for whatever application the actuator is designed, it will only be able to be used for one particular task. One exception is the possibility for actuators to be used for both as a deployment device and an attitude control device (e.g. to deploy and point solar arrays).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 1.6 Automatic Switching Systems

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g67, g148, g177

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Dedicated Manipulator under Computer Control

CODE NUMBER: 2.2 DATE: 7/12/82 NAME(S): Dalley/Ferreira

DESCRIPTION OF CAPABILITY: Manipulator which performs a pre-assigned task, using a specific end effector within a specific worksite geometry, making use of force and proximity sensing, under computer control.

WHO IS WORKING ON IT AND WHERE: John Birk, U. of Rhode Island; Sinclaire Scala, GE Re-entry and Environmental Systems; JPL; IRI, Carlsbad CO; Tom Williams, DEC; Unimation; General Motors Research Lab; Automatix, Burlington, MA; Neville Hogan, MIT Mech. Eng.; Ken Fernandez, NASA MSFC.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: 1984 LEVEL7: 1986

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Current tevel from general literature. Estimate to level 6 from study group's background research. Robert F. Goeke of MIT Center for Space Research estimated 2 years to space-rate such a manipulator.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: see below 6-7: see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Ken Fernandez stated that a dedicated manipulator had been built by Martin Marietta under a contract from MSFC for $50,000, which was now at Tech. level 6 and could be ready for use in space in two years. This manipulator lacks feedback, however.

REMARKS ON SPECIAL ASPECTS: A dedicated manipulator is designed for one purpose, and for one purpose only. If the need should arise to perform a different task, a new manipulator must be designed.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 2.1 Onboard Deployment/ Retraction Actuator; 25.1 Onboard Dedicated Microprocessor.

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g67, g73, g134, g148, g177

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Automated Docking Mechanism

CODE NUMBER: 3.1 DATE: 5/28/82 NAME(S): Glass/Ferreira/Spofford

DESCRIPTION OF CAPABILITY: System for docking two spacecraft under preprogrammed control, including activation of docking motors and latches.

WHO IS WORKING ON IT AND WHERE: The Soviet Space Program; NASA MSFC (mostly on teleoperated docking).

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Aviation Week and Space Technology (for Soviet docking systems).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: None.

REMARKS ON SPECIAL ASPECTS: While this capability has been demonstrated already, development is necessary to adapt it for use with current U.S. hardware.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 6.1 Optical Scanner (Passive Cooperative Target); 6.3 Radar (Passive Target); 6.5 Onboard Navigation And Telemetry; 15.4 Teleoperated Docking Mechanism; 25.3 Onboard Deterministic Computer Program.

CAPABILITY APPLIES TO (GFE NUMBERS): g146

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Computer-Controlled Specialized Compliant Manipulator

CODE NUMBER: 4.1 DATE: 6/22/82 NAME(S): Ferreira/Dalley/Marra

DESCRIPTION OF CAPABILITY: A Computer-Controlled Specialized Compliant Manipulator is a manipulator with a compliant wrist capable of molding itself to small amounts of error. It has no active feedback and relies only on an accurate dead reckoning model stored in its computer. The manipulator is also capable of changing its own end effector, and is able to execute several tasks without outside interaction.

WHO IS WORKING ON IT AND WHERE: Dan Whitney, Automation Research, Draper Laboratory, Cambridge, Massachuesetts

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: 1983 LEVEL7: 1985

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Levels 1-6 Whitney (Draper Labs), Level 7 Robert F. Goeke estimates two years to space rate such a system.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: see below 6-7: see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Whitney estimates 10-20 million dollars to bring this system up to level 7 .

REMARKS ON SPECIAL ASPECTS: The difference between a Computer-Controlled Specialized Compliant Manipulator and a Dedicated Manipulator under Computer Control, aside from the compliance, is that a dedicated manipulator can only do one task, while a specialized manipulator is only limited by the number of end effectors it has.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 7.1 Dead Reckoning from Stored Model; 15.1 Specialized Manipulator under Human Control; 25.2 Onboard Microprocessor Hierarchy

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g73, g134, g148, g177

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Computer-Controlled Dextrous Manipulator with Force Feedback

CODE NUMBER: 4.2 DATE: 6/28/82 NAME(S): Kurtzman/Paige/Ferreira

DESCRIPTION OF CAPABILITY: A multipurpose multifingered manipulator, under computer control, and capable of operating under various geometries. The system would be reprogrammable and would use input from force-feedback sensors for final guidance and motion control.

WHO IS WORKING ON IT AND WHERE: Ewald Heer and Antal Bejczy (JPL); Marvin Minsky (MIT AI Lab); Dan Whitney (Draper Labs); Victor Sheinman (Automatix, Burlington, MA); Tom Williams (DEC, Maynard, MA).

TECHNOLOGY LEVELS:	LEVEL1:	Now	LEVEL2:	Now	LEVEL3:	Now
LEVEL4:	Now	LEVEL5:	1986	LEVEL6:	1986	LEVEL7:	1989

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Present and future levels were provided by Marvin Minsky. The intermediate levels were computed by interpolation based on the background of the study group.

R&D COST ESTIMATES BETWEEN LEVELS;	1-2:	N/A		2-3:	N/A		
3-4:	N/A	4-5:	$10-20 Million	5-6:	N/A	6-7:	$2.5 Million

REMARKS AND DATA SOURCES ON COST ESTIMATES: Dan Whitney suggested a figure of $10-20 million to develop the whole system to level 6. Cost to go from level 6 to level 7 was estimated at $2.5 million by extrapolating from a figure of $1 million to space rate a dedicated manipulator under computer control (Robert F. Goeke, MIT Center for Space Research).

REMARKS ON SPECIAL ASPECTS: None

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 4.1 Computer-Controlled Specialized Compliant Manipulator; 15.2 Dextrous Manipulator under Human Control; 19.1 A/D Converter.

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g67, g73, g134, g148, g177.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Computer-Controlled Dextrous Manipulator With Vision and Force Feedback

CODE NUMBER: 4.3 DATE: 6/29/82 NAME(S): Kurtzman/Paige

DESCRIPTION OF CAPABILITY: A multipurpose maneuvering arm with a multifingered hand combined with force-feedback sensors and an imaging camera system, under computer control, and capable of performing autonomous manipulative operations. This capability approaches artificial intelligence in its control system.

WHO IS WORKING ON IT AND WHERE: Little work has been done which combines both force-feedback and vision systems. Vision and/or manipulator researchers include: Hans Moravec, Carnegie-Mellon University, Schenly Park, Pittsburgh, Pennsylvania 15213, (412) 578-3829; Carl Ruoff, Group Supervisor, Jet Propulsion Laboratory, 4800 Oak Grove, Pasadena, California 91103, (213) 354-6101; Gerald Gleason and Gerald Agin (SRI); R. Brooks and Tom Binford, Stanford University Robotics Laboratory, Stanford, California; Frank Glaser (U. of Mass.); James Albus, Director of Robotics Research, National Bureau of Standards, Gaithersburg, Maryland.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: 1985
LEVEL4: 1986 LEVEL5: 1990 LEVEL6: 1994 LEVEL7: 1997

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Marvin Minsky (MIT AI Lab) - Level 7 could be reached in 15 years but a concentrated effort might reduce this to 10 years. Tom Williams (DEC) estimated level 7 in year 2000. The other levels were estimated by interpolation and the study group's own background).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: see below 5-6: see below 6-7: see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Cost estimates are not available for the individual levels, but combining an estimate from Ruoff of $20 million for a vision system and and estimate from Daniel Whitney (Draper Labs) of $10-20 million for computer-controlled dextrous manipulator gives and estimate of $30-40 million. If a great deal of autonomous intelligent behavior is expected, this figure could be larger.

REMARKS ON SPECIAL ASPECTS: NASA needs inhouse expertise in order to intelligently oversee development of this capability (Carl Ruoff - JPL).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 4.2 Computer-Controlled Dextrous Manipulator with Force Feedback; 11.2 Imaging (Non-Stereo) with Machine Processing.

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g67, g73, g134, g148, g177.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Optical Scanner (Passive Cooperative Target)

CODE NUMBER: 6.1 DATE: 7/5/82 NAME(S): Thiel/Katz

DESCRIPTION OF CAPABILITY: This system uses a laser to determine position and velocity information for a passive cooperative target. This target does not actively respond to the laser radiation, but has corner cubes (retroreflectors) at strategic locations to reflect laser radiation to a detector near the laser source.

WHO IS WORKING ON IT AND WHERE: GTE Sylvania PATS (Precision Automated Tracking System) being developed for the military. ITT, RCA and Lockheed have worked on similar devices. Lockheed presently has a device being developed for JPL which is specifically designed for space use.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: NOW LEVEL5: NOW LEVEL6: 1984 LEVEL7: 1986

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Glenn Overstreet of GTE Marketing estimates 4 years to modify PATS for short-range work and to space rate the system. The Lockheed system could probably be ready in two years since prototype versions for ground test already exist.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: 8.5 Million 6-7: 1.5 Million

REMARKS AND DATA SOURCES ON COST ESTIMATES: Jimmy Lamb at GTE estimates that 10 Million would be necessary to modify PATS and to space rate the system. Lockheed estimates that it can finish development for 1.5 Million and sell the units for 0.5 Million.

REMARKS ON SPECIAL ASPECTS: The laser device has important growth potential. First, it could be modified to read identification codes similar to the laser scanners currently in use at many grocery stores. This would allow easy identification of components on a spacecraft. Second, it could be made to work in parallel with a machine vision system and greatly reduce the information processing requirements by eliminating the need for the vision system to "recognize" spacecraft components.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 16.1 Computer Modeling and Simulation; 25.1 Onboard Dedicated Microprocessor; Laser Technology.

CAPABILITY APPLIES TO (GFE NUMBERS): g33, g49, g69, g132, g243, g245

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Proximity Sensors

CODE NUMBER: 6.2 DATE: 6/29/82 NAME(S): Katz/Kurtzman

DESCRIPTION OF CAPABILITY: Short range photo-electric sensor able to determine if it is within or beyond a designated range of a target.

WHO IS WORKING ON IT AND WHERE: James S. Albus, National Bureau of Standards (NBS); Dr. Antal K. Bejczy and Alan R. Johnston, Jet Propulsion Laboratory, 4800 Oak Grove, Pasadena, California 91103.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: See below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The present NBS system is currently at level 6 (See James S. Albus, "Proximity-Vision System For Protoflight Manipulator Arm," National Bureau of Standards, 1979, NBSIR 78-1576). To progress to level 7 requires adaptation for automation and space rating, which the study team estimates would take approximately 3 years.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Study team estimate: approximately $2 million.

REMARKS ON SPECIAL ASPECTS: Proximity sensors will usually be used in conjunction with other (e.g. imaging) sensors if they are to be used in performing the applicable functional element (See NBSIR 78-1576).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 25.1 Onboard Dedicated Microprocessor.

CAPABILITY APPLIES TO (GFE NUMBERS): g69

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Radar (Passive Target)

CODE NUMBER: 6.3 DATE: 3/19/82 NAME(S): Jones-Oliveira/Katz/Ferreira

DESCRIPTION OF CAPABILITY: Millimeter wave radars and data processors are used in finding, identifying and locating noncooperative targets. Use of radar in "near fields," i.e., in ranges within 200 meters, is limited by the angular resolution required to perform the given task. This is more difficult for smaller objects.

WHO IS WORKING ON IT AND WHERE: Defense Advanced Research Projects Agency (Project Assault Breaker); US Air Force (WASP - Wide Area Sensing Projectile); Sperry; Raytheon; Bendix; Hughes; and Honeywell (Defense Systems Division, Minneapolis).

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: 1983 LEVEL6: 1986 LEVEL7: 1987

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Aviation and Space Technology 1/29/79, 9/24/79, 3/9/81; Bendix Corp. - Marketing; Raytheon - Theodore Hudson. The levels were assigned relative to the engineering estimates projected for Radar (Active Target).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: See below 6-7: See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: R&D cost estimates are difficult to acquire due to high security maintained on this military-related research. It is agreed that this capability can be developed based upon already established technology; however, because this capability is more difficult to produce than its Active Target counterpart, R&D costs will be higher.

REMARKS ON SPECIAL ASPECTS: For some applications, this capability is more difficult to develop than Radar (Active Target); this is because the signals generated have twice the distance to travel and must therefore be stronger. This, in turn, will require more powerful and sensitive equipment.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 6.4 Radar (Active Target)

CAPABILITY APPLIES TO (GFE NUMBERS): g132, g243, g245

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Radar (Active Target)

CODE NUMBER: 6.4 DATE: 3/19/82 NAME(S): Jones-Oliveira/Katz

DESCRIPTION OF CAPABILITY: Radar is an electronic device for the detection and location of objects. The active (cooperative) aspect presupposes that the target is capable of emitting and/or amplifying a signal, thereby affording the tracker with a stronger signal to lock onto. Use of radar in "near fields," i.e., in ranges within 200 meters, is limited by the angular resolution required to perform the given task. This is more difficult for smaller objects.

WHO IS WORKING ON IT AND WHERE: Raytheon, in Wayland, MA; Bendix, in Detroit; Hughes, in Fullerton, CA; and Honeywell, in Minnetonka, Min.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: 1982 LEVEL7: 1985

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Prof. J. Francis Reintjes (MIT/EE&CS); Bendix Corp. - Norman Anschuestz; Raytheon - Theodore Hudson.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: See below 6-7: See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Hudson (Raytheon) - To bring current prototypes to an unmanned space rating, 3 years of RDT&E are necessary, i.e., approximately 60 man-years.

REMARKS ON SPECIAL ASPECTS: Reintjes (MIT/EE&CS) - Technologies developed by the FAA for air-to-air collision avoidance may be directly applicable. This technology is easier to develop than Radar (Passive Target).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 25.1 Onboard Dedicated Microprocessor

CAPABILITY APPLIES TO (GFE NUMBERS): g132, g243, g245

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Onboard Navigation and Telemetry

CODE NUMBER: 6.5 DATE: 7/9/82 NAME(S): Kurtzman/Thiel

DESCRIPTION OF CAPABILITY: Orbital position and velocity will be determined with the use of the NAVSTAR Global Positioning System (GPS). GPS is a passive all-weather navigation satellite system proposed for operation after 1985. The system uses highly accurate atomic frequency standards to enable determination of three-dimensional position, velocity, and time instantaneously on a continuous world-wide basis. Range and range-rate measurements will be reduced to determine those parameters. A total of twenty-four satellites with twelve hour orbits (altitude 20,183 km) in three orbit planes will be available for navigation, giving accuracies and availability far exceeding the current Navy Navigation Satellite System or Transit System which GPS is designed to replace for navigation. Signals are transmitted at two L-band frequencies (1227 and 1575 MHz). With the number of satellites in view always exceeding the required number for navigation, the user may select a subset of four based on some criterion which optimizes the geometric strength of the navigation solution. Navigation fixes can be made in time intervals of from tens of seconds to several minutes. See Patrick J. Fell, "Geodetic Positioning Using a Global Positioning System of Satellites," NASA-CR-163609, June, 1980.

This capability also includes processing on-board the spacecraft and telemetry between spacecraft, so that the relative positions of spacecraft can be determined from the GPS data. This information is used either for final approach before docking, or for avoidance of potential collisions.

WHO IS WORKING ON IT AND WHERE: Applications to satellite navigation: A. J. Fuchs, NASA Goddard Space Flight Center; Joan B. Dunham, Computer Sciences Corporation, El Segundo and Sunnyvale, California. NAVSTAR receiver production: Stanford Telecommunications; Texas Instruments; Magnavox; Rockwell International, Collins Division.

TECHNOLOGY LEVELS:	LEVEL1:	Now	LEVEL2:	Now	LEVEL3:	Now	
LEVEL4:	Now	LEVEL5:	Now	LEVEL6:	Now	LEVEL7:	1985

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The GPS system is organized into three phases of operation; Phase I is concept validation, Phase II is system validation, and Phase III consists of production and validation. GPS is currently at the Phase II stage, and Phase III is scheduled to begin in 1985 (ibid.).

R&D COST ESTIMATES BETWEEN LEVELS;	1-2:	N/A	2-3:	N/A			
3-4:	N/A	4-5:	N/A	5-6:	N/A	6-7:	Not available

REMARKS AND DATA SOURCES ON COST ESTIMATES: None.

REMARKS ON SPECIAL ASPECTS: The NAVSTAR system will be useful in collision-avoidance systems, navigation, survey and mapping, aircraft rendezvous, aircraft landing, and many other applications. The system will give absolute position accuracy to within 10 meters rms. Relative position error between two receivers, as would be employed for collision-avoidance, should be as small as two meters. For a good nontechnical overview of NAVSTAR system operation and construction, see Tom Logsdon, "Satellites Bring New Precision To Navigation," High Technology, July/August 1982, Volume 2, Number 4, pp. 61-66.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Global Positioning System; Communications Techniques.

CAPABILITY APPLIES TO (GFE NUMBERS): g243.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Dead Reckoning From Stored Model

CODE NUMBER: 7.1 DATE: JUNE 26, 1982 NAME(S): Glass/Marra

DESCRIPTION OF CAPABILITY: Given desired location coordinates in a known working area, this capability finds a possible path to the location. Maneuvers are calculated to avoid known hazards (barriers, sun exposure, etc.) by referring to desired points' locations in a previously stored computer model of the working area.

WHO IS WORKING ON IT AND WHERE: General Motors; Japanese robotics companies (most current industrial robots use this kind of guidance system, on a very basic level)

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: N/A

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: None.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 16.1 Computer Modeling and Simulation; 25.3 Onboard Deterministic Computer Program

CAPABILITY APPLIES TO (GFE NUMBERS): g69

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Tactile Sensors

CODE NUMBER: 8.1 DATE: 6/24/82 NAME(S): Ferreira/Paige/Spofford

DESCRIPTION OF CAPABILITY: A sensor capable of sensing pressure distribution in a matrix. The sensor consists of a conductive rubber grid pattern, with contact resistance proportional to pressure. The resistance at each grid intersection gives information about the pressure applied at that point. Resolutions of 0.6 mm have been demonstrated in a 16 by 16 array. The data may be displayed graphically on a video screen, used to actuate piezo-electric actuators (for telepresence), or may be machine-processed.

WHO IS WORKING ON IT AND WHERE: D. Hillis and J. Purbrick at the M.I.T. Artificial Intelligence Laboratory; M. Raibert and R. Eskenazi at JPL.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: 1983 LEVEL6: 1984 LEVEL7: 1984

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Patent application from M. Raibert and R. Eskenazi (NASA contract NAS7-100).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: Estimates are not yet avaiable.

REMARKS ON SPECIAL ASPECTS: None.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 25.1 Onboard Dedicated Microprocessor.

CAPABILITY APPLIES TO (GFE NUMBERS): g69

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Thermal Imaging Sensor With Human Processing

CODE NUMBER: 10.1 DATE: 7/12/82 NAME(S): Kurtzman

DESCRIPTION OF CAPABILITY: Use of thermal infrared imaging sensors (thermography) to obtain a thermal profile of a structure in order to evaluate the object's thermal behavior. The sensor output is given to a human via a graphic display to show the object's temperature characteristics, usually in a color-coded form. The human then evaluates and monitors the object's thermal profile and makes any necessary actions based upon those observations.

WHO IS WORKING ON IT AND WHERE: Flir Systems, Inc., Oswego, Oregon; Texas Instruments; Martin Marietta Corporation, Denver.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: See below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: It would take an estimated two years to space-rate a thermal imaging system.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Study team estimate: $3 million.

REMARKS ON SPECIAL ASPECTS: Flir Systems has developed a system where a scanner signal is processed and supplied to a standard television monitor in an aircraft cockpit where a real-time black-and-white, 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, structural surveys, pipeline patrol and many agricultural uses. See William B. Scott, "Civil Thermal Imaging System Developed," Aviation Week & Space Technology, March 29, 1982, Volume 116, Number 13, p. 52-53. NASA has conducted thermal imaging tests to study the space shuttle upon reentry, and a temperature profile accurate to within 10-20K has been obtained. See Richard G. O'Lone, "NASA Studying Data On Reentry Heating Of Columbia," Aviation Week & Space Technology, April 12, 1982, Volume 116, Number 15, p. 68-71. Thermal imaging may also be used to evaluate structural characteristics such as stress contours and crack development. See D. S. Mountain, J. M. B. Webber, "Stess Pattern Analysis by Thermal Emmission (SPATE)," in Fourth European Electro-Optics Conference, October 1978, Utrecht, Netherlands, SPIE Volume 164.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 13.2 Human Eyesight via Graphic Display; 19.1 A/D Converter; Communications Techniques.

CAPABILITY APPLIES TO (GFE NUMBERS): g48.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Imaging (Stereo) With Machine Processing

CODE NUMBER: 11.1 DATE: 6/29/82 NAME(S): Kurtzman/Glass

DESCRIPTION OF CAPABILITY: To recognize and track known objects, in the space environment, via an imaging camera-computer system, by means of triangulation between two or more views from different perspectives to give three dimensional imaging information. Stereo imaging can be achieved through the use of several configurations, including: 1) two or more cameras; 2) one camera on a movable arm; or 3) one camera with an attached mirror arrangement.

WHO IS WORKING ON IT AND WHERE: Carl Ruoff, Group Supervisor, Jet Propulsion Laboratory, 4800 Oak Grove, Pasadena, California 91103, (213) 354-6101; Hans Moravec, Carnegie-Mellon University, Schenly Park, Pittsburgh, Pennsylvania 15213, (412) 578-3829; Clifford Geschke, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign; R. Brooks and T. Binford, Stanford University Robotics Laboratory, Stanford, California; Gerald Gleason and Gerald Agin (SRI); Berthold K. P. Horn, Artificial Intelligence Laboratory, Massachusetts Institute of Technology.

TECHNOLOGY LEVELS:	LEVEL1:	Now	LEVEL2:	Now	LEVEL3:	Now
LEVEL4:	Now	LEVEL5:	1985	LEVEL6:	1987	LEVEL7:	1990

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Ruoff - The processing of stereo images is computationally harder than non-stereo, but requires less "smart" software. It should therefore take an approximately equivalent effort. Technology currently under development can track simple objects at 1-2 Hertz.

R&D COST ESTIMATES BETWEEN LEVELS;	1-2:	N/A		2-3:	N/A
3-4:	N/A	4-5:	see below	5-6:	see below	6-7:	see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Ruoff - From present to Level 7 should cost $10-20 million for a specific effort.

REMARKS ON SPECIAL ASPECTS: In many of its applications a vision system will be part of a larger system, such as a manipulator, which can alter the environment which it senses. Ruoff - It should be possible to develop a robust stereo system as the computational problems are well defined. Ruoff believes that this option will be the capability ultimately used in many of its applications. Technology will probably proceed to level 6 without a specific NASA effort, but it will take several years longer. A vision system, by virtue of its resolution and recognition capabilities, will have many other uses which a radar or optical scanner system will not have. NASA must obtain in-house expertise in order to intelligently select and oversee the development of a vision system.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 11.2 Imaging (Non-Stereo) with Machine Processing.

CAPABILITY APPLIES TO (GFE NUMBERS): g33, g49, g69, g132, g243, g245.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Imaging (Non-Stereo) With Machine Processing

CODE NUMBER: 11.2 DATE: 6/29/82 NAME(S): Kurtzman/Glass

DESCRIPTION OF CAPABILITY: To recognize and track known objects, in the space environment, via an imaging camera-computer system, by means of computer interpretation of one camera (monocular) imaging information.

WHO IS WORKING ON IT AND WHERE: Carl Ruoff, Group Supervisor, Jet Propulsion Laboratory, 4800 Oak Grove, Pasadena, California 91103, (213) 354-6101; Hans Moravec, Carnegie-Mellon University, Schenly Park, Pittsburgh, Pennsylvania 15213, (412) 578-3829; Clifford Geschke, Coordinated Science Laboratory, University of Illinois at Urbana-Champaign; R. Brooks and T. Binford, Stanford University Robotics Laboratory, Stanford, California; Gerald Gleason and Gerald Agin (SRI); Berthold K. P. Horn, Artificial Intelligence Laboratory, Massachusetts Institute of Technology.

TECHNOLOGY LEVELS:	LEVEL1:	Now	LEVEL2:	Now	LEVEL3:	Now
LEVEL4:	Now	LEVEL5:	1985	LEVEL6:	1987	LEVEL7:	1990

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Ruoff - The processing of non-stereo images is computationally easier than stereo, but requires a "smarter" recognition system. It should therefore take an approximately equivalent effort.

R&D COST ESTIMATES BETWEEN LEVELS;	1-2:	N/A	2-3:	N/A
3-4:	N/A	4-5:	see below	5-6:	see below	6-7:	see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Ruoff - From present to Level 7 should cost $10-20 million for a specific effort.

REMARKS ON SPECIAL ASPECTS: In many of its applications a vision system will be part of a larger system, such as a manipulator, which can alter the environment which it senses. Ruoff - It is possible that a cooperative (labeled) target will be necessary to achieve this capablity in some of its applications by 1990 without stereo. Technology will probably proceed to level 6 without a specific NASA effort, but it will take several years longer. A vision system, by virtue of its resolution and recognition capabilities, will have many other uses which a radar or optical scanner system will not have. NASA must obtain in-house expertise in order to intelligently select and oversee the development of a vision system.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 19.1 A/D Converter; 25.2 Onboard Microprocessor Hierarchy; Computer Memory Development.

CAPABILITY APPLIES TO (GFE NUMBERS): g33, g49, g69, g132, g243, g245.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Thermal Imaging Sensor With Machine Processing

CODE NUMBER: 11.3 DATE: 7/12/82 NAME(S): Kurtzman

DESCRIPTION OF CAPABILITY: Use of thermal infrared imaging sensors (thermography) to obtain a thermal profile of a structure in order to evaluate the object's thermal behavior. The sensor output is then processed by a computer which evaluates and monitors the objects thermal characteristics and makes any necessary actions based upon those observations.

WHO IS WORKING ON IT AND WHERE: Flir Systems, Inc., Oswego, Oregon; Texas Instruments; Martin Marietta Corporation, Denver.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: 1984 LEVEL6: 1986 LEVEL7: 1988

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The thermal imaging sensor is currently at level 6, but no effort has yet been made to apply machine vision techniques to thermal data for evaluation.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: See below 5-6: See below 6-7: See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Study team estimate: $10-20 million to level 7.

REMARKS ON SPECIAL ASPECTS: Flir Systems has developed a system where a scanner signal is processed and supplied to a standard television monitor in an aircraft cockpit where a real-time black-and-white, 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, structural surveys, pipeline patrol and many agricultural uses. See William B. Scott, "Civil Thermal Imaging System Developed," Aviation Week & Space Technology, March 29, 1982, Volume 116, Number 13, p. 52-53. NASA has conducted thermal imaging tests to study the space shuttle upon reentry, and a temperature profile accurate to within 10-20K has been obtained. See Richard G. O'Lone, "NASA Studying Data On Reentry Heating Of Columbia," Aviation Week & Space Technology, April 12, 1982, Volume 116, Number 15, p. 68-71. Thermal imaging may also be used to evaluate structural characteristics such as stress contours and crack development. See D. S. Mountain, J. M. B. Webber, "Stess Pattern Analysis by Thermal Emmission (SPATE)," in Fourth European Electro-Optics Conference, October 1978, Utrecht, Netherlands, SPIE Volume 164.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 10.1 Thermal Imaging Sensor With Human Processing; 11.2 Imaging (Non-Stereo) with Machine Processing.

CAPABILITY APPLIES TO (GFE NUMBERS): g48.

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ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Human Eyesight Via Video

CODE NUMBER: 13.1 DATE: 5/5/82 NAME(S): Glass/Spofford

DESCRIPTION OF CAPABILITY: A human operator looks at the image from remote camera(s) on a video screen. The work scene is illuminated by spotlights.

WHO IS WORKING ON IT AND WHERE: Thomas Sheridan, MIT Mechanical Engineering; Thomas Binford, Stanford; Ewald Heer's group at JPL; Essex Corp., Huntsville.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: J.R. Tevel & R.A. Spencer, AIAA paper 78-1665; Essex EOTS reports.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6 N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: None.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 14.1 Direct Human Eyesight.

CAPABILITY APPLIES TO (GFE NUMBERS): g33, g49, g69, g132, g243, g245

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Human Eyesight Via Graphics Display

CODE NUMBER: 13.2 DATE: June 1982 NAME(S): Howard/Marra

DESCRIPTION OF CAPABILITY: Observation of environment by human using a graphic display. This includes the display hardware as well as software, which isolates and presents the relevant information in an effective manner. Data from a variety of sensors may be combined and analyzed in this process.

WHO IS WORKING ON IT AND WHERE: A. Bejczy, G. Paine at JPL; Warren A Manison, MITRE Corp., McLean, Virginia

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Examples are the CRT displays in modern fighter aircraft, and the shuttle cockpit displays.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: One useful feature not yet fully exploited is the potential of reducing the data rate required for image transmission by extracting the relevant geometric features from a scene and presenting them graphically, rather than the whole video image.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 13.1 Human Eyesight Via Video; 25.1 Onboard Dedicated Microprocessor

CAPABILITY APPLIES TO (GFE NUMBERS): g69, g109, g132, g221, g224, g243, g245

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Docking Under Onsite Human Control

CODE NUMBER: 13.3 DATE: June 1982 NAME(S): Howard/Glass

DESCRIPTION OF CAPABILITY: Final approach, docking motors, and latches are activated and controlled by an onsite human operator.

WHO IS WORKING ON IT AND WHERE: Various NASA Centers (e.g. JSC, MSFC).

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: TRW Space Platform and Materials Experiment Carrier studies.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: This capability usually requires the astronaut to be able to view the docking operation either through a window or via video.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 6.2 Proximity Sensors; 13.2 Human Eyesight via Graphic Display; 13.5 Computer-Generated Audio; 13.6 Stereoptic Video; 13.7 3-D Display; 14.8 Onsite Human Judgment

CAPABILITY APPLIES TO (GFE NUMBERS): g146

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Computer Printout

CODE NUMBER: 13.4 DATE: 6/29/82 NAME(S): Kurtzman/Thiel

DESCRIPTION OF CAPABILITY: The output of data on paper, from a computer system.

WHO IS WORKING ON IT AND WHERE: IBM, as well numerous other manufacturers of computer peripherals.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: N/A

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: Now 2-3: Now
3-4: Now 4-5: Now 5-6: Now 6-7: Now

REMARKS AND DATA SOURCES ON COST ESTIMATES: This is a currently available capability (for on ground) although research is still done to manufacture less expensive, faster, and more reliable printers. The Space Shuttle currently has a teletype, and it would not be difficult to adapt similar hardware for computer printouts.

REMARKS ON SPECIAL ASPECTS: None.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None.

CAPABILITY APPLIES TO (GFE NUMBERS): g109.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Computer-Generated Audio

CODE NUMBER: 13.5 DATE: June 1982 NAME(S): Howard/Kurtzman

DESCRIPTION OF CAPABILITY: The use of an audio signal to indicate information to a human, such as proximity of a manipulator to its target, amount of force being exerted, etc. This information can be conveyed by varying volume, pitch, or modulation. This also includes the use of computer-generated verbal information.

WHO IS WORKING ON IT AND WHERE: James L. Flanagan, Bell Telephone Laboratories

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: At the basic level, the hardware exists; it is merely a matter of further implementation. Audio enunciators are already used in the space shuttle for a variety of functions. There are still significant technical problems with true computer speech synthesis, and quantitative cost estimates to overcome them are not available. Source: "The Synthesis of Speech," James L. Flanagan, Scientific American v.226 no.2, Feb. 1972, pp. 48-58.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: The operating environment is a critical factor: distractions may be too great. Only one or two quantities can be continuously monitored this way at one time.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer Programming Techniques; Computer Memory Development

CAPABILITY APPLIES TO (GFE NUMBERS): g109

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Stereoptic Video

CODE NUMBER: 13.6 DATE: 4/13/82 NAME(S): Spofford/Howard

DESCRIPTION OF CAPABILITY: A video display system which simulates a three-dimensional display for a human viewer. The video information comes from a pair of co-located remote cameras. One example of a stereoptic display uses two images projected on a Fresnel screen which has a precisely determined matrix of exit pupils. Other examples use polarization or color to encode the two images, and may require special viewing hoods or glasses.

WHO IS WORKING ON IT AND WHERE: Robert L. Wernli, Naval Ocean Systems Center (San Diego); Dr. Roger T. Schappell, Martin-Marietta Aerospace (Denver).

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The hardware has been tested for undersea teleoperator applications, which involve display requirements very similar to space applications. The level seven assesment assumes that the display is located on the ground, with the cameras in orbit.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: None.

REMARKS ON SPECIAL ASPECTS: The three-dimensional effect is achieved at the expense of a restricted viewing angle or location. Also, for many common data displays, three dimensions are unnecessary. Older stereoptic system often led to operator fatigue and headaches; newer systems are expected to be more comfortable.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 13.1 Human Eyesight Via Video.

CAPABILITY APPLIES TO (GFE NUMBERS): g109

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: 3-D Display

CODE NUMBER: 13.7 DATE: 6/30/82 NAME(S): Thiel/Marra

DESCRIPTION OF CAPABILITY: There are several methods for displaying a 3-D image. The technique described here is considered to be the most promising. Holographic projection is not discussed because it is not feasible in the foreseeable future. The technology considered here uses a flat LED array spinning at high speed to generate the image. A computer controls the activation and intensity of each LED. The persistence of the image in the human eye causes the illusion of a 3-D image. Unlike most other attempts at 3-D display this technique allows the viewer to move and see another part of the image, e.g. look at the right side and then move and look at the left, top or bottom etc.

WHO IS WORKING ON IT AND WHERE: Professor David G. Jansson (MIT Innovation Center) and Dash, Straus, Goodhue Inc.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: NOW LEVEL5: NOW LEVEL6: N/A LEVEL7: N/A

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: "Medical Applications of a New 3-D Display System", Jansson and Goodhue, MIT, 1981. (MIT Innovation Center Document).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: The developers of this device are currently in the development, investment, and marketing process; therefore cost estimates are not available.

REMARKS ON SPECIAL ASPECTS: This device is desirable because it offers a 3-D image that can be viewed from multiple locations. Its major drawback is the high bandwidth data tranfer through a rotating interface.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 13.1 Human Eyesight via Video; 19.1 Analog/Digital Converter; 25.1 Onboard Dedicated Microprocessor.

CAPABILITY APPLIES TO (GFE NUMBERS): g109

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Direct Human Eyesight

CODE NUMBER: 14.1 DATE: June 1982 NAME(S): Howard/Marra

DESCRIPTION OF CAPABILITY: Estimation of position, velocity, or configuration of target by human observer with direct line-of-sight. Illumination will be provided by spot lights. Observer may be in EVA or observing through window.

WHO IS WORKING ON IT AND WHERE: Data Sources: The Eye, Physiology Dept., University College, London, England, 1976, Ed. Hugh Davson; Helmholtz's Treatise on Physiological Optics, 1962, James P.L. Southall, editor.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: N/A

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: This capability carries an "overhead" of training, human safety and life support, to be traded off with versatility and selectivity, particularly in evaluating 3-D scenes. The human eye's abilities are most useful if the data is to be used by the human (i.e., transferring the information to another device is slow and cumbersome).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None.

CAPABILITY APPLIES TO (GFE NUMBERS): g33, g49, g69, g132, g243, g245

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Human On Ground With Computer Assistance

CODE NUMBER: 14.2 DATE: 3/18/82 NAME(S): Spofford/Howard

DESCRIPTION OF CAPABILITY: Decisions are made by a human with the aid of computer routines for data handling, analysis, and mission simulation. The computer software of this capability is not as advanced as that of other capabilities such as Computer Modeling And Simulation (16.1).

WHO IS WORKING ON IT AND WHERE: IBM and many other companies; NASA Centers (JSC, MSFC, KSC, ARC); JPL.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: None.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: None.

REMARKS ON SPECIAL ASPECTS: This is one of the traditional methods of monitoring, decision-making, and control of spacecraft functions. This capability is extremely versatile, in that it is a candidate for 30 of the 69 GFE's researched in detail by this study.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 13.2 Human Eyesight Via Graphic Display; 13.4 Computer Printout; 25.4 Deterministic Computer Program On Ground.

CAPABILITY APPLIES TO (GFE NUMBERS): g1, g5, g10, g24, g37, g38, g47, g56, g57, g58, g60, g64, g65, g83, g87, g88, g92, g93, g94, g97, g98, g103, g107, g110, g184, g185, g221, g244, g318, g325.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Human In EVA With Tools

CODE NUMBER: 14.3 DATE: June 1982 NAME(S): Howard/Akin

DESCRIPTION OF CAPABILITY: A human directly operating manual or power-assisted tools at worksite (EVA or IVA, with or without mobility aids).

WHO IS WORKING ON IT AND WHERE: NASA JSC, NASA MSFC, NASA Langley, Lockheed Missiles & Space, MIT Space Systems Lab, Essex Corp. (Huntsville, Alabama), Hamilton-Standard (Windsor Locks, Connecticut)

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: N/A

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: This capability carries an "overhead" of training, human safety, and life support, to be traded off with very high versatility and fault recovery. Also, it is easier to provide in certain orbits (e.g. LEO vs. GEO).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 14.7 Onsite Human With Computer Assistance; EVA Tools

CAPABILITY APPLIES TO (GFE NUMBERS): g23, g27, g31, g48, g67, g73, g134, g146, g148, g177, g260

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Human With Checklist

CODE NUMBER: 14.4 DATE: June 1982 NAME(S): Howard/Akin

DESCRIPTION OF CAPABILITY: A human on the ground following a preplanned sequence of operations, which includes decision points directing him to alternate sequences, based on information gathered in each operation.

WHO IS WORKING ON IT AND WHERE: Various NASA Centers.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: N/A

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: All the work is done in advance, with every possible alternative planned for. This capability carries an "overhead" of training and support costs (including salary) to be traded off with versatility and selectivity. If a human on ground is making decisions that affect in-space operations, there is also the associated cost of a communications system and communications delays.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None.

CAPABILITY APPLIES TO (GFE NUMBERS): g24, g37, g38, g47, g57, g58, g60, g64, g83, g87, g93, g94, g97, g105, g110, g184, g185, g194, g220

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Human Judgment on Ground

CODE NUMBER: 14.5 DATE: 6/29/82 NAME(S): Kurtzman/Akin

DESCRIPTION OF CAPABILITY: The use of Earth-based human perception and comprehension to form an opinion or evaluation of a situation.

WHO IS WORKING ON IT AND WHERE: NASA.

TECHNOLOGY LEVELS: LEVEL1: N/A LEVEL2: N/A LEVEL3: N/A
LEVEL4: N/A LEVEL5: N/A LEVEL6: N/A LEVEL7: N/A

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: N/A

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: None.

REMARKS ON SPECIAL ASPECTS: This capability is a currently available technology. This capability carries an "overhead" of training and support costs (including salary) to be traded off with versatility and selectivity. If a human on ground is making decisions that affect in-space operations, there is also the associated cost of a communications system and communications delays.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 14.4 Human with Checklist.

CAPABILITY APPLIES TO (GFE NUMBERS): g57, g58, g60, g65, g77, g107, g184, g194, g223, g244.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Manual Testing On Ground

CODE NUMBER: 14.6 DATE: June 1982 NAME(S): Howard/Glass

DESCRIPTION OF CAPABILITY: Sample instructions or other input is given to the system under study, either prior to launch or to a ground-based mock-up system. System performance is compared to expected performance.

WHO IS WORKING ON IT AND WHERE: NASA Centers; many contractors (Hughes, TRW, Ford Aerospace)

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Sources: NASA KSC Guides; Materials Experiment Carrier experimental package test procedures in TRW study

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: This requires a large amount of personnel-time, particularly for a complex system.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 14.5 Human Judgment of Ground

CAPABILITY APPLIES TO (GFE NUMBERS): g1, g5, g10

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Onsite Human With Computer Assistance

CODE NUMBER: 14.7 DATE: June 1982 NAME(S): Howard/Spofford

DESCRIPTION OF CAPABILITY: This is a human onboard the shuttle orbiter, assisted by the standard shuttle computer system.

WHO IS WORKING ON IT AND WHERE: IBM Corporation, NASA Centers

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: N/A

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: Since the critical flight software is run in these computers, their availability may be restricted at certain times of the mission. Also, there is a substantial overhead cost in writing and modifying software, since it must be thoroughly checked for interference with critical routines. This capability should not be confused with Equipment Function Test by Onsite Human, or Equipment Data Checks by Onsite Human, which use dedicated microprocessors to support the onsite human (instead of the orbiter computers).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 13.1 Human Eyesight via Video; 14.2 Human on Ground with Computer Assistance; 14.8 Onsite Human Judgment

CAPABILITY APPLIES TO (GFE NUMBERS): g23, g24, g33, g35, g47, g48, g49, g50, g51, g52, g54, g56, g57, g58, g60, g65, g92, g150, g185, g194, g244, g260, g318, g325

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Onsite Human Judgment

CODE NUMBER: 14.8 DATE: 6/29/82 NAME(S): Kurtzman/Akin

DESCRIPTION OF CAPABILITY: The use of on-location human perception and comprehension to form an opinion or evaluation of a situation.

WHO IS WORKING ON IT AND WHERE: NASA.

TECHNOLOGY LEVELS: LEVEL1: N/A LEVEL2: N/A LEVEL3: N/A
LEVEL4: N/A LEVEL5: N/A LEVEL6: N/A LEVEL7: N/A

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: N/A

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: This is a currently available technology, but considerable investment is still being made into human support in space.

REMARKS ON SPECIAL ASPECTS: This capability carries an "overhead" of training, human safety and life support, to be traded off with versatility and selectivity.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 14.5 Human Judgment on Ground.

CAPABILITY APPLIES TO (GFE NUMBERS): g57, g58, g60, g65, g185, g194, g244, g325.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Specialized Manipulator under Human Control

CODE NUMBER: 15.1 DATE: 6/23/82 NAME(S): Marra/Paige

DESCRIPTION OF CAPABILITY: Manipulator remotely controlled by a human operator and designed for specific functions, in specific work-site geometries. The number of degrees of freedom is determined by the function(s) for which the manipulator is designed. The manipulator may have interchangable end-effectors for various tasks.

WHO IS WORKING ON IT AND WHERE: Thomas Sheridan M.I.T., Man-Machine Systems Lab; Don Peiper, Automatix; Sinclaire Scala, General Electric, Reentry and Environmental Systems; Carl Ruoff, JPL. The Shuttle RMS is a low-level version of this capability (no end-effectors).

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: 1984

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Robert F. Goeke (M.I.T. Center for Space Research) estimated two years to space rate such a device.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: $1,000,000

REMARKS AND DATA SOURCES ON COST ESTIMATES: Robert F. Goeke estimates $1,000,000 to space rate such a device.

REMARKS ON SPECIAL ASPECTS: The operator may be in space or on the ground. If on the ground , the non-recurring cost will be higher because of the need of a real-time communications system, but the recurring cost will go down. There may also be time-delay problems. The Capability Application Forms have been completed assuming that the operator is in space.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 2.2 Dedicated Manipulator under Computer Control; 6.2 Proximity Sensors; 13.1 Human Eyesight via Video; 13.2 Human Eyesight via Graphics Display; 13.5 Computer-Generated Audio; 13.6 Stereoptic Video; 13.7 3-D Display; 14.8 Onsite Human Judgement; Manipulator End-Effectors; Supervisory Control

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g67, g73, g134, g148, g177

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Dextrous Manipulator Under Human Control

CODE NUMBER: 15.2 DATE: 6/30/82 NAME(S): Spofford/Marra

DESCRIPTION OF CAPABILITY: A multi-fingered multi-purpose manipulator under remote human control. This manipulator is capable of operating in various geometries.

WHO IS WORKING ON IT AND WHERE: JPL, Carnegie-Mellon, University of Rhode Island, and other manipulator research organizations. The current level of dexterity is low, and little effort is being applied to improving it.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: see below LEVEL6: see below LEVEL7: see below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Estimates not available yet.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: see below 5-6: see below 6-7: see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Estimates not available yet.

REMARKS ON SPECIAL ASPECTS: The operator may be in space or on the ground. If the operator is on the ground, the non-recurring costs will be higher because of the need for a real-time communications and control system (possibly including predictive displays) but the recurring costs will go down.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Microactuators; 8.1 Tactile Sensors; 15.1 Specialized Manipulator Under Human Control; 25.5 Onboard Adaptive Control System.

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g67, g73, g134, g148, g177

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Teleoperator Maneuvering System With Manipulator Kit

CODE NUMBER: 15.3 DATE: 6/30/82 NAME(S): Spofford/Paige

DESCRIPTION OF CAPABILITY: This capability incorporates a dextrous manipulator kit mounted on a Teleoperator Maneuvering System (TMS) spacecraft. This analysis considers the TMS to be developed and operational, so the TMS R&D costs are not carried by this capability. Essentially, this capability has a set of dextrous manipulators on a free-flying platform, all of which is remotely operated by a human. Visual feedback is provided by the TMS cameras, and optionally by the manipulator kit. If the manipulators are dextrous, other types of feedback may also be included.

WHO IS WORKING ON IT AND WHERE: Vought Corp. and Martin Marietta (on the TMS);NASA MSFC and JPL (on dextrous manipulators).

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: see below LEVEL6: see below LEVEL7: see below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Estimates not available yet.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: see below 5-6: see below 6-7: see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Estimates not available yet.

REMARKS ON SPECIAL ASPECTS: The operator may be in space or on the ground. If the operator is on the ground, the non-recurring costs will be higher because of the need for a real-time communications and control system (possibly including predictive displays), but the recurring costs will go down.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Communications techniques; 6.1 Optical Scanner (Passive Cooperative Target); 6.3 Radar (Passive Target); 6.5 Onboard Navigation And Telemetry; 14.3 Human In EVA With Tools; 15.2 Dextrous Manipulator Under Human Control; 15.4 Teleoperated Docking Mechanism.

CAPABILITY APPLIES TO (GFE NUMBERS): g27, g31, g67, g73, g134, g148, g177.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Teleoperated Docking Mechanism

CODE NUMBER: 15.4 DATE: 5/27/82 NAME(S): Glass/Spofford

DESCRIPTION OF CAPABILITY: A docking mechanism teleoperated by a remote operator. This operator receives visual feedback (and possibly other types of feedback), and controls the docking actuators. The worksite is illuminated by spotlights.

WHO IS WORKING ON IT AND WHERE: Martin Marietta (Denver); NASA MSFC, JSC; Essex Corp. (Hunstville, AL).

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: 1983 LEVEL7: 1987

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: TRW and McDonnell-Douglas Space Platform studies.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: $2M 6-7: $2M

REMARKS AND DATA SOURCES ON COST ESTIMATES: Study group estimates.

REMARKS ON SPECIAL ASPECTS: Depending on the locations of worksite and operator, time delays in transmission may pose problems, requiring move-and-wait strategies or supervisory control. Real-time feedback to the operator requires a substantial data rate (minimum of 3 kilobits/sec for a black-and-white TV picture).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Communications techniques; Supervisory control; 13.3 Docking Under Onsite Human Control.

CAPABILITY APPLIES TO (GFE NUMBERS): g146

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Computer Modeling And Simulation

CODE NUMBER: 16.1 DATE: 3/19/82 NAME(S): Spofford/Akin/Oliveira

DESCRIPTION OF CAPABILITY: 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.

WHO IS WORKING ON IT AND WHERE: Intermetrics, TRW, Rockwell, Martin Marrieta, JPL, Draper Laboratories.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The data base must be developed for each new application, but these techniques are in use today.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: The cost to develop a data base depends on its scale and complexity.

REMARKS ON SPECIAL ASPECTS: None.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer memory development; 25.4 Deterministic Computer Program On Ground.

CAPABILITY APPLIES TO (GFE NUMBERS): g1, g5, g64, g77, g97, g110, g194

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Tracking and Data Relay Satellite System

CODE NUMBER: 17.1 DATE: 6/15/82 NAME(S): Jones-Oliveira/Kurtzman

DESCRIPTION OF CAPABILITY: TDRSS is a digital transmission system operating in the S & K bands, 6 megabits and 300 megabits respectively. Each satellite can provide 4 video links simultaneously. The limitations of TDRSS are not presented by the TDRSS, but rather by the capacity of the ground systems to manage the information sent down for processing(e.g. the system is limited by capabilities of ground transmission of the data from the ground station to the computers designated the task of analysis). Therefore, in order to optimize TDRSS, data compression is a necessity, and immediate recognition of bad data is essential. (With improvements in ground-to-ground data transmission techniques/capacities, TDRSS may be expanded to the X band by the year 2000.) There will be one user per antenna, i.e., Single Access (SA) using steerable parabolic antennas. However, if there is more than one user within a given field of view, it can provide services on each band. There are two satellites proposed with a third as a spare. By 1989-1990, 80% user orbit coverage will be achieved, and the third satellite can increase that capacity by 50%, i.e., to 90% user orbit coverage. There are also available Multiple Access (MS) downlinks using a TDRS array antenna with ground implemented phasing; however, it is not ca able of using the K band.

WHO IS WORKING ON IT AND WHERE: NASA/OSTS, Goddard Space Flight Center

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: 1983

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Eugene Ferrick, NASA/OSTS. Tracking and Data Relay Satellite System (TDRSS), User's Guide, Revision 4.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: The R&D phase is coming to completion with a January 1983 expected delivery date to orbit.

REMARKS ON SPECIAL ASPECTS: Three significant benefits of TDRSS are its capacity, near to 100% orbit coverage, and the necessity of fewer ground stations.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Communications Techniques.

CAPABILITY APPLIES TO (GFE NUMBERS): g79

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Direct Transmission To/From Ground

CODE NUMBER: 17.2 DATE: 5/12/82 NAME(S): Thiel/Marra

DESCRIPTION OF CAPABILITY: By using the STDN and sometimes the DSN the spacecraft communicates directly with the ground (as opposed to transmitting via the orbiter or TDRSS).

WHO IS WORKING ON IT AND WHERE: The ground station network is usually operated by NASA and in some cases DoD. The spacecraft side of the link is the contractor's responsibility. This technology is well developed, although there is much room for improvement as communications technology advances.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: NOW LEVEL5: NOW LEVEL6: NOW LEVEL7: NOW

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: This is the present technology for spacecraft communications. More advanced methods (20-30 GHz) are being developed, but this is an evolving technology. The basic technology is operational today.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: Technology already in use.

REMARKS ON SPECIAL ASPECTS: For many NASA operations this communications method will be replaced by TDRSS.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Communications Techniques

CAPABILITY APPLIES TO (GFE NUMBERS): g79

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Direct Transmission To/From Orbiter

CODE NUMBER: 17.3 DATE: 7/3/82 NAME(S): Thiel/Marra

DESCRIPTION OF CAPABILITY: Direct communication between a spacecraft and the orbiter via S-band communications link or the Ku-band communications/radar system.

WHO IS WORKING ON IT AND WHERE: Rockwell International is responsible for overall system integration and has several subcontractors for the S-band system. Hughes Aircraft Co. is responsible for the Ku-band communications/radar system.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: NOW LEVEL5: NOW LEVEL6: NOW LEVEL7: 1983-1984

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Both communications systems have been developed and are awaiting an opportunity for testing in space, expected to occur soon.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: The S and Ku-band systems are developed. Both are awaiting the opportunity to be tested in space. The exact cost, if any, of such a test is not available since the test will be part of other operations.

REMARKS ON SPECIAL ASPECTS: The Ku-band system is also designed to be the main mode of communications with TDRSS.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None

CAPABILITY APPLIES TO (GFE NUMBERS): g79

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Direct Communication To/From Orbiter Via Cable

CODE NUMBER: 17.4 DATE: 6/24/82 NAME(S): Marra/Spofford

DESCRIPTION OF CAPABILITY: Data is passed directly to or from the orbiter through a communications cable.

WHO IS WORKING ON IT AND WHERE: NASA JSC, KSC

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: N/A

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: In order to use this capability, the spacecraft with which the orbiter is communicating must be close enough to the orbiter to allow a cable to be connected between them.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Communications Techniques

CAPABILITY APPLIES TO (GFE NUMBERS): g79

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Onboard Data Recorder

CODE NUMBER: 18.1 DATE: 6/3/82 NAME(S): Thiel/Spofford

DESCRIPTION OF CAPABILITY: This device is almost identical to 18.3 Magnetic Tape (in some cases it is the same) except that the Onboard Data Recorder is only used to take data and store it for later playback. The Magnetic Tape device is more sophisticated because it is part of a computer memory system which may access parts of the tape while ignoring others. In most cases the difference is not in the hardware, but in its application.

WHO IS WORKING ON IT AND WHERE: The two major manufacturers of tape units for space use are RCA and Odetics.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: NOW LEVEL5: NOW LEVEL6: NOW LEVEL7: NOW

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: This technology has been used for several years and is fully developed. However, solid state devices are likely to replace tape units soon.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: The development costs for this technology are zero because it is a mature technology. Individual units are expensive because they are usually custom made for each user.

REMARKS ON SPECIAL ASPECTS: None

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None

CAPABILITY APPLIES TO (GFE NUMBERS): g218, g264

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Random Access Memory

CODE NUMBER: 18.2 DATE: 6/12/82 NAME(S): Spofford/Jones-Oliveira

DESCRIPTION OF CAPABILITY: Random Access Memory is high-speed semiconductor memory used as main memory in a computer. This memory retains its contents only while power is applied to the circuits. Several companies (Bell Laboratories/Western Electric, IBM, Intel, Texas Instruments, Mostek, Hitachi, and Motorola) are developing or about to start production of 256K-bit memory devices.

WHO IS WORKING ON IT AND WHERE: Integrated circuit manufacturers

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: This reflects current space-rated random access memory devices. More advanced devices are at a lower level of development.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: This reflects current space-rated random access memory devices. More advanced devices will require space-rating.

REMARKS ON SPECIAL ASPECTS: The state of the art in semiconductor memory is still improving. These integrated circuits may need to be shielded or radiation-hardened for use in a space environment. The memory devices commercially available have significantly more capability than current space-qualified devices.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer memory development; Space-rated integrated circuits.

CAPABILITY APPLIES TO (GFE NUMBERS): g89

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Magnetic Tape

CODE NUMBER: 18.3 DATE: 6/4/82 Thiel/Spofford

DESCRIPTION OF CAPABILITY: This capability is essentially identical to ground based tape memory units except it is adapted for space use. It is likely that by the time space computers need tape units for memory the tape units will be obsolete.

WHO IS WORKING ON IT AND WHERE: For ground use just about every large computer company produces tape drives. For space use RCA and Odetics are the leading manufacturers.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: NOW LEVEL5: NOW LEVEL6: NOW LEVEL7: 1983

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Since tape units have been used in space very little modification would be necessary for computer memory use.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: 1 Million

REMARKS AND DATA SOURCES ON COST ESTIMATES: This includes the space rating of upgraded motor drives and related equipment for application to computer memory use. (Study group estimate).

REMARKS ON SPECIAL ASPECTS: This technology will probably become obsolete before it is ever used because of the increasing capabilities of solid state memory units.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None

CAPABILITY APPLIES TO (GFE NUMBERS): g89, g90

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Magnetic Bubble Memory

CODE NUMBER: 18.4 DATE: 6/3/82 NAME(S): Spofford/Kurtzman

DESCRIPTION OF CAPABILITY: A solid-state memory device that stores data bits as magnetic "bubbles" in a thin film of magnetic material. Data is accessed serially; bits are organized sequentially in many loops. This is a non-volatile storage medium; memory contents are maintained without power.

WHO IS WORKING ON IT AND WHERE: Bell Laboratories; Intel Magnetics; Texas Instruments; and other integrated circuit manufacturers.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: see below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Time required to space-rate bubble mmories is estimated at two years.

R&D COST ESTIMATES BETWEEN LEVELS: 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: None.

REMARKS ON SPECIAL ASPECTS: These integrated circuits may have to be shielded or radiation-hardened for use in a space environment. The theoretical storage density of a bubble memory is greater than is possible with a semiconductor memory, as the bubbles may be smaller than the transistors used in other memories. The energy required to move the bubbles is less than that required to switch a transistor.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer memory development; Space-rated integrated circuits.

CAPABILITY APPLIES TO (GFE NUMBERS): g89. g90

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ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Magnetic Disk Memory

CODE NUMBER: 18.5 DATE: 6/4/82 NAME(S): Spofford/Thiel

DESCRIPTION OF CAPABILITY: Bulk storage device which records data on a rotating platter coated with a magnetic film. This capability describes a integral drive/platter unit with an environmentally sealed housing (generally refered to as a "Winchester" disk).

WHO IS WORKING ON IT AND WHERE: Seagate Technology, Shugart Associates, and others (mini-Winchesters).

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: see below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The effort required to space-rate a disk memory unit is estimated by the study group to be comparable to that required for a magnetic tape unit.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: This is not known at present.

REMARKS ON SPECIAL ASPECTS: The state of the art in magnetic disk memory devices is still improving. These units must be shielded or radiation-hardened for use in a space environment. Small Winchester drives have been developed extensively for the personal computer industry. Disk units capable of storing fifty megabytes in a five-inch package have been developed.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer memory development.

CAPABILITY APPLIES TO (GFE NUMBERS): g89, g90

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Optical Disc

CODE NUMBER: 18.6 DATE: 7/1/82 NAME(S): Marra

DESCRIPTION OF CAPABILITY: Analog or digital data is permanently stored on an optical disk by a laser. The data cannot be updated or erased.

WHO IS WORKING ON IT AND WHERE: RCA Advanced Technology Laboratory, Camden, New Jersey; Storage Technology, Louisville, Colorado.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: 1983 LEVEL7: see below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The sources on the technology levels are "Optical Disks Excite Industry", Electronics, May 5,1981; Gerald Claffie, RCA Advanced Technology Lab, Camden, New Jersey. An estimate for when Optical Disks will reach level 7 is not available.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: see below 6-7: not available

REMARKS AND DATA SOURCES ON COST ESTIMATES: The cost estimates for reaching level 6 are proprietary due to competitive business reasons.

REMARKS ON SPECIAL ASPECTS: The optical disk mechanism is physically smaller than a magnetic disk system.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer Memory Development; Laser Technology

CAPABILITY APPLIES TO (GFE NUMBERS): g90

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Erasable Optical Disc

CODE NUMBER: 18.7 DATE: 7/1/82 NAME(S): Marra

DESCRIPTION OF CAPABILITY: Data is read and written by a laser onto an optical disc. The data can be written and overwritten many times. The data is non-volatile (i.e. no power is necessary to keep the data intact).

WHO IS WORKING ON IT AND WHERE: RCA Advanced Technology Labs, Camden, New Jersey; Storage Technology, Louisville, Colorado.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: 1983 LEVEL6: 1985 LEVEL7: see below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The sources on the technology levels are "Optical Disks Excite Industry", Electronics, May 5,1981; Gerald Claffie, RCA Advanced Technology Lab, Camden, New Jersey. An estimate for when Optical Disks will reach level 7 is not available.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: see below 6-7: not available

REMARKS AND DATA SOURCES ON COST ESTIMATES: Cost estimates for reaching level 6 are not available due to competitive business reasons.

REMARKS ON SPECIAL ASPECTS: Erasable optical discs should have the same characteristics as 18.6 Optical Disc except for the ability to revise data (Gerald Claffie, RCA).

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 18.6 Optical Disc

CAPABILITY APPLIES TO (GFE NUMBERS): g89, g90

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Holographic Storage

CODE NUMBER: 18.8 DATE: June 1982 NAME(S): Howard/Jones-Oliveira

DESCRIPTION OF CAPABILITY: A large capacity (terabit) read-write optical mass memory, using laser holography for storage and retrieval.

WHO IS WORKING ON IT AND WHERE: Institut fuer Informationsverarbeitung in Technik und Biologie, Karlsruhe, West Germany; Harris Corporation, Electro-Optics Department, Melbourne, Florida; Grumman Aerospace Corporation, Research Department, Bethpage, New York

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Not available LEVEL7: Not available

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Efficiency and reliability of lasers and the recording medium must be improved, and power consumption reduced to be feasible for space applications. Quantitative estimates are not available (Source: Linda Ralston at Harris Corp.)

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: Not available 6-7: Not available

REMARKS AND DATA SOURCES ON COST ESTIMATES: Quantitative estimates are not available.

REMARKS ON SPECIAL ASPECTS: As currently envisioned, this system can be tape-, block-, or fiche-oriented with a photoplastic material as the storage medium, with the fiche-oriented type being favored. This requires a few moving parts to implement, which may limit its reliability and useful life. As in all such systems with mechanical drives, there is a trade-off between random access time and power consumption. The attainable values are much better than for current magnetic tape systems, which are the only memories available today in large (terabit) capacity. Compared with semiconductor memories, the write-time and random access time for the holographic system is long. Also, the largest technological obstacle is the lack of a storage medium which can be reliably recycled a large number of times. On the other hand, the advantages of this system are no power consumption when not writing or reading and low vulnerability to degradation by radiation. This system would be most useful for long-term storage of large amounts of data, with infrequent rewrites.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer Memory Development; Laser Technology

CAPABILITY APPLIES TO (GFE NUMBERS): g89, g90

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Microform on Ground

CODE NUMBER: 18.9 DATE: 6/22/82 NAME(S): Marra

DESCRIPTION OF CAPABILITY: Data is recorded in reduced form on film. Microform includes Microfiche, Microfilm, and similar media. The microform is stored on shelves or in cabinets until needed. An automatic accession system could be developed.

WHO IS WORKING ON IT AND WHERE: Bell & Howell

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: N/A

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: Microform has a higher storage density than paper. One advantage of microform is that it is in a form that is readily readable by humans, unlike the electronic forms of data storage. However to transmit the data, the microform itself must be sent, or the data converted to another medium; electronic memories can be sent over phone wires or such similar means.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None.

CAPABILITY APPLIES TO (GFE NUMBERS): g90

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Electrically Alterable Read Only Memory

CODE NUMBER: 18.10 DATE: 6/7/82 NAME(S): Spofford/Thiel

DESCRIPTION OF CAPABILITY: A semiconductor memory which retains data without power (non-volatile). This device is read like a ordinary read-only-memory, but may be erased electrically while in-circuit.

WHO IS WORKING ON IT AND WHERE: Integrated circuit manufacturers

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: see below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Estimated time to space-rate this memory device is two years.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Comparable to other MOS integrated circuits.

REMARKS ON SPECIAL ASPECTS: The state of the art in semiconductor memory is still improving. These integrated circuits may have to be shielded or radiation-hardened for use in a space environment. These memories are useful for recording data that changes occasionally.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer memory development; Space-rated integrated circuits.

CAPABILITY APPLIES TO (GFE NUMBERS): g90

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Cryoelectronic Memory

CODE NUMBER: 18.11 DATE: 6/21/82 NAME(S): Kurtzman/Marra

DESCRIPTION OF CAPABILITY: Computer memory which uses superconducting Josephson junction technology to achive extremely high density storage, and operating speeds higher than today's fastest electronic memories.

WHO IS WORKING ON IT AND WHERE: Dennis Herrell, Engineering Manager, Josephson Computer Technology Program, IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598 (914) 945-1650

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: 1987 LEVEL7: 1992

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Levels 1-4 Juri Matisoo (IBM); Level 5 Juri Matisoo (estimate); Levels 6-7 study team estimate

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: see below 6-7: see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: $35,000,000 to level 7 (100,000 per man-year for 10 years with 35 man-years per year)

REMARKS ON SPECIAL ASPECTS: Can only operate at cryogenic temperatures (4 deg. Kelvin). IBM is the lead researcher of computer applications of Josephson technology, and will not disclose future technology level and cost estimates for competitive reasons.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Cryogenic Cooling Techniques; Computer Memory Development

CAPABILITY APPLIES TO (GFE NUMBERS): g89

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Electron Beam Memory

CODE NUMBER: 18.12 DATE: 6/15/82 NAME(S): Jones-Oliveira/Spofford

DESCRIPTION OF CAPABILITY: This type of memory uses a scanning electron beam to retrieve information from silicon storage wafers. Using state-of-the-art semiconductors and two computers for beam control, the current development system has 128 megabit memory storage, 16-bit information packets, 30 microsecond access time, 4 megahertz read/write rate, 95% duty cycle, and automatic self-diagnosis for fault tolerance. The system is block-oriented in its software architecture, and the memory is non-volatile.

WHO IS WORKING ON IT AND WHERE: Micro-Bit Division of Control Data Corp., Lexington, MA.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: 1985 LEVEL6: 1990 LEVEL7: 1995

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Allen Sliski at Micro-Bit

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: See below 5-6: See below 6-7: See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Over 500-man years of work have been invested in this research to date by Micro-Bit; however, there remains anywhere up to 300 man-years of R&D before this capability will be space rated.

REMARKS ON SPECIAL ASPECTS: It is quite possible that this capability may be made technically obsolete by Magnetic Bubble Memory before it will be space rated in 1995. The research has been shelved, although parallel research is being conduced on an electron beam lithography machine.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 21.2 Operations Optimization Program; 25.2 Onboard Microprocessor Hierarchy; Computer Programming Techniques.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Charge-Coupled Device Memory

CODE NUMBER: 18.13 DATE: 7/9/82 NAME(S): Kurtzman/Spofford

DESCRIPTION OF CAPABILITY: A semiconductor computer memory technology employing charge coupled devices (CCDs) which perform sequential (serial) access where each bit is transfered sequentially as if they were in a closed pipeline. This is in contrast to Random Access Memory (RAM) where the access time is independent of the physical location within the storage array.

WHO IS WORKING ON IT AND WHERE: The Fairchild Camera and Instrument Corporation.

TECHNOLOGY LEVELS:	LEVEL1:	Now	LEVEL2:	Now	LEVEL3:	Now	
LEVEL4:	Now	LEVEL5:	Now	LEVEL6:	Now	LEVEL7:	See below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: It would take an estimated two years to space-rate a charge-coupled device memory.

R&D COST ESTIMATES BETWEEN LEVELS;	1-2:	N/A	2-3:	N/A			
3-4:	N/A	4-5:	N/A	5-6:	N/A	6-7:	See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Costs to space-rate currently available technology should be comparable to that for any other semiconductor memory device. CCDs have already been used in space as an imaging sensor component.

REMARKS ON SPECIAL ASPECTS: The sequential access feature (shared by Magnetic Bubble Memories) provides a reduction in cost per bit at a tradeoff of a decrease in speed over a Random Access Memory. The CCD's high performance in terms of dynamic range and low power, its high packing density and potentially low cost make it a potentially profitable technology for computer memory applications. CCDs are also used in imaging sensors, variable delay lines and filters.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer Memory Development; Space-Rated Integrated Circuits.

CAPABILITY APPLIES TO (GFE NUMBERS): g89.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Analog/Digital Converter

CODE NUMBER: 19.1 DATE: 6/3/82 NAME(S): Spofford/Thiel

DESCRIPTION OF CAPABILITY: A dedicated hard-wired electronic system for converting analog voltage levels to digital signals. This device may be implemented on a single integrated circuit or may require external components. These devices are specialized to their application and are available in a range of resolutions and speeds.

WHO IS WORKING ON IT AND WHERE: Integrated circuit manufacturers

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: None.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: None.

REMARKS ON SPECIAL ASPECTS: This is a commonly used current technology.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Space-rated integrated circuits.

CAPABILITY APPLIES TO (GFE NUMBERS): g78

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Onboard Sequencer

CODE NUMBER: 21.1 DATE: 6/9/82 NAME(S): Thiel/Dalley

DESCRIPTION OF CAPABILITY: A programmable device that sends commands to spacecraft systems either at preset times or under a limited set of predetermined conditions. This device is comparable in sophistication to early programmable calculators, but is not capable of performing calculations. A good example is the Pioneer Venus Stored Command Processor.

WHO IS WORKING ON IT AND WHERE: Most spacecraft companies have used devices of this sort. Pioneer Venus (Hughes Aircraft) and other similar spacecraft have used these devices. Most of today's communications satellites have similar devices onboard.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: NOW LEVEL5: NOW LEVEL6: NOW LEVEL7: NOW

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: These devices employ simple electronics and require no technology development.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: The only cost is the specific design and procurement cost.

REMARKS ON SPECIAL ASPECTS: These devices are very reliable at what they do, but their simplicity severely limits their capabilities. Onboard Sequencers will become obsolete as onboard computers and microprocessors become common on spacecraft.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): None

CAPABILITY APPLIES TO (GFE NUMBERS): g47, g83, g87

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Operations Optimization Program

CODE NUMBER: 21.2 DATE: 6/20/82 NAME(S): Thiel/Akin

DESCRIPTION OF CAPABILITY: This is a computer program using a dynamic model of available resources and mission objectives to determine optimal scheduling and optimal resource allocation. It then can 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 considerations of cost, time and resource levels.

WHO IS WORKING ON IT AND WHERE: David L. Akin (MIT), Richard Bellman and Stuart Dreyfuss (Rand Corp.), JPL.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: N/A LEVEL5: N/A LEVEL6: 1984 LEVEL7: N/A (Ground based.)

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: David L. Akin. Assumes that a development effort is started soon. Level 7 does not apply because initial applications of this program would be in ground based computation.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: See Below 4-5: See Below 5-6: See Below 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: $370,000 to proceed from level 3 to 6. (This would be the figure necessary to enhance the DALP program written by Akin , by adding 2000 lines of code at an average cost of $185 per line.)

REMARKS ON SPECIAL ASPECTS: None

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 25.3 Onboard Deterministic Computer Program.

CAPABILITY APPLIES TO (GFE NUMBERS): g38, g83, g87, g94, g98.

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ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Automatic Programmer And Program Tester

CODE NUMBER: 22.1 DATE: 5/27/82 NAME(S): Thiel/Glass

DESCRIPTION OF CAPABILITY: This program, given a high level description of a programming task, creates a computer algorithm to accomplish the task. The 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's software system).

WHO IS WORKING ON IT AND WHERE: Richard Stallman (MIT AI), Douglas Smith (Naval Postgraduate School), Richard H. Brown (GTE Labs).

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: N/A LEVEL5: N/A LEVEL6: 1986 LEVEL7: N/A

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: IJCAI-81 Papers. Richard Stallman (MIT AI Lab).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: See Below 4-5: See Below 5-6: See Below 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: Due to difficulty of determining the amount of time and effort necessary to make advances in a new field such as this, specific cost estimates are not available. It will probably take several man-years of effort, plus testing time, to develop this technology. (Richard Stallman).

REMARKS ON SPECIAL ASPECTS: This technology, while not directly applicable to most space operations, could play a significant role in the development of any software system by reducing programming time and errors, thus reducing costs. This technology could have a dramatic impact on software development operations for NASA, the military, and industry.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 23.1 Expert System With Human Supervision.

CAPABILITY APPLIES TO (GFE NUMBERS): g77

OF POOR QUALITY

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Expert System with Human Supervision

CODE NUMBER: 23.1 DATE: 5/12/82 NAME(S): Jones-Oliveira/Glass/Oliveira

DESCRIPTION OF CAPABILITY: Given an extensive data base consisting of consistent, logical models ("representations") of information known to be true, an expert systems 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.

WHO IS WORKING ON IT AND WHERE: Randall Davis (MIT AI Lab); Fred Hayes-Roth and Edward Feigenbaum (Stanford AI and SRI); Oliver G. Selfridge (Bolt, Beranek & Newman, Cambridge,MA); several groups at Carnegie-Mellon; JPL.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: 1985 LEVEL7: N/A (ground based)

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: AAAI Tutorial by Hayes-Roth; Randall Davis (MIT AI Lab); Terrence Winograd (Stanford AI Lab); International Joint Conference on AI (IJCAI-81) Proceedings.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: See below 6-7: See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Davis:System R&D (from conception) is asymptotically approaching 5 man-years of effort.

REMARKS ON SPECIAL ASPECTS: Davis and Feigenbaum: older systems, e.g., MYCIN, can be easily adapted for new uses by changing the production rules and data base. MYCIN is a medical diagnostic system with competence comparable to a first-year intern. For a good overview of how an Expert System works, the interested reader may be best directed to the following publications: 1) Hayes-Roth, A.I. Tutorial on Expert Systems: "Putting Knowledge to Work", The IJCAI - 81 Symposium, 1981. 2) N.J. Nilsson, Principles of A.I., Tioga Publishing Co., Palo Alto, CA., 1980; 3) W. B. Gevarter, An Overview of Expert Systems, National Bureau of Standards no. NBSIR 82-2505, May 1982.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 16.1 Computer Modeling and Simulation; 21.2 Operations Optimization Program; 24.1 Theorem Proving Program

CAPABILITY APPLIES TO (GFE NUMBERS): g24, g37, g57, g58, g60, g93, g94, g97, g105, g107, g184, g185, g325

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Learning Expert System with Internal Simulation

CODE NUMBER: 23.2 DATE: 3/17/82 NAME(S): Oliveira/Jones-Oliveira/Dalley

DESCRIPTION OF CAPABILITY: Given an extensive data base consisting 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 imputs 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. The system can then define and initiate actions based on the computer probabilities. The "learning" aspect adds the ability to evaluate the accuracy of former predictions, and the ability to modify the data base and the production rules to improve future predictions so as to give "better" directives.

WHO IS WORKING ON IT AND WHERE: Olivier Selfridge (Bolt, Beranek & Newman); Marvin Minsky, Randall Davis, and Patrick Winston, (MIT A.I. Lab); Nils Nilson, Edward Feigenbaum, Terry Winograd, and Fred Hayes-Roth (Stanford AI & SRI); John Prager (IBM).

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: 1982
LEVEL4: N/A LEVEL5: N/A LEVEL6: 1990 LEVEL7: N/A (ground based)

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Marvin Minsky (MIT A.I. Lab), Joseph Oliveira (MIT S.S.L.).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: See below 4-5: See below 5-6: See below 6-7: See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Minsky - R&D costs for learning software are very difficult to estimate, because they depend strongly on the unforeseen problems that crop up during the development.

REMARKS ON SPECIAL ASPECTS: Minsky, Selfridge, Oliveira, Winston, Nilson, Feigenbaum, Woods, Hayes-Roth, Michie. Since the issue of a Learning Expert System is still in its infancy there are few published sources which directly address all aspects of such a system and its operations. For reference, the interested reader may do best to investigate the most current research literature on Expert Systems and pursue individual discussions with researchers in Knowledge Engineering. It should be noted that Expert Systems which learn and in fact adapt themselves to new problem domains need extensive fundamental research. The reader is initially referred to the following publications: 1) W.B. Gevarter, "An Overview of Expert Systems," U.S. Department of Commerce National Bureau of Standards. Report No. NBSIR 82-2505 May 1982, Metrology Building, Room A127, Washington, DC 20234. 2) Hayes-Roth, "Tutorial on Expert Systems: Putting Knowledge to Work," International Joint Conference on A.I., 1981.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 23.1 Expert System with Human Supervision; 25.5 Onboard Adaptive Control System; 26.1 Fault Tolerant Software.

CAPABILITY APPLIES TO (GFE NUMBERS): g5, g24, g37, g56, g57, g58, g60, g64, g87, g93, g94, g97, g98, g105, g107, g110, g184, g185, g194, g223, g244, g325.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Theorem Proving Program

CODE NUMBER: 24.1 DATE: 6/29/82 NAME(S): Glass/Kurtzman/Oliveira/Smith

DESCRIPTION OF CAPABILITY: 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 leads to internal contradictions in all cases; then the opposite is false, and therefore the assertion must be true. The opposite is called the "negation of the assertion". In general, it is easier to prove that a statement is false than to prove that a statement is true; therefore the program tries to prove the falsehood of the negation, which in turn implies the truth of the assertion.

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.

As an example, consider the assertion: $2 + 3 = 5$. The program first forms the negation of the assumption: 2 + 3 is not equal to 5. It then decomposes this negation by the rules of inference (in this case, the laws of logic which define "="). The program finds contradictions in all cases, i.e., it cannot find any logical inference which supports "2 + 3 is not equal to 5". The program thus concludes that this negation is false, and therefore the theorem ($2 + 3 = 5$) is true.

This example is exceedingly simple; theorem proving programs can be applied to much more complex assertions. In many cases, however, a complex assertion may require the checking of an enormous number of logical interpretations of the assertion, and therefore theorem proving programs are combinatorially limited. In comparison, expert systems also have the ability to tackle theorem proving problems, but they can stop part-way and compute probabilities based on what they've accomplished, rather than having to pursue the problem all the way to an exact solution.

WHO IS WORKING ON IT AND WHERE: Ehud Shapiro, Yale; Herbert A. Simon, Carnegie-Mellon; Robert Veroff, Argonne; W. W. Bledsoe & Gordon S. Novak, U. Texas (Austin); S. Kalowski, U. Edinburgh; D. Fishmann, Bell Labs; R. Moll, U. Mass. Computer Science; Minker, U. Maryland; JPL.

TECHNOLOGY LEVELS:	LEVEL1:	Now	LEVEL2:	Now	LEVEL3:	Now
LEVEL4:	Now	LEVEL5:	1986	LEVEL6:	N/A	LEVEL7:	1988

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Study team estimate.

R&D COST ESTIMATES BETWEEN LEVELS;	1-2:	N/A	2-3:	N/A
3-4:	N/A	4-5:	see below	5-6:	N/A	6-7:	see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Costs to level 5 consist of adapting existing systems to a new data base type. Costs to level 7 depend on rating of needed CPU power available, and input/output methods.

REMARKS ON SPECIAL ASPECTS: A theorem proving program would probably be one part of a Learning Expert System with Internal Simulation, if a learning expert system were developed.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer Programming Techniques.

CAPABILITY APPLIES TO (GFE NUMBERS): g57, g65, g77, g194.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Onboard Dedicated Microprocessor

CODE NUMBER: 25.1 DATE: 5/19/82 NAME(S): Spofford/Thiel

DESCRIPTION OF CAPABILITY: A digital computer (processing unit, program and data storage, and input/output interface) implemented in one or more integrated circuits. This microprocessor is dedicated to performing one task such as monitoring a subsystem or controlling an actuator.

WHO IS WORKING ON IT AND WHERE: Integrated circuit manufacturers

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Currently, the only space-rated general-purpose microprocessor is a version of the Intel 8080 chip. This device has been commercially available since 1975 and is now obsolete.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: The cost to space-rate a newer, more powerful, microprocessor is not known.

REMARKS ON SPECIAL ASPECTS: The state of the art in microprocessors is still improving. Devices under development commercially have the processing power of an IBM 360 mainframe computer. These integrated circuits may have to be shielded or radiation-hardened for use in a space environment. The microprocessors commercially available have significantly more capability than current space-qualified devices.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer memory development; Space-rated integrated circuits; 25.3 Onboard Deterministic Computer Program.

CAPABILITY APPLIES TO (GFE NUMBERS): g24, g35, g47, g78, g83, g87, g88, g92, g93, g103, g150, g218, g221, g224, g239, g240, g241, g260, g264, g318, g325

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Onboard Microprocessor Hierarchy

CODE NUMBER: 25.2 DATE: 6/28/82 NAME(S): Kurtzman/Glass

DESCRIPTION OF CAPABILITY: A command and control structure consisting of multiple microprocessors ("distributed intelligence") in which goals and tasks are selected at the highest level and are decomposed into sequences of subtasks which are passed to the next lowest level in the hierarchy. This same procedure is repeated at each level until, at the bottom of the hierarchy, there is generated a sequence of primitive tasks which can be executed with single actions. Sensory feedback enters the hierarchy at many different levels to alter the task decomposition so as to accomplish the highest level goal in spite of uncertainties or unexpected conditions in the environment.

WHO IS WORKING ON IT AND WHERE: James S. Albus, Anthony J. Barbera and Roger N. Nagel, A123, Metrology Bldg., Programmable Automation, National Bureau of Standards, Washington, D.C. 20234 (301) 921-2381; Stephen Kahne, Irving Lefkowitz, and Charles Rose, Case Institute of Technology of Case Western Reserve University, Cleveland, Ohio; Ewald Heer, Jet Propulsion Laboratory, 4800 Oak Grove, Pasadena, California.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: See below LEVEL7: See below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The types of goal-seeking behavior we might obtain from industrial robots over the next decade or two is of the same general level of complexity as that of an insect or simple fish. This is more than adequate to generate extremely complex sensory-interactive goal-directed behavior in a constrained environment (Theory and Practice of Hierarchial Control, 1 November 1980, by J. Albus, A. Barbera, R. Nagel).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: See below 6-7: See below

REMARKS AND DATA SOURCES ON COST ESTIMATES: The R&D costs to develop an Onboard Microprocessor Hierarchy are highly dependent on several factors. If the hierarchy is to perform only one task, such as GFE 240, Maintain Safe Battery Charge Levels, and the task does not require any "smart" software, then the hierarchy could probably be implemented cheaply (on the order of $2-4 million) on currently existing space-rated microprocessors and with already developed control theory. It is much more likely, however, that spacecraft designers will desire a single hierarchy to perform many of the tasks to which it can be applied, thus necessitating the development of more sophisticated control algorithms than are currently available, along with the space-rating of significantly more powerful microprocessors. In this case, costs could conceivably be an order of magnitude larger ($20-40 million), although it must be emphasized that this large investment will be distributed among the many uses of the hierarchy as well as future spacecraft designs. More powerful space-rated microprocessors will be beneficial to a variety of other applications.

REMARKS ON SPECIAL ASPECTS: The state of the art in microprocessors continues to improve rapidly. Comercially available devices have the processing power of an IBM 360 mainframe computer. These integrated circuits may need to be shielded or radiation-hardened for use in a space environment. The

microprocessors commercially available have significantly more capability than current space-qualified devices.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 25.1 Onboard Dedicated Microprocessor.

CAPABILITY APPLIES TO (GFE NUMBERS): g24, g47, g83, g87, g88, g92, g93, g94, g103, g218, g224, g240, g241, g260, g318, g325.

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Onboard Deterministic Computer Program

CODE NUMBER: 25.3 DATE: 7/6/82 NAME(S): Oliveira/Glass/Smith

DESCRIPTION OF CAPABILITY: An onboard deterministic computer program is a software package which uses an algorithmic language (e. g. FORTRAN), implemented on a spacecraft computer or microprocessor. Its functions might include scheduling, monitoring data from components, numerical computation, control of subsystems, and simple evaluations of performance. This is an onboard equivalent to 25.4 Deterministic Computer Program on Ground.

WHO IS WORKING ON IT AND WHERE: Intermetrics, Rockwell, Martin Marietta, TRW, Honeywell, and other spacecraft software contractors.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Although each new program must be developed, the methods to do so have been used before, and are well established.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
2-3: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: The costs of individual programs depend on complexity and safety requirements.

REMARKS ON SPECIAL ASPECTS: None.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 25.4 Deterministic Computer Program on Ground

CAPABILITY APPLIES TO (GFE NUMBERS): g24, g35, g37, g38, g47, g78, g83, g87, g88, g92, g93, g94, g97, g103, g110, g218, g220, g221, g223, g224, g239, g240, g241, g244, g318, g325

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Deterministic Computer Program on Ground

CODE NUMBER: 25.4 DATE: 7/8/82 NAME(S): Oliveira/Smith

DESCRIPTION OF CAPABILITY: This capability is defined as a software package which uses an algorithmic language (e.g. FORTRAN), implemented on a mainframe computer or microprocessor, on the ground. Computer programs of this type perform a broad spectrum of computational and organizational tasks, (e.g. scheduling, monitoring telemetry from spacecraft, numerical computation, control of subsystems (via telemetry), and simple evaluations of system performance). Such programs are defined and optimized for their functions, and therefore dedicated to their tasks.

WHO IS WORKING ON IT AND WHERE: Intermetrics, Martin Marietta, TRW, Rockwell, Draper Labs, and many other ground support software contractors.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Although each new program must be developed, the methods to do so have been used before, and are well established.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: Quality software may take anywhere from 2-5 man years from the conceptual state to the actual debugged fully operational package. The costs of individual programs depend on complexity and safety requirements.

REMARKS ON SPECIAL ASPECTS: None.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): Computer Programming Techniques.

CAPABILITY APPLIES TO (GFE NUMBERS): g10, g24, g35, g37, g38, g47, g56, g60, g78, g83, g87, g88, g92, g93, g94, g97, g110, g184, g194, g220, g221, g223, g224, g239, g240, g244, g318, g235

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Onboard Adaptive Control System

CODE NUMBER: 25.5 DATE: June 1982 NAME(S): Howard/Glass/Kurtzman/Smith

DESCRIPTION OF CAPABILITY: A control system which monitors its surroundings as well as its own performance, to adjust its control strategy to compensate for changes in its working environment. The system develops a dynamic, variable model to predict trends, and can therefore anticipate problems and optimize responses. By monitoring its own performance, the system is able to deduce sensor or actuator malfunctions, and adjust control algorithms accordingly. Although certain parameters are allowed to vary, and the model can be updated by the system to some extent, an adaptive control system is less sophisticated than a true learning expert system.

WHO IS WORKING ON IT AND WHERE: O. Selfridge, BB&N; D. Michie, University of Illinois, Champaign-Urbana; B. Govin and B. Claudinon, Matra Espace, France; W. Vander Velde and C. Carignan, MIT Space Systems Lab.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: 1984 LEVEL6: 1985 LEVEL7: 1987

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Source: Joseph Oliveira, MIT-SSL.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: $1 million 5-6: $1 million 6-7: $.5 million

REMARKS AND DATA SOURCES ON COST ESTIMATES: The cost and time estimates refer to the task of developing this technology for a particular application. The basic theoretical work has been done.

REMARKS ON SPECIAL ASPECTS: An Onboard Adaptive Control System is often best implemented on a hierarchy of microprocessors (distributed intelligence). This allows the complexity of individual subsystems to be kept within tolerable limits regardless of the complexity of the overall system. Also, the functional structure of an adaptive system is hierarchical in nature, which makes it well suited for this type of implementation.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 25.2 Onboard Microprocessor Hierarchy

CAPABILITY APPLIES TO (GFE NUMBERS): g83, g87, g88, g103, g240, g318

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Fault Tolerant Software

CODE NUMBER: 26.1 DATE: 5/10/82 NAME(S): Thiel/Dalley

DESCRIPTION OF CAPABILITY: The term Fault Tolerant Software has two meanings. The definition most commonly used is a software package which is capable of responding to hardware faults and errors. This technology is actively being researched for the military by various industrial and research laboratories. Aircraft computers now use some fault tolerant software. The second definition is much less common because this particular technology is in its infancy. This more advanced technology concerns software that is tolerant of software errors and design faults. The software continuously monitors itself and its operations to insure that it is performing correctly. It is also capable of correcting these errors and continuing with its normal operations.

WHO IS WORKING ON IT AND WHERE: Some theoretical work has been done at the MIT Artificial Intelligence Laboratory, but in general this technology has had little work done on it. Sussman (MIT AI) wrote a program called Hacker which generates software and then verifies that the software is correct. This proves the concept of self-checking software, but Hacker is more of an Automatic Programmer than a fault tolerant software package. (See 22.1 Automatic Programmer and Program Tester).

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: N/A
LEVEL4: N/A LEVEL5: N/A LEVEL6: N/A LEVEL7: N/A

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: So little development has been done in this area that it is impossible to say when this technology will be available. Also, many software technologies will benefit from fault tolerant software, but these same technologies (such as expert systems) may contribute to the development of fault tolerant software as well, thus complicating the problem of predicting when this technology will be developed. Finally, fault tolerant software requires some fundamental developments in the AI field which are not possible to predict in advance. (D. Hillis, MIT AI).

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: The same reasons that prevent a reasonable extimate of development schedule prevent cost estimates as well.

REMARKS ON SPECIAL ASPECTS: The fundamental developments in the field of artificial intelligence which enhance other advanced software technologies, such as learning expert systems and automatic programmers, enhance fault tolerant software as well.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 27.1 Equipment Function Test by Onboard Computer; (See remarks above).

CAPABILITY APPLIES TO (GFE NUMBERS): g56, g77, g194, g241

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Equipment Function Test by Onboard Computer

CODE NUMBER: 27.1 DATE: 6/26/82 NAME(S): Marra/Dalley/Smith

DESCRIPTION OF CAPABILITY: Spacecraft equipment is activated and performance is monitored and compared to expected levels, by an onboard computer. This is done entirely by the computer and there is no active human component. A "function test" is an intrusive procedure, i.e. commands are sent by the computer to spacecraft components, requesting specific actions used in status monitoring of fault diagnosis. This differs from "data checks" (i.e. capabilities 27.4, 27.5, 27.6) which only operate on normally available data.

WHO IS WORKING ON IT AND WHERE: IBM; NASA GSFC; Jet Propulsion Laboratory, California Institue of Technology; NASA Ames (JPL and Ames specialize in planetary probes); Draper Laboratories.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: 1983 LEVEL7: 1983

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: Adequate spacecraft computers are available today. What needs to be developed is the software for each application.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: see below 6-7: see below

REMARKS AND DATA SOURCES ON COST ESTIMATES: Assuming that the necessary computers are already available, about it will take about $300,000 to bring an onboard function test online (study team estimate).

REMARKS ON SPECIAL ASPECTS: This is an accurate method for evaluating status and diagnosing failures, since it uses checking routines on spacecraft components. However, a function test applied to a defective subsystem can make the problem worse.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 27.2 Equipment Function Test by Onsite Human; 25.2 Onboard Microprocessor Hierarchy

CAPABILITY APPLIES TO (GFE NUMBERS): g1, g10, g23, g33, g48, g49, g50, g51, g52, g60, g194, g260

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Equipment Function Test by Onsite Human

CODE NUMBER: 27.2 DATE: 6/25/82 NAME(S): Marra/Glass/Smith

DESCRIPTION OF CAPABILITY: Equipment is activated and the performance is measured and compared to expected levels by an onsite human. The human will have the equipment necessary to perform the tests, including a dedicated microcomputer. A "function test" is an intrusive procedure, i.e. commands are sent by the computer to spacecraft components, requesting specific actions used in status monitoring of fault diagnosis. This differs from "data checks" (i.e. capabilities 27.4, 27.5, 27.6) which only operate on normally available data.

WHO IS WORKING ON IT AND WHERE: NASA Centers (JSC, MSFC)

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The specific function test, including necessary hardware, must be developed in each case, but such techniques are currently in use.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: This is an accurate method for evaluating status and diagnosing failures, since it uses checking routines on spacecraft components. However, a function test applied to a defective subsystem can make the problem worse. This capability should not be confused with Onsite Human with Computer Assistance, which is an astronaut in the Shuttle, using the orbiter computers. The Equipment Function Test uses a dedicated microprocessor (if needed) to support the onsite human.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 27.5 Equipment Data Checks by Onsite Human

CAPABILITY APPLIES TO (GFE NUMBERS): g1, g10, g23, g24, g33, g48, g49, g50, g51, g52, g60, g194, g260

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Equipment Function Test via Telemetry

CODE NUMBER: 27.3 DATE: 7/1/82 NAME(S): Marra/Jones-Oliveira/Smith

DESCRIPTION OF CAPABILITY: Equipment is activated commands from the ground. The performance of the equipment is then measured and compared to expected levels. All of the testing is carried out through a telemetry link. A "function test" is an intrusive procedure, i.e. commands are sent by the computer to spacecraft components, requesting specific actions used in status monitoring of fault diagnosis. This differs from "data checks" (i.e. capabilities 27.4, 27.5, 27.6) which only operate on normally available data.

WHO IS WORKING ON IT AND WHERE: NASA GFSC; NASA JSC; NASA Ames Research Center; JPL; also the operators of weather, resource monitoring, communications, surveillance, and scientific satellites.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: This is a commonly used current technology.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: None.

REMARKS ON SPECIAL ASPECTS: One advantage of this concept is that the same ground equipment can be used for more than one spacecraft; this helps reduce costs. This is an accurate method for evaluating status and diagnosing failures, since it uses checking routines on spacecraft components. However, a function test applied to a defective subsystem can make the problem worse.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 27.6 Equipment Data Checks via Telemetry; 25.4 Deterministic Computer Program on Ground

CAPABILITY APPLIES TO (GFE NUMBERS): g23, g33, g48, g49, g50, g51, g52, g60, g194, g260

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Equipment Data Checks By Onboard Computer

CODE NUMBER: 27.4 DATE: 6/22/82 NAME(S): Thiel/Dalley

DESCRIPTION OF CAPABILITY: This is a nonintrusive method of verifying the correct operation of space systems and components. An onboard computer samples the inputs and/or outputs of a component or system and compares them to expected values. Therefore this method can only apply to equipment which processes data or generates some kind of telemetry. Also, the computer does not command the equipment it is testing; it only monitors the data generated by the equipment's operation.

WHO IS WORKING ON IT AND WHERE: This is not a specific area of technology that is being developed on its own. It is a byproduct of present testing techniques performed by ground controllers and of the advancing level of computer technology. The Voyager spacecraft performed some equipment checkout by onboard computer.

TECHNOLOGY LEVELS: LEVEL1: NOW LEVEL2: NOW LEVEL3: NOW
LEVEL4: NOW LEVEL5: NOW LEVEL6: NOW LEVEL7: NOW

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The techniques for performing this kind of operation are present technology and have had limited demonstration in space (Voyager). The use of Equipment Data Checks by Onboard Computer will become very common as spacecraft computers become more common.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: This capability has been demonstrated in space and therefore may be considered a current technology. Further work will involve the writing of algorithms for spacecraft computers to perform the equipment data checks. The costs of these algorithms depend on their individual complexity.

REMARKS ON SPECIAL ASPECTS: This test does not disturb the normal operation of the equipment being tested; therefore it is not capable of testing a quiescent piece of equipment or commanding it to change operating modes.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 25.2 Onboard Microprocessor Heirarchy; 27.5 Equipment Data Checks by Onsite Human.

CAPABILITY APPLIES TO (GFE NUMBERS): g10, g23, g33, g48, g49, g54, g56, g150, g264

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Equipment Data Checks By Onsite Human

CODE NUMBER: 27.5 DATE: June 1982 NAME(S): Howard/Glenn/Smith

DESCRIPTION OF CAPABILITY: Sample data is read and compared to a system model by an onsite human, with assistance of a dedicated microprocessor. The human does not have to be in EVA; more likely, the operator will be in the Shuttle or in a station. Such "data checks" are a nonintrusive procedure, i.e. they only operate on normally available data. This differs from "function tests" (i.e. capabilities 27.1, 27.2, 27.3) which apply test commands to the spacecraft subsystems.

WHO IS WORKING ON IT AND WHERE: Various NASA Centers (e.g. JSC, MSFC).

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: Now
LEVEL4: Now LEVEL5: Now LEVEL6: Now LEVEL7: Now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: The specific data checks, including necessary test hardware, must be developed in each case, but such techniques are currently in use.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: N/A

REMARKS ON SPECIAL ASPECTS: Data checks are similar to monitoring telemetry; no commands or test input are transmitted to the unit under test. This capability should not be confused with Onsite Human with Computer Assistance, which is an astronaut in the Shuttle, using the orbiter computers. The Equipment Data Checks use a dedicated microprocessor (if needed) to support the onsite human.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 14.3 Human In EVA With Tools; 25.1 Onboard Dedicated Microprocessor

CAPABILITY APPLIES TO (GFE NUMBERS): g23, g33, g48, g49, g54, g56, g150

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ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Equipment Data Checks via Telemetry

CODE NUMBER: 27.6 DATE: 5/12/82 NAME(S): Jones-Oliveira/Smith

DESCRIPTION OF CAPABILITY: Sampled spacecraft data is sent down to ground stations via telemetry. This data is then compared to a system model, to evaluate spacecraft status and to diagnose failures. Such "data checks" are a nonintrusive procedure, i.e. they only operate on normally available data. This differs from "function tests" (i.e. capabilities 27.1, 27.2, 27.3) which apply test commands to the spacecraft subsytems.

WHO IS WORKING ON IT AND WHERE: Various NASA Centers, including Ames, Goddard, and JSC; JPL; General Electric in Philadelphia, PA; TRW in Redondo Beach, CA; also the operators of weather, resource monitoring, communications, surveillance, and scientific satellites.

TECHNOLOGY LEVELS: LEVEL1: now LEVEL2: now LEVEL3: now
LEVEL4: now LEVEL5: now LEVEL6: now LEVEL7: now

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: This is a commonly used current technology.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: None.

REMARKS ON SPECIAL ASPECTS: This capability can be written into software as a routine subsystem checkout. One advantage of this concept is that the same ground equipment can be used for more than one spacecraft; this helps reduce costs.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 13.2 Human Eyesight via Graphic Display; 13.4 Computer Printout; Communications Techniques.

CAPABILITY APPLIES TO (GFE NUMBERS): g23, g33, g48, g49, g54, g56, g150, g264

ARAMIS CAPABILITY GENERAL INFORMATION FORM

CAPABILITY NAME: Internal Acoustic Scanning

CODE NUMBER: 27.7 DATE: 7/2/82 NAME(S): Marra/Jones-Oliveira

DESCRIPTION OF CAPABILITY: This is a non-destructive method of determining the status of a given structural system. Acoustic signals are sent through the structure. The acoustic signature is recorded and compared by a computer to a library of signatures of the structure in various states. The status of the structure is determined by this comparison.

WHO IS WORKING ON IT AND WHERE: General Electric Co., Space Div., Daytona Beach, Fla.

TECHNOLOGY LEVELS: LEVEL1: Now LEVEL2: Now LEVEL3: see below
LEVEL4: see below LEVEL5: see below LEVEL6: see below LEVEL7: see below

REMARKS AND DATA SOURCES ON TECHNOLOGY LEVELS: General Electric has done a study on this system. However, only the abstract was available to the study group and no one who was related to the project could be contacted. The name of the study is:

> Mechanical Systems Readiness Assessment and Performace Monitoring Study: Final Report. Contract No. NAS10-7788. General Electric Co. Space Div., Daytona Beach, Florida, May, 1972.

R&D COST ESTIMATES BETWEEN LEVELS; 1-2: N/A 2-3: N/A
3-4: N/A 4-5: N/A 5-6: N/A 6-7: N/A

REMARKS AND DATA SOURCES ON COST ESTIMATES: The cost estimates were not available to the study group.

REMARKS ON SPECIAL ASPECTS: This system is dedicated specifically to the structure subsystem checkout.

TECHNOLOGY TREES (PRIOR R&D OF THESE IS DESIRABLE.): 19.1 A/D Converter; 25.1 Onboard Dedicated Microprocessor

CAPABILITY APPLIES TO (GFE NUMBERS): g49

APPENDIX 3.D:
TECHNOLOGY TREES

3.D.1 Notes on this Appendix

Technology Trees are representations of favorable sequences of development of ARAMIS capabilities. In other words, they identify those capabilities and technologies whose development benefits the later R&D of other capabilities. Technology Trees therefore map out evolutionary paths of ARAMIS development.

As it turns out, the R&D of almost all of this study's 78 capabilities is interrelated, and these capabilities also benefit from 12 fundamental technologies (although some of these technologies only enhance one or two capabilities). These fundamental technologies are listed in Table 3.D.1.

TABLE 3.D.1: FUNDAMENTAL TECHNOLOGIES, WHICH ENHANCE R&D OF ARAMIS CAPABILITIES

Computer Programming Techniques
Computer Memory Development
Space-Rated Integrated Circuits
EVA Tools
Laser Technology
Cryogenic Cooling Techniques
Communications Techniques
Global Positioning System
Supervisory Control
Space-Rated Polymers
Manipulator End-Effectors
Micro-Actuators

The study group therefore separated the overall tree into 8 more specific Technology Trees, with interconnections between the trees. Section 3.4.3 presented an example to illustrate the rules devised to set up these trees. For convenience, this section repeats the example (as Figure 3.D.1) and the rules used in the display of the Technology Trees:

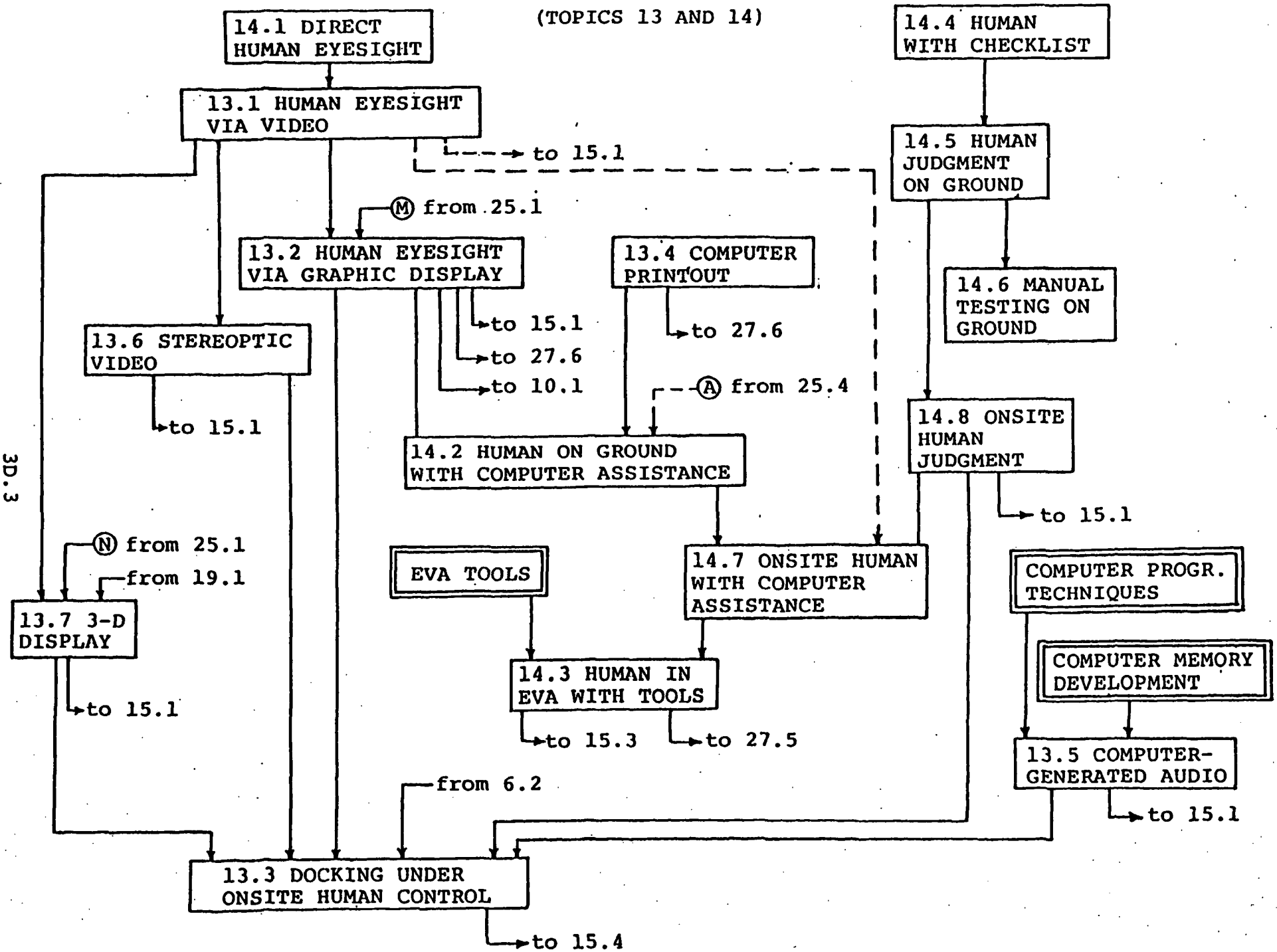
1) The Trees are presented as flowcharts, to be read from top to bottom (i.e. the development of the capabilities and technologies at the top of the figure enhances the R&D of the capabilities lower down).

2) Each capability is displayed in a single box, and appears only once in all the Trees. The fundamental technologies, however, are displayed in double boxes, and can appear in several Trees; for example, Computer Programming Techniques appears in several other Trees, besides the one in the example.

3) A direct enhancement of a capability's R&D by the prior development of a capability or technology is indicated by a solid arrow between them. However, capabilities are also considered to benefit from items further up the trees. For example, 14.2 Human on Ground with Computer Assistance benefits directly from earlier R&D of 13.4 Computer Printout and of 13.2 Human Eyesight via Graphic Display. However the Human on Ground with Computer Assistance, through 13.2, also benefits from development of 13.1 Human Eyesight via Video and 25.1 Onboard Dedicated Microprocessor (from another Tree), and so on up the Trees. The capabilities or technologies up those trees are said to be "available" to 14.2 Human on Ground with Computer Assistance.

FIGURE 3.D.1: ARAMIS TECHNOLOGY TREE (NO. 3 of 8)

(TOPICS 13 AND 14)



4) Although a capability may have several strings of capabilities and technologies "available" to it in the Trees, not all of these are necessarily useful to the capability's R&D in a particular application. For example, some applications of Human on Ground with Computer Assistance would not benefit from earlier R&D of 13.2 Human Eyesight via Graphic Display, but might benefit from Human Eyesight via Video, available through 13.2. Therefore some engineering judgment is needed in evaluating the actual contributions of other capabilities or technologies. As another example, Human on Ground with Computer Assistance benefits from the software development behind 25.1 Onboard Dedicated Microprocessor, not from the development of the space-rated microprocessor itself.

5) In those cases where one of the "available" capabilities several levels up the Tree is particularly relevant, this is indicated by a dashed arrow. In the example, 14.7 Onsite Human with Computer Assistance benefits from 13.1 Human Eyesight via Video, through 14.2 and 13.2. However, 13.1 is considered to contribute significantly to the R&D of 14.7, and therefore a dashed arrow emphasizes the connection.

The study group found that the clearest separation of the 8 Technology Trees came from clustering ARAMIS topics into individual trees. In the example, topics 13 (Human-Machine Interfaces) and 14 (Human Augmentation and Tools) are closely interrelated, and are therefore displayed together in one Tree. In general, clustering by topics minimizes the numbers of interconnections between the Trees, simplifying the overall presentation. For

the convenience of the reader, the ARAMIS topics are listed in Table 3.D.2.

The eight Technology Trees follow. The topics presented in each tree are identified above the flowchart. Most of the interconnections between the eight trees extend from the 5 capabilities associated with topic 25 (Computer Architecture): these enhance 24 capabilities in other trees. Therefore these 24 capabilities are listed out by name in Technology Tree no. 1, to emphasize the potential effect of development of the computer architecture capabilities.

TABLE 3.D.2: 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

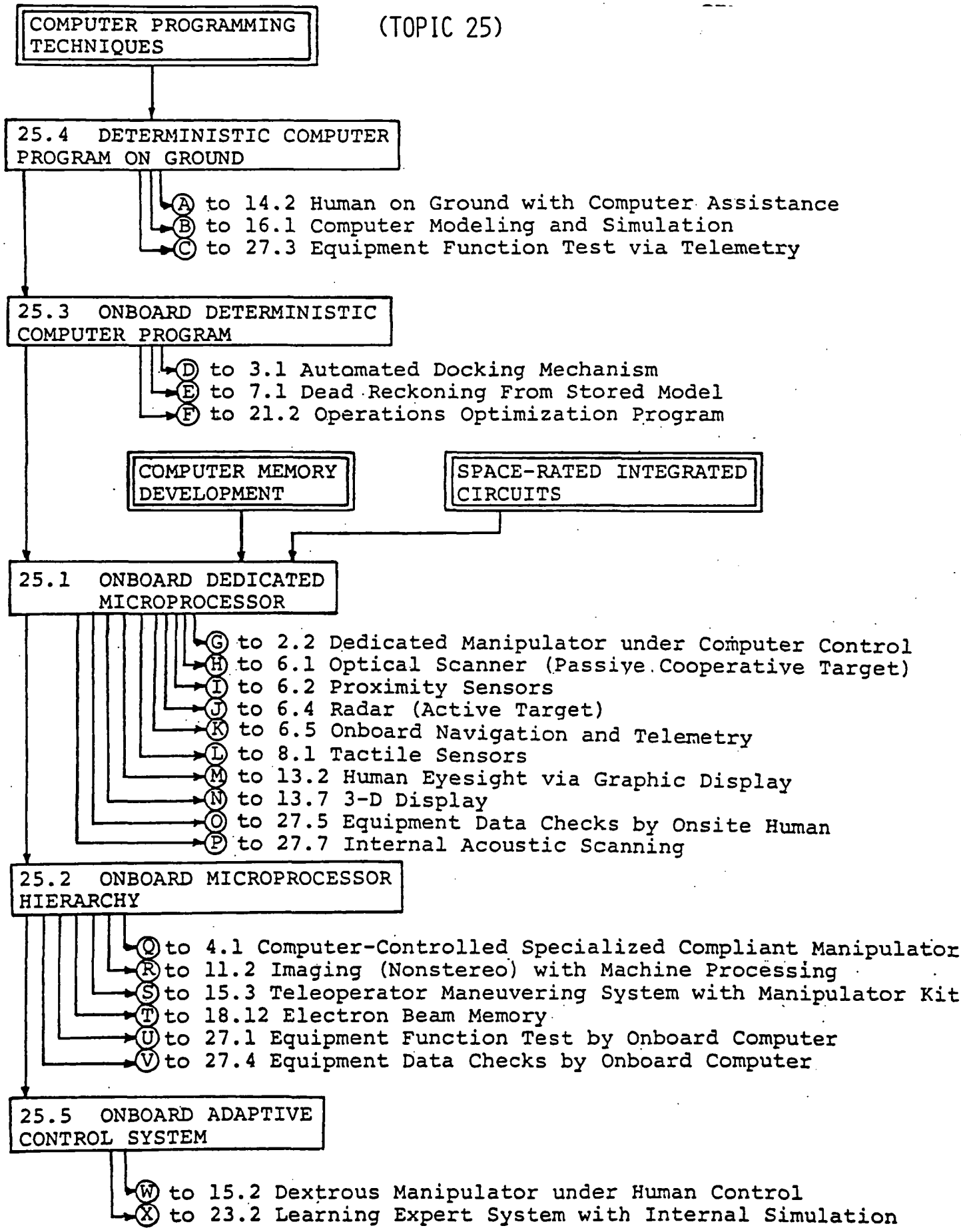
COMPUTER INTELLIGENCE

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

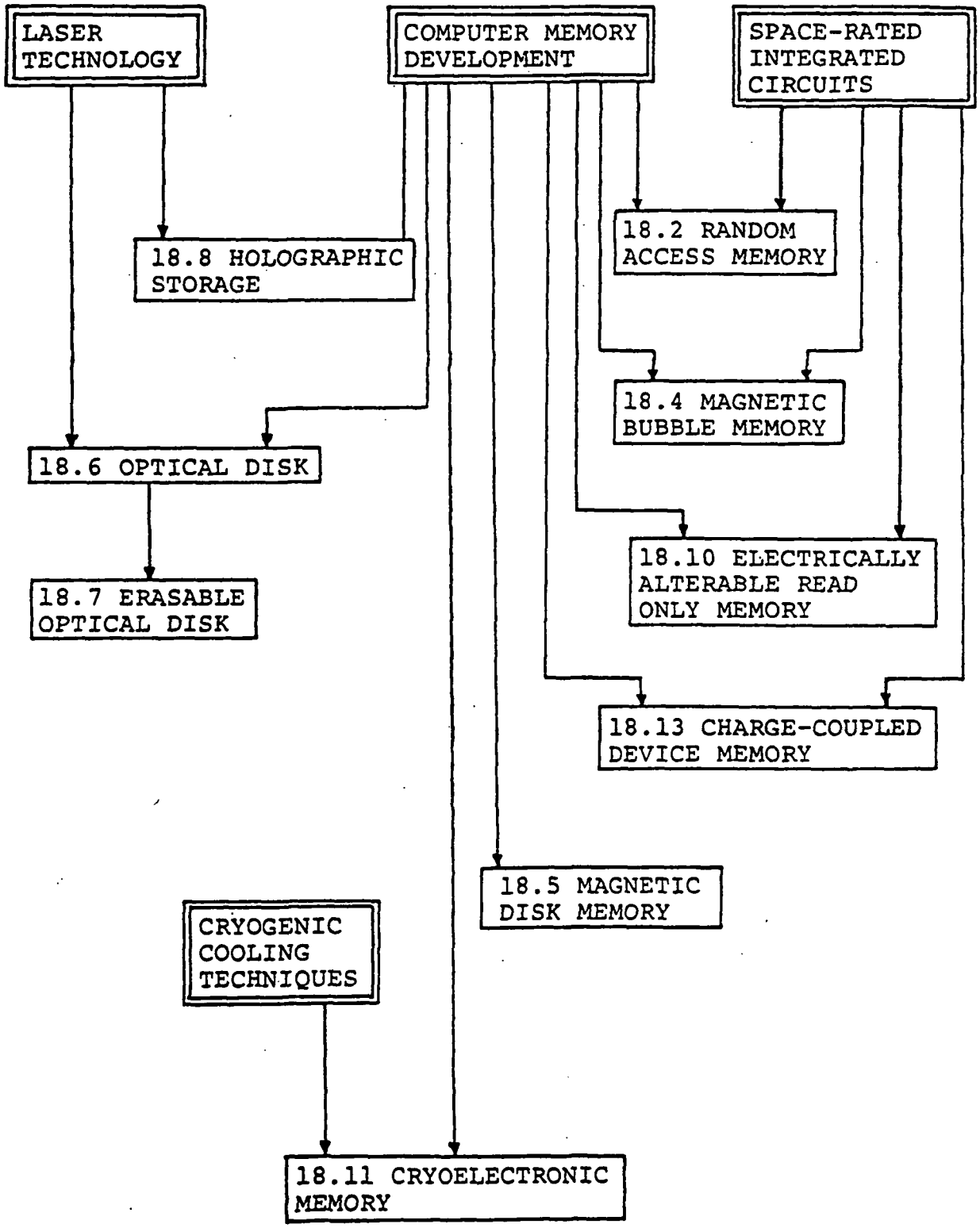
FAULT DETECTION & HANDLING

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

ARAMIS TECHNOLOGY TREE (NO. 1 OF 8)

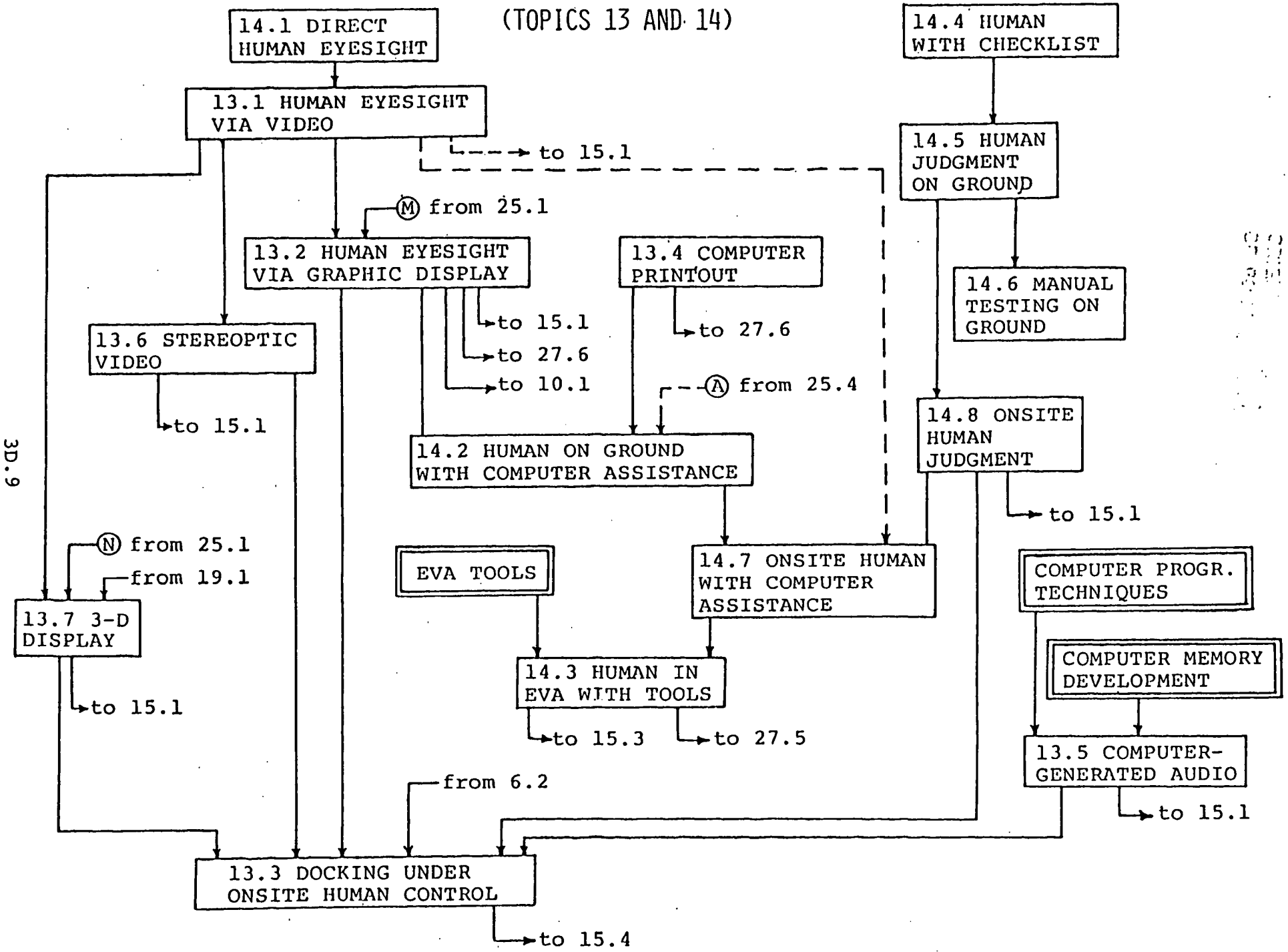


ARAMIS TECHNOLOGY TREE (NO. 2 OF 8)
(TOPIC 18, EXCEPT CAPABILITY 18.12)



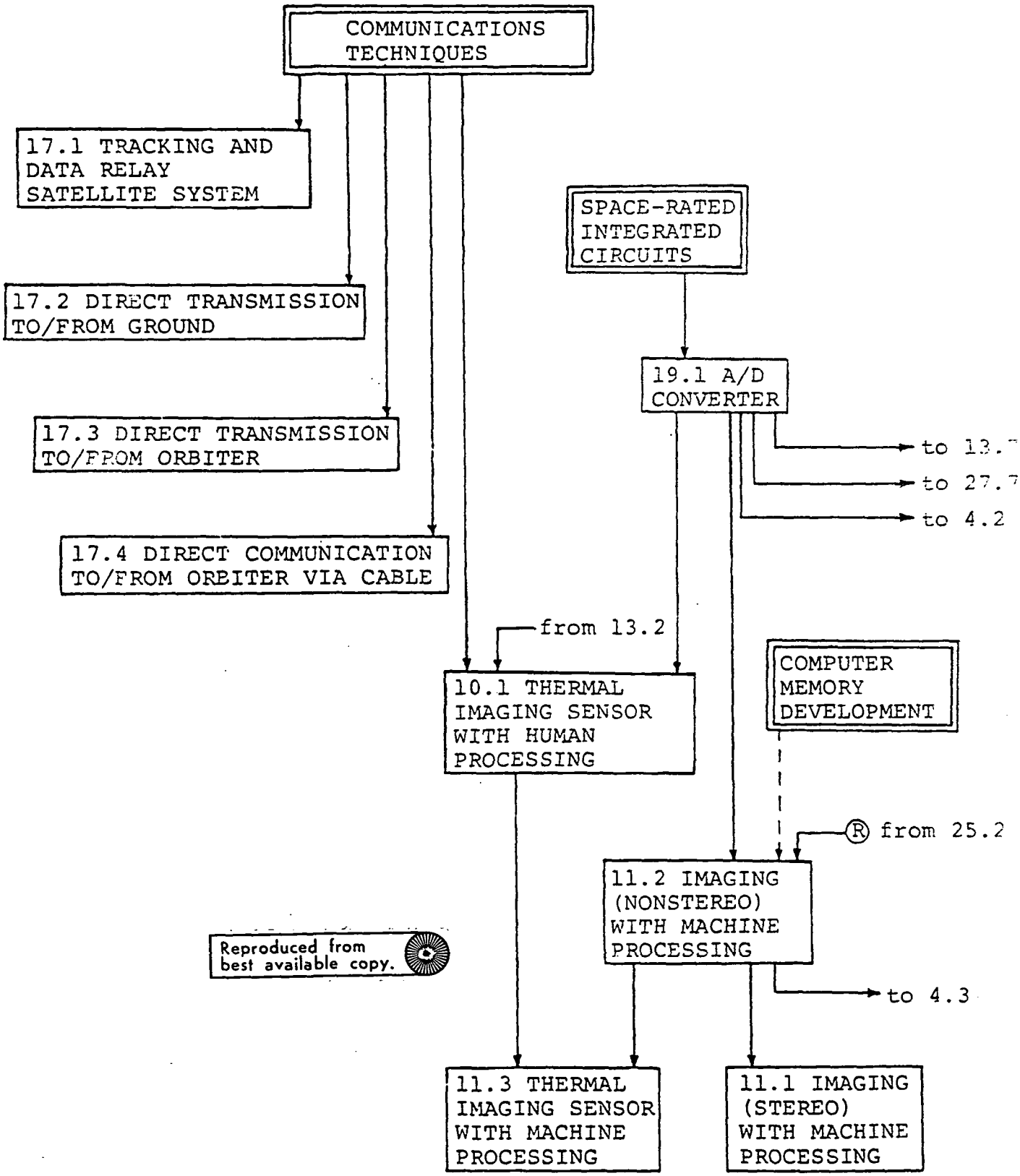
ARAMIS TECHNOLOGY TREE (NO. 3 OF 8)

(TOPICS 13 AND 14)



ARAMIS TECHNOLOGY TREE (NO. 4 OF 8)

(TOPICS 10, 11, 17, AND 19)



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ARAMIS TECHNOLOGY TREES (NO. 5 OF 8)

(TOPICS 2, 4, AND 8; ALSO CAPABILITIES 1.6, 6.2, 15.1, 15.2)

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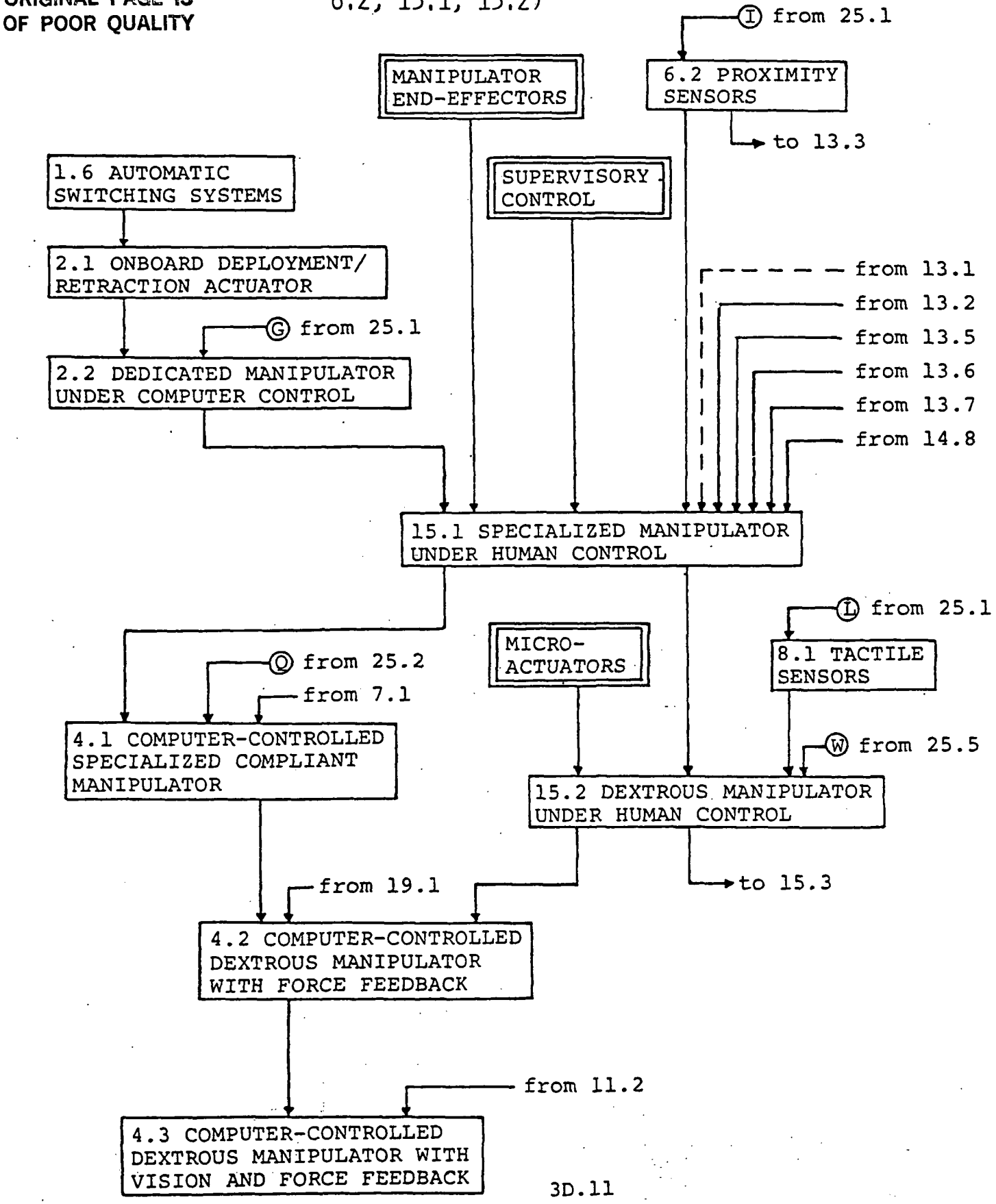
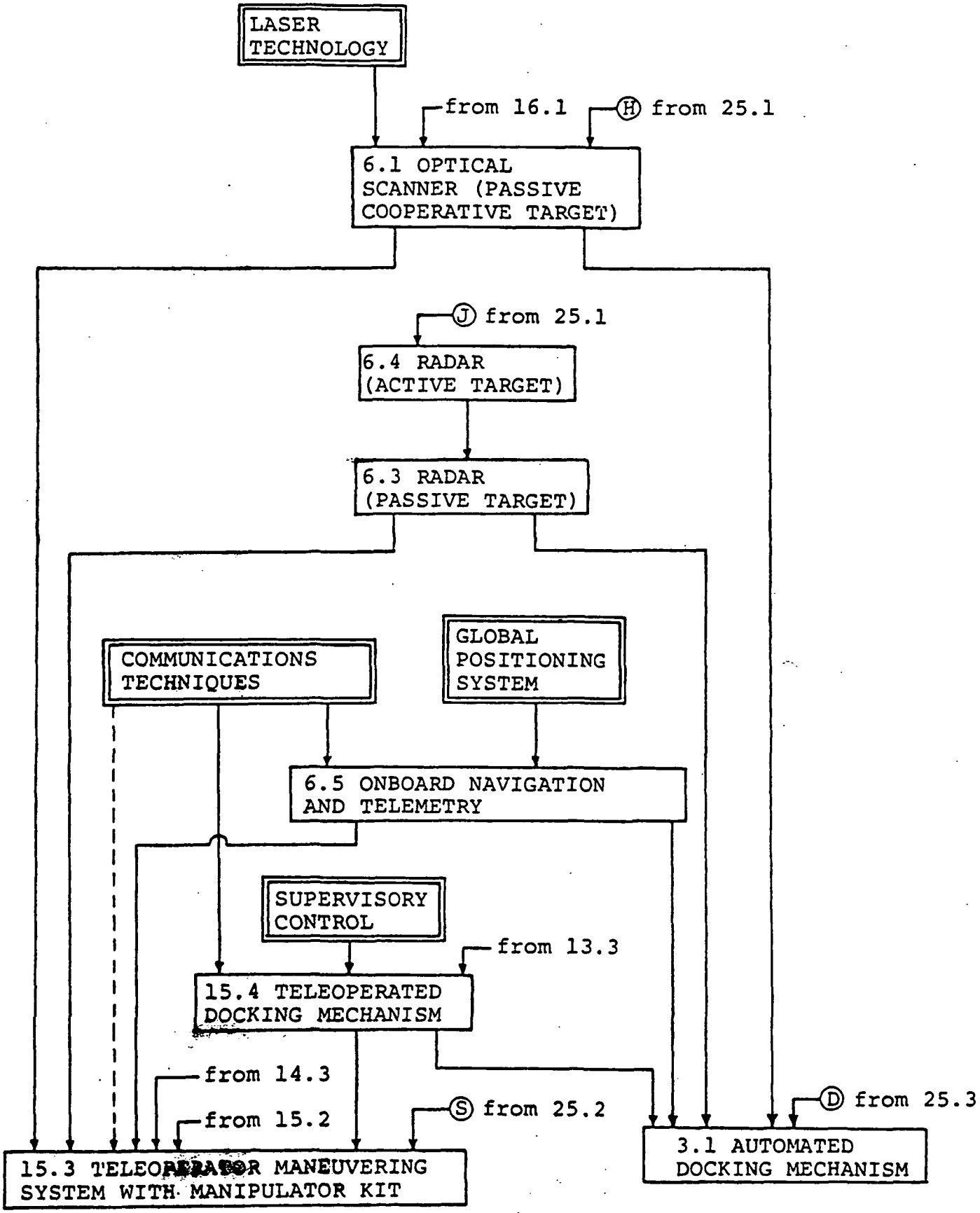
OF POOR QUALITY

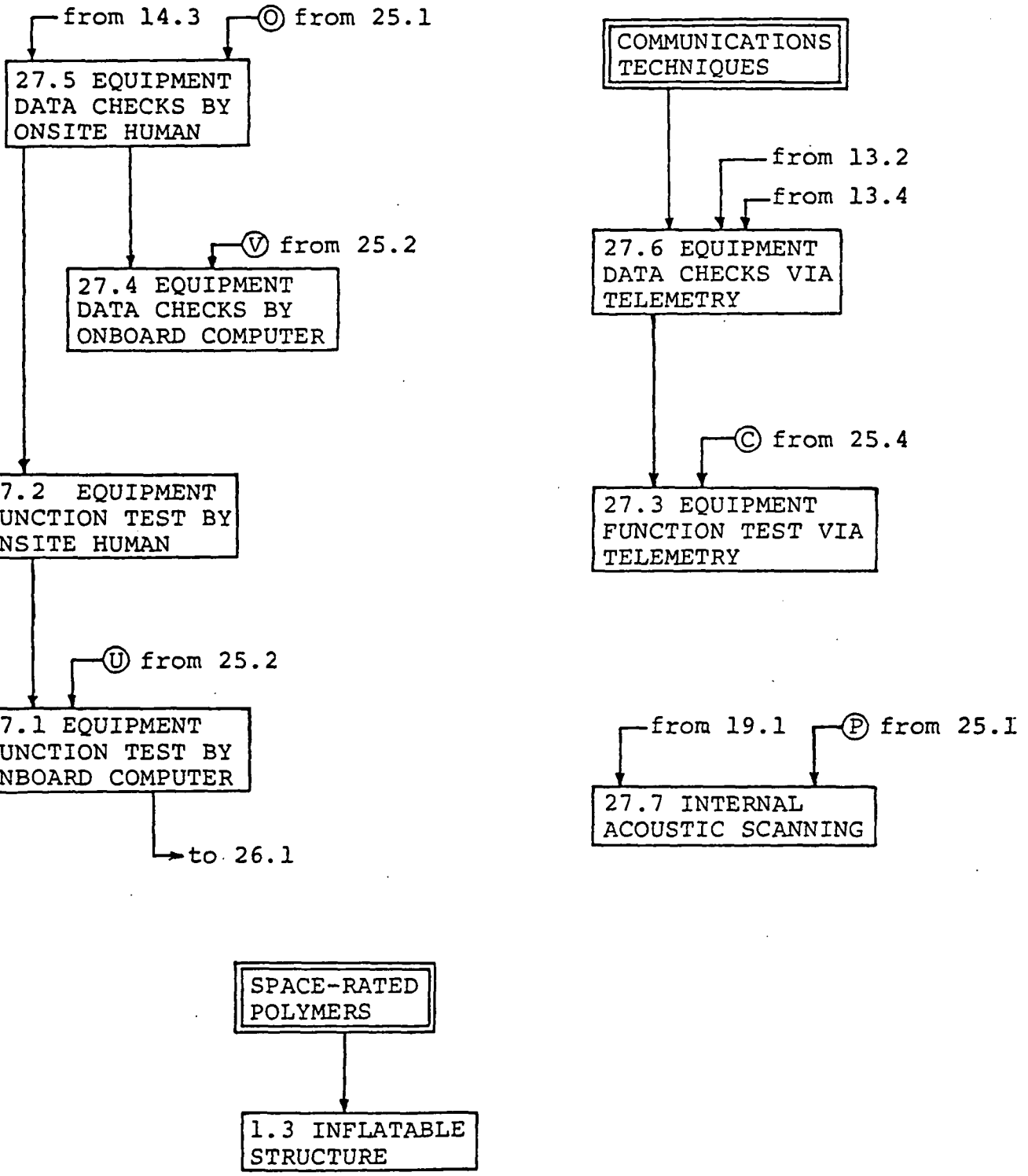


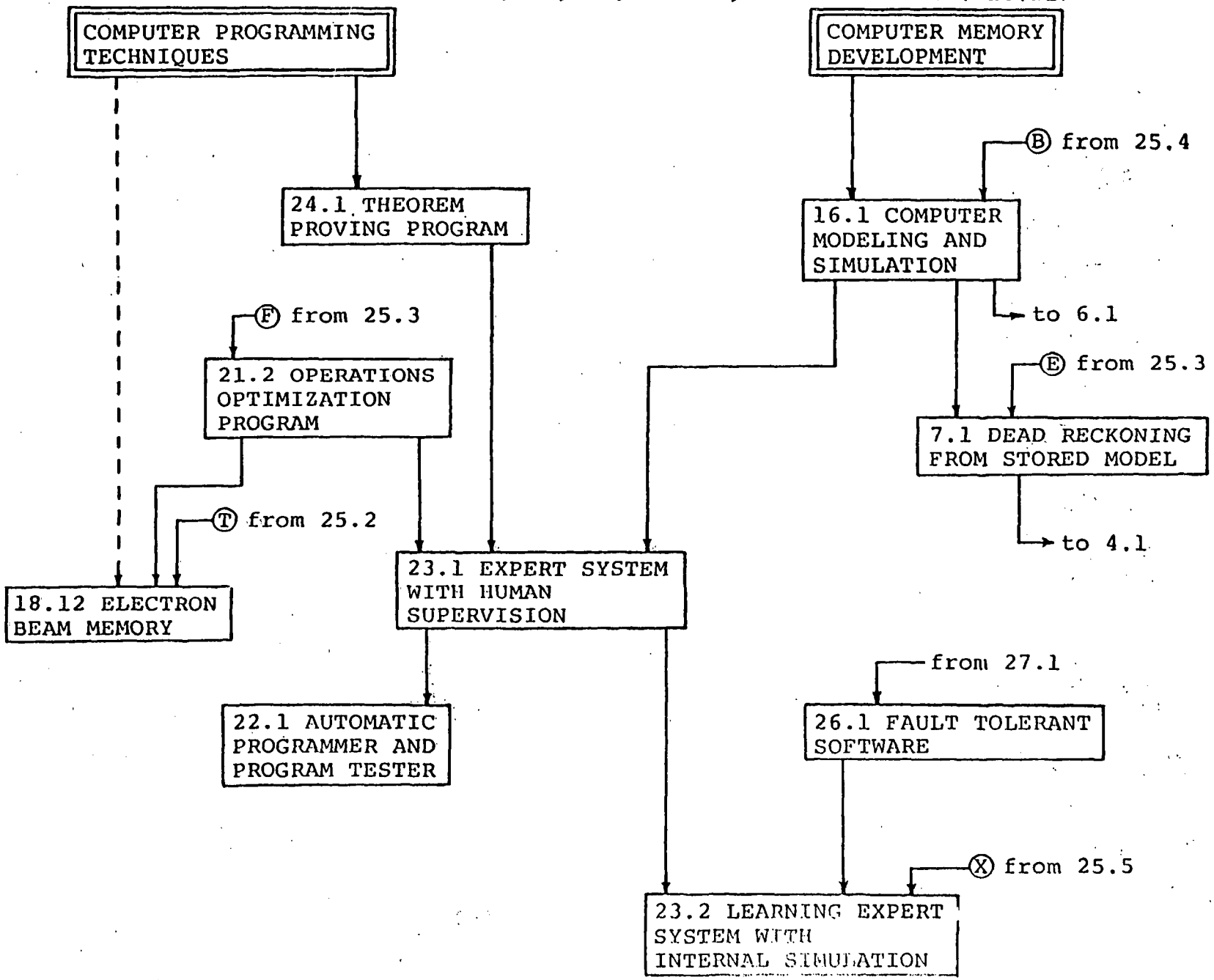
ARAMIS TECHNOLOGY TREE (NO. 6 OF 8)

(TOPICS 3 AND 6, EXCEPT CAPABILITY 6.2; ALSO CAPABILITIES 15.3, 15.4)



ARAMIS TECHNOLOGY TREE (NO. 7 OF 8)
(TOPICS 1 AND 27)



ARAMIS TECHNOLOGY TREE (NO. 8 OF 8)

(TOPICS 7, 16, 21, 22, 23, 24, AND 26; ALSO CAPABILITY 18.12)