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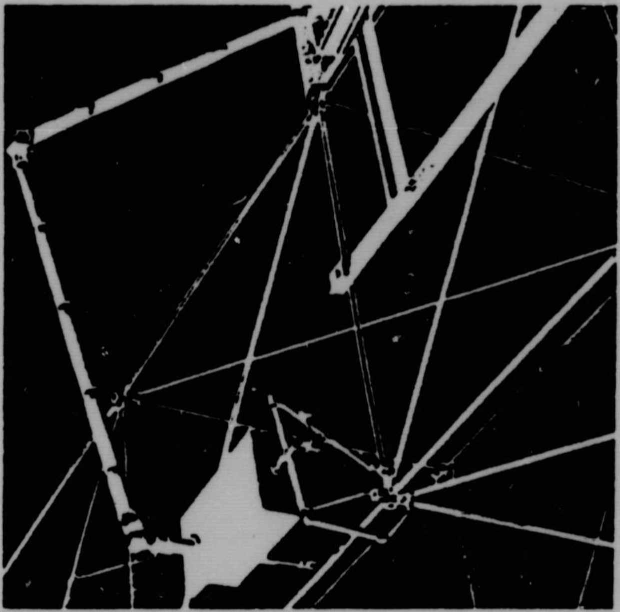
Volume I

Final Report November 1984

Executive Summary

Autonomous Systems and Assembly

Space Station Automation Study



MARTIN MARIETTA

MCR 84-1878
November 1984

FOREWORD

This final report, prepared by Martin Marietta Denver Aerospace, provides the technical results to the Space Station Automation Study. The report is submitted in volumes:

Volume 1 - Executive Summary

Volume 2 - Technical Report

These documents are submitted in accordance with the requirements of contract NAS8-35042. They reflect the work performed under task 5.3, "Space Station Automation Study", for the George E. Marshall Space Flight Center of the National Aeronautics and Space Administration.

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1.0 INTRODUCTION

1.1 PURPOSE

The purpose of the Space Station Automation Study (SSAS) was to develop informed technical guidance for NASA personnel in the use of autonomy and autonomous systems to implement Space Station functions.

1.2 GENERAL APPROACH

The initial step taken by NASA in organizing the SSAS was to form and convene a panel (Figure 1-1) of recognized expert technologists in automation, space sciences and aerospace engineering to produce a Space Station automation plan.

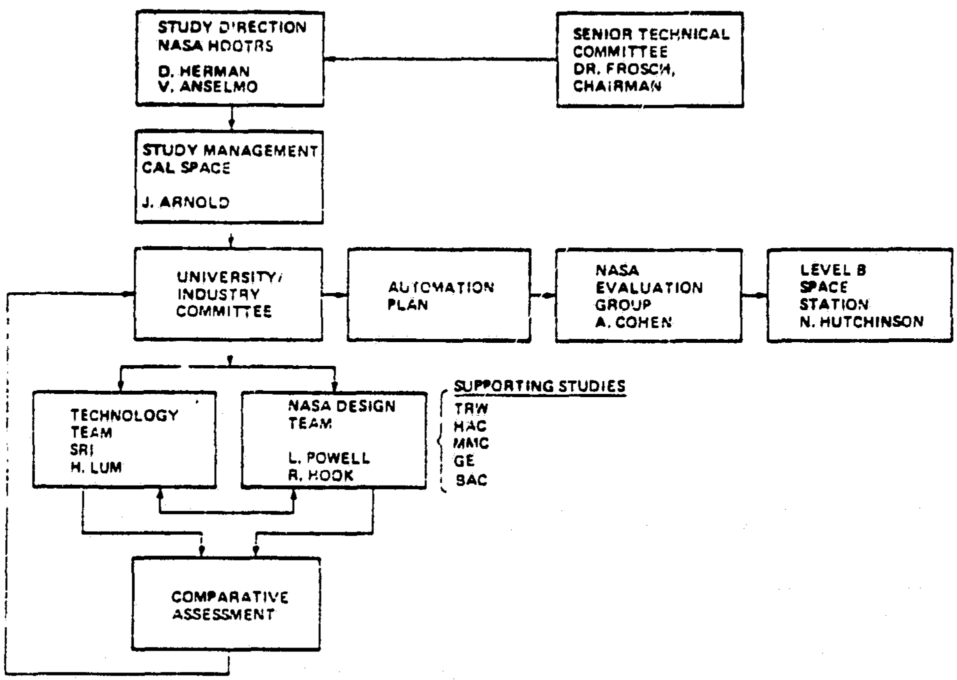


Figure 1-1 SSAS Organization

As indicated on this schematic, California Space Institute (CSI) was assigned the responsibility for study management. A Senior Technical Committee, chaired by Dr. Robert Frosch, was appointed to provide overall technical guidance.

A NASA Technology Team was convened to produce focused technology forecasts, supporting panel analyses, and system concept designs. Stanford Research Institute (SRI) International was assigned to this team.

A NASA Design Team was also convened to produce innovative, technologically-advanced automation concepts and system designs supporting and expressing panel analyses. The emphasis of this effort was to strengthen NASA understanding of practical autonomy and autonomous systems. Four aerospace contractors--General Electric (GE), Hughes Aircraft Company (HAC), TRW and Martin Marietta Corporation (MMC, Denver Division Aerospace)--were assigned to this team. Halfway through the study, a fifth contractor, Boeing Aerospace Company (BAC), was also assigned to this team.

A work breakdown for the original four contractors was assigned as shown in Figure 1-2. The fifth contractor, Boeing, was assigned to investigate and report on man-machine interfaces.

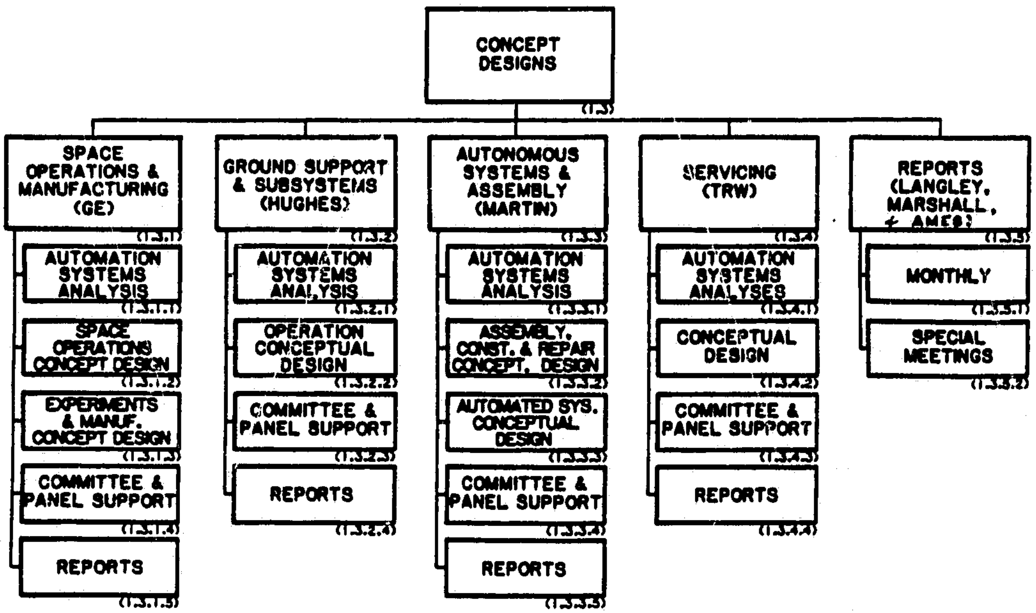


Figure 1-2 SSAS Work Breakdown Structure

1.3 MMC OBJECTIVES

Martin Marietta's assigned study responsibility covered two specific and significant areas relating to projection of a futuristic Space Station and the type of scarring necessary for evolutionary implementation. The two basic objectives of the MMC effort were:

a) Define through analysis the potential ultimate conceptual design of the Space Station systems to the highest level of automation that can be perceived to be accomplished by circa 2000. Specifically, this involved the overall system and selected subsystems (environmental control and life support, electrical power and information and data management). In a parallel effort, Hughes Aircraft Company addressed the other subsystems.

b) Define through analysis the system-level applications of automation technology for assembly, construction, repair and modification of a Space Station and its various elements.

The system automation was conceptualized at circa 2000, then backed toward the Initial Operational Capability (IOC) space station. Conversely, the assembly and construction technologies were built on IOC reference concepts, then extended from IOC to circa 2000.

1.4 BACKGROUND

The Space Station concept currently conceived encompasses both manned and unmanned operations. A crew of six to eight flight personnel will be employed in various tasks where past experience indicates a strong need for human presence.

The application of automation to Space Station is a topic of great current interest and controversy. At the extreme ends of this controversy is the tradeoff of a total autonomous system versus a highly human activity intensive system. Two major issues within this controversy are: 1) does the incorporation of automation significantly reduce the "cast of thousands" on the ground?; and 2) does technology availability push or mission requirements pull the autonomy technology? Many approaches are available to address these issues; however, a better understanding is required of future goals, interactions, and impacts.

It is apparent that future space systems will be required to remain operational for 20 years and longer. Over this life cycle, they will be required to adapt to constantly evolving and challenging requirements. Both systems and subsystems need to deal with this reality in the best possible way. One method used successfully on prior programs is to use a form of long-range planning through futuristic forecasting. Long-range planning is a keystone to providing flexibility, productivity and life cycle cost improvements.

A timely issue is how to project the future missions and define which of the associated operational functions would be better satisfied by automating a few or many of the subsystems. This future insight provides the capability to build in or "scar" the IOC Space Station for later adaptation to evolving technology.

The challenge is to define a Space Station that combines the proper mix of man and machine, while retaining a high degree of backup capability with ease of growth.

2.0 APPROACH AND GUIDELINES

2.1 MMC STUDY APPROACH

Figure 2-1 shows the study task flow organized into five main activities or thrusts for the assigned MMC study areas: 1) Summary of Space Station 2000 (plus) Tasks and Activities, 2) Perceived Highest Level of Automation, 3) Assessment of Automation, 4) Identification of Automation Needs and Time Plans, and 5) Presentation, Documentation and Sustaining Engineering support.

A special feature of this flow is the parallel focus of the Space Station system automation and the space assembly and construction automation. The tasks were designed and organized to meet the study objectives in a timely manner.

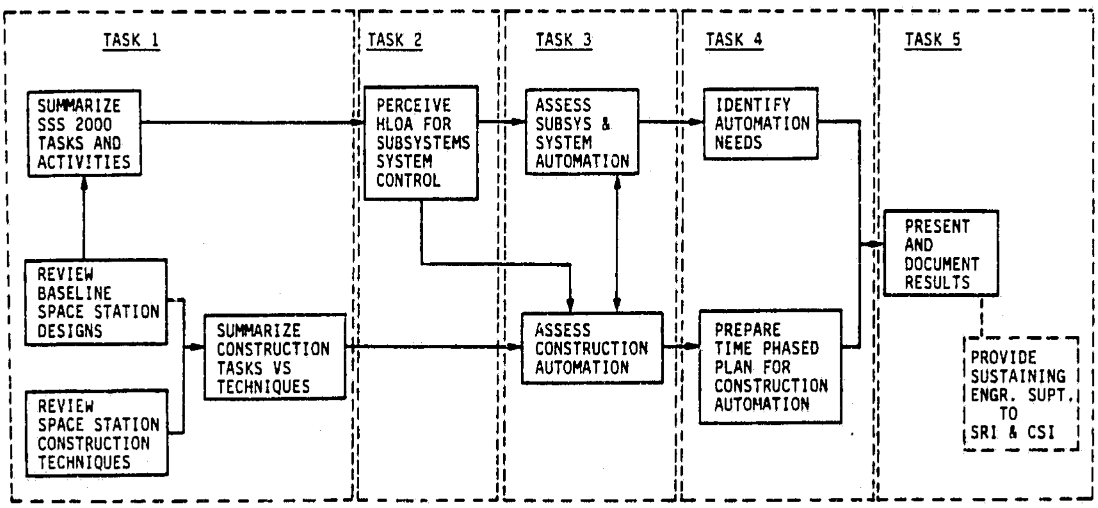


Figure 2-1 Approach to Space Station Automation Study

As shown in the Study Flow Plan (Figure 2-1), there are five major task areas. The results of each task effort feed into and provide the basis for the following task work. By following this disciplined approach, each task area should receive the proper emphasis to provide meaningful results.

The basic approach was further structured in a matrix format in which both the automated systems assembly and construction activities were directed through each of the five major tasks in a parallel manner. A brief description of the activities involved in conducting the major tasks is presented in volume 2, along with the work breakdown structure and definition of terminology, acronyms and abbreviations.

2.2 GUIDELINES

The guidelines used to bound this study and to provide focus and direction are listed below:

a) Maximum use was to be made of related government-sponsored space automation studies.

b) The associated lead time needed to prepare the technology base and to perform the necessary advanced development activities was estimated to be four to five years.

c) In addition to the Manned Maneuvering Unit (MMU) and Remote Manipulator System (RMS), an Orbital Maneuvering Vehicle (OMV) and Orbital Transfer Vehicle (OTV) would be available to support orbital construction and assembly operations.

d) The Space Station mission requirements identified by NASA/LaRC, dated 7 June 1984, would be used as a representative mission model where practical.

e) A power tower concept with gravity gradient stabilization would be used as a Space Station configuration focus.

The emphasis of these guidelines was on the role of automation technology and its projected evolutionary growth out through the year 2000 and beyond.

3.0 SIGNIFICANT STUDY RESULTS AND RECOMMENDATIONS

3.1 SIGNIFICANT STUDY RESULTS

The complete output of this study effort is included in the Final Report, Volume 2, Technical Report. Some of the more significant results and observations have been collected, summarized and presented herein.

a) Large Space Structure Commonality -- Four different space structure configurations were assessed during this study. While the basic configurations differed, the principles of assembly and construction were found to be similar. As a result, many of the assembly and construction support equipment (ACSE) items defined were common irrespective of the particular space structure configuration.

b) ACSE Configuration — Based on results of this study and some of the prior studies there is a general trend in material and personnel handling mechanisms. For example, both long booms and small dexterous manipulators were found to have a major role in autonomous orbital construction. The long boom provides a reach capability and a transport path for the material supply function, while the small manipulator provides dexterous physical activities similar to those required for small parts assembly.

c) Man's Involvement — Man's involvement in the construction process starts with an intensive involvement (EVA and teleoperation) and slowly decreases until he provides only a contingency capability. An evolving work shift and task responsibility philosophy as a function of risk, productivity and cost should be established.

d) Construction Aids - Additional emphasis should be placed on the use of flexible jigs, fixtures, and scaffolding in the construction of large space systems. In many cases, these items would be similar in size as the large space system structure but in general would be stiffer, built to close tolerances, inherent alignment capability, alignment references, and location references. Since these aids provide a basic support platform for the ACSE, the ACSE requirements are dependent on a number of interrelationships. Constructions aids and ACSE interfaces relevant to fixed, mobile and portable types should be investigated for impacts.

e) Orbital Construction Equipment -- The need for interactions between orbital construction equipment, assembly/construction support equipment, and operational maintenance equipment is apparent. Interactive parallel studies addressing on-orbit automation in these areas should be initiated.

f) Operational Maintenance -- After completion of constructing a large space structure, the ACSE is available to move on to the next construction site to start a new project. However, the ACSE currently envisioned is aptly suited to perform operational maintenance activities. This role along with the number of units, serviceability, availability and control mode should all be investigated.

g) Simulation -- New simulation techniques will be required for large-scale space operations, i.e. assembly, construction, repair, modification, disassembly, etc. Major factors to consider include space simulation in one-"g" environment, scaling of structures, and predictive models. In many cases an historical knowledge base must be initiated in conjunction with computer aided engineering and design (CAE/CAD) at the program start and maintained and updated throughout the program life.

h) Flexible Assembly -- It is very apparent that any space operation that is basically a replace or assembly activity should consider flexible assembly. This can be accomplished through simple guidelines that address issues such as access to and from orbital replacement units (ORUs), common/manipulator compatible attachment fasteners, multiple grip/hold points on ORUs, and labeling compatible with both humans and machines.

i) Design Challenge -- While it may be apparent, this study has time and again discovered the importance of good design. There is nothing inherent in certain technologies which will obviate the need for good design - especially in the data management system. It is possible to have a well designed keyboard based man-machine interface outperform a poorly designed voice interface. Consequently, abstract issues such as functional structure or the relationship of functional architecture to physical architecture becomes important.

j) Data Management -- The data management system is pervasive and will be complex. Its ability to tolerate faults, assess its own state, and function under a variety of transient loads will be key. It should be seen as a command and control system as opposed to a mission sequencer and data storage system. The two are very different. Command and control relates to the presence of software more highly integrated with human users, and consequently more complex.

Experience with such systems in the DOD arena shows that designing for growth and evolution are an absolute necessity - there is no way that the requirements for such a system can be known completely a priori. This will require significant overdesign and careful examination of underlying protocols such as timeslicing to project their adequacy against several space station growth scenarios.

k) Exploitation of Artificial Intelligence -- The space station must accommodate large quantities of artificial intelligence technology on ground, in experiments, on board as part of the system, and in the development tooling enabling its definition and development. While this is an arena of some risk, it has high payoff as well. It can allow significant workload reduction for the crew as well as increased safety. The stabilization of the process by which AI technology is developed is at the base of its risk. Inclusion of AI development into a properly tailored engineering method would have high payoff.

3.2 RECOMMENDATIONS

Based on investigations and discussions presented during this study and the initial study objectives to identify and define automation candidates, a number of ACSE and system architecture were outlined along with recommended follow-on design, technology development, fabrication and testing.

a) Supporting Research and Technology — Key technology areas were identified for each of the selected ACSE. A summary listing of these technologies along with a priority ranking is shown below:

- Teleoperation
- Proximity, Touch, and Force Sensors
- Predictive Displays
- Low Weight-Dexterous Arm
- Dual Arm Coordination
- Advanced Activators
- Knowledge Based Systems
- Planners, Strategic and Tactical
- Expert Systems
- Machine Vision
- Special and Multi-Finger End Effectors
- Multi System Coordination

In many of the items identified above a number of similar or identical technology concerns were associated with more than one ACSE. These overlapping key technologies can be investigated in single studies covering requirements that address the spectrum of ACSE technologies. The results of this prioritization were intended to show trends rather than exact conclusions.

b) Automation Growth Impacts on Space Station IOC -- The overall emphasis of this study was to project into the future and forecast initial requirements needed to adapt to future uncertainties. The incorporation of flexibility into all phases of the program helps in planning for many of the future uncertainties. One cost effective approach is to incorporate a structured and modular technology implementation capability. Some of this capability can be achieved by including early in the program design and build phase a number of "scars" that aid in future station modifications and growth. A brief summary of the major "scars" proposed are:

ACCESSIBILITY: Design access corridors to allow for growth MRMS and working envelopes at selected worksites.

BERTHING: Provide additional berthing/docking ports at multiple locations throughout the Space Station. As the program matures, the number of free flyers will increase, i.e., stowed or crippled.

HARD POINTS: Design system to have "hard" or rest points at worksites to aid in stabilizing manipulator end effector motion. Hard points located at structure nodes provides considerable flexibility to many other A&C activities.

LABELING: Labeling, marking, or coding of all modules, assemblies, and components with viewing access is required for replacement operations. Marking or coding the complete Space Station into 3-D grid is needed for early autonomous robots with machine vision.

MODULARIZATION: Modular design of all systems and subsystems should be a primary Space Station ground rule to accommodate growth, servicing, and updating. Module (ORUs) should have replacement interfaces compatible with EVA and manipulators.

STOWAGE: Much of the A&C support equipment, i.e., small tools, materials/parts, etc. Look at providing holes in structural surfaces to accommodate temporary item attachments. Also consider for mobility (crawling).

KNOWLEDGE BASE: Establish and maintain a process for "skill" or "knowledge" retention where knowledge and experience of experts working the Space Station program would codify their expertise and lessons learned into inference rules of a KBS for future use in an expert system.

TEST PORTS: Design test ports into the data management system to accommodate autonomous checkout and troubleshooting capability of a mobile robot or intelligent servicer.

c) Fault Tolerance and Redundancy -- Major subsystem computers should make use of fault-tolerant techniques. These processors should be sized to allow adequate throughput performance in spite of the fault tolerant processing overhead. Key computers should have backup or redundant processors.

d) Functional Encapsulation — Within the data management system the need for communicating software processes should be kept to a minimum. Efforts should be made to keep the processes which do communicate residing within the same processor. Some limited number of optimization or simulation programs may require parallel operation running on different processors but they should be kept to a minimum. Further the bus interface units should be significantly overdesigned to accommodate an increase in subsystem activity.

e) Status/Warning System — There should be a status and warning system to aggregate the state of the space station and provide the crew with advice. This component can also function as a mission control surrogate from the ground if the space station becomes isolated.

f) Knowledge Based Systems (KBS) — The space station should be designed to accommodate KBS on board. The need for a development environment to support the knowledge engineering and domain modeling for the space station is apparent. KBS should be used to monitor and advise. Techniques to fluently integrate knowledge bases and conventional software should be developed.

g) System Performance Prediction — The space station data management system needs extensive performance prediction modeling to validate the design concepts. Specifically, data bus loading, time slicing plans, inter-process communication, and access to peripheral memory are important.

h) System Automation Growth Impacts — The scarring or IOC design aspects and prioritization needed to accommodate the system automation techniques derived from this study are shown in Table 3-1.

Table 3-1 Scarring and Prioritization

SCARRING	PRIORITIZATION
- SUBSYSTEMS USING FAULT TOLERANT COMPUTERS - ADEQUATE SIZING OF PERIPHERAL MEMORY ACCESSIBLE ON THE ODDNET - EFFECTIVE USE OF TIMESLICING FOR MEMORY ACCESS - ACCOMMODATION OF 32-BIT PROCESSORS IN THE SDPs - SIGNIFICANT OVERDESIGN OF ID UNITS (BASED ON EXTENSIVE PERFORMANCE MODELING) - ABILITY TO ADD AT LEAST ONE NEW SUBSYSTEM TO THE ODDNET - ACCOMMODATION OF TOP-LEVEL ADVISOR - ENFORCEMENT OF FUNCTIONAL BOUNDING WITHIN THE HIERARCHY - PROVISION OF A DEVELOPMENT SYSTEM FOR GROUND BASED KBS DEVELOPMENT - EXTENSIVE USE OF MISSION TEMPLATES MAY DRIVE UP PERIPHERAL MEMORY REQUIREMENTS - CAREFUL INTEGRATION OF KBS WITH STANDARD SOFTWARE AND DATA BASES	- PERIPHERAL MEMORY ACCESS - TOP-LEVEL ADVISOR - DEVELOPMENT SUPPORT TOOLS

4.0 SYSTEM AUTOMATION

There are several goals for automation on the Space Station, as shown in Table 4-1. Automation may reduce crew workload or, stated another way, could allow more complex tasks to be performed by the crew at constant work levels. Automation could allow the Space Station to be less dependent upon ground telemetry, tracking, and control. This would allow the Space Station to survive if cut off from the ground for an extended period of time. This decreased ground dependancy could allow select payloads to be flown during Space Station development prior to a fully operational crew staffed station. This relates to earlier return on investment.

Automation could significantly reduce the number of ground personnel necessary to run the mission. The reduction would not be so much in the area of mission operations and direct support, but rather in the "standing army" of support personnel. This would be a cost saver for the government and again lead to an earlier return on investment for the government.

Table 4-1 Goals of Automation

AUTOMATION GOAL	AFFECT	PAYOFF
o Reduce crew workload o Allow more complex crew activities	o Increase number & complexity of payloads	o More revenues o Lower user cost
o Less ground dependancy o Longer time between TT&C	o Select payloads flown sooner o Assure SS will attain its life expectancy	o More revenues o Reduced risk of mission failure

Table 4-1 Goals of Automation (continued)

o Less ground personnel than otherwise would be needed o Less training of a mission staff separate from STS	o Limit mission support staff costs	o Cost savings
o Testbed for American industry	o Space Stations o Underwater Systems o Flow-down to commercial side of technology	o Strengthen our high technology competitive stance

4.1 FUNCTIONAL CHARACTERISTICS

4.1.1 General

It was attempted to establish the ultimate attainable level of automation for the Space Station circa 2000. While somewhat unclear, this point in the evolution of the Space Station becomes an important study tool. The expected IOC was then analyzed to determine what were logical and reasonably manageable steps to take towards the maximal automation configuration were then evaluated.

This portion of the study dealt with Space Station systems. It is assumed that:

- o The computer and software across the subsystems was a key accommodator of automation.
- o The design of the computer and software, considered as a system, was crucial to allowing the highest levels of automation, especially intelligent automation.

- The portions of the Automatic Data Processing (ADP) system which perform mission elements, now thought of as ground-based and complex, are what provides the context for the stepping from IOC.
- Those portions of the ADP deal with planning and scheduling, and caution, warning, and status monitoring.

Therefore, the functional components of the ADP were analyzed, the logical steps from the ultimate back to IOC were established, and the technology that could improve feasibility was considered. The approach may be summarized by the following set of sequential study objectives:

- Conceptualize 2000+ information system architecture
- Establish ultimate levels of automation
- Conceptualize design sufficient for those levels
- Show phased stepping towards ultimate automation levels
- Is the system design which accommodates high automation levels reasonable?

4.1.2 Data Management System

As an example, Figure 4-1 shows the data management system (DMS) and its corresponding subsystem specific components. There are two avenues to approach automation. The first is referred to as hard automation and those aspects of the DMS shown in the hard automation column can affect Space Station autonomy. The second column, intelligent automation, refers to the newer field of using knowledge based system (KBS) techniques. The elements of that column are some key issues discussed herein. While the study involved issues and subsystems other than these, those shown are considered important. Refer to Volume 2 for the other subsystem discussions.

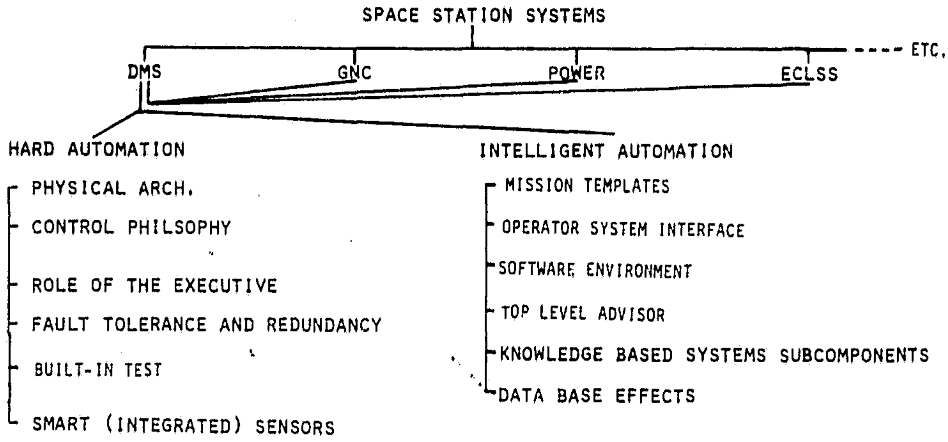


Figure 4-1 Elements to be Implemented on Space Station ADP

4.1.3 Development Process

A large portion of the work focused on what tools and techniques would be necessary to support the development of the Space Station. Adequate tooling in the area of software and systems development support can make the difference between success and failure of a software intensive system. Often, two important facts are missed: first, tools must be ready and relatively stable in advance of the application need date; second, the investment in tool development may be larger than the cost to develop a system component through the use of that tool.

However, the tools can be applied over and over to, in this instance, space systems. Further, some key problems one must overcome to build a tool specific for the Space Station are generic to a wide number of applications throughout American industry. Tools are clearly productivity accelerators.

4.1.4 Summary Conclusions

The space station provides new and challenging problems for NASA. Some of these problems have been attacked by DoD and industry; however, integrating previous work with a space station acquisition as well as commencing new solutions will be major.

The expected life of the space station as well as the desire for its autonomy and efficiency force the data management system to act like a command and control system. Its function will be mode sequencing and data collection, but, also, will be the support of human cognitive processing. Requirements for such decision support systems are fuzzy and changeable. The use of evolutionary acquisition as a formal strategy has proven successful with the DOD. Each system version is seen as a prototype of subsequent systems. There is an intentional abandonment of the goal of specifying the complete requirements set a priori. Instead, careful long-range design analysis must be instituted. This results in seemingly over-engineering the initial versions of a system so as to minimize the likelihood of design inadequacy later.

a) Crew as Decision Makers - With increased use of microprocessors, graphic displays, and automation, the role of the crew appears to be shifting from that of controller and flight engineer (attitude and systems monitor) to that of manager and decision maker. Interactions between crew members and systems will change.

b) Command and Control System - The problem here is how to configure microprocessor and multi-function display systems to enable crews to assimilate information readily and effectively.

c) Subsystem Status Monitoring/Caution & Warning - One additional function per subsystem is anticipated and one corresponding additional computer to process that function. The need for symbolic processors among these additional computers is anticipated. Communications system sizing will likely be adequate if local storage either through RAM discs or Winchester based peripherals is provided. The system should be designed so as not to preclude the inclusion of 32-bit processors in the standard data processors (SDP).

d) Development Support - The need for adequate software tooling and laboratories should be respected. Some of these are shown in Table 4-2.

Table 4-2 Development Support Needs

- Software Prototyping and Development Environment
- Test for Distributed Systems
- Intelligent Validation & Verification
- KBS Development Environment
- Test for KBS
- VLSI Design Aids
- VLSI Transition Laboratory

4.2 CONCEPTUAL DESIGN

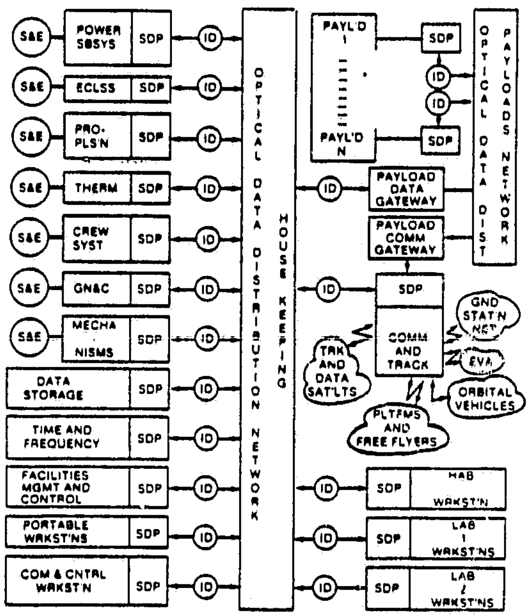
The design aspects are based on the ADP elements, shown in Figure 4-1, to be implemented on Space Station.

4.2.1 Hard Automation

Of the two paths toward automation, the most familiar are those techniques which are immediate extensions of current system design. These include the physical architecture, the philosophy of process control/coordination, and functional allocation to an executive. Some supplemental areas on a less abstract level are also relevant to space station. These include fault tolerance and redundancy, smart sensors, and built-in test. Aspects of these are discussed as they relate to Space Station Automation below.

4.2.1.1 Physical Architecture - The space station will make use of a hierarchical distributed physical architecture for its ADP. Such an architecture has achieved success in real-time process control; and, properly designed, provides reasonable flexibility. The Space Station IOC workbook adopts this approach. The ability to have subsystem busses is important to being able to interconnect the necessary computers.

If the Standard Data Processor (SDP) discussed in the IOC document allows for 32-bit processors and the optical data distribution network (ODDNET) and interface device (ID) are sized accordingly, the IOC physical architecture should suffice. The architecture is shown in Figure 4-2. A distributed system offers processing flexibility, expandability without redesign and, generally, size and weight advantages.



LEGEND:

S&E- Sensors and Effectors
SDP- Standard Data Processor
GN&C- Guidance Navigation and Control
COM- Communications
HAB- Habitation

Figure 4-2 Physical Architecture- Information and Management System

4.2.1.2 Control Philosophy - A reasonable way to view the organization of the functional architecture is hierarchically. This is useful from at least two perspectives. The first deals with the context of analyzing possibilities for automation. The architecture arranges functions so those most akin to higher level human cognitive processes are in the center. Those most removed are correspondingly representative of less complex cognitive processes. The second reason for such an arrangement is the flexibility of the structure.

As the functional definition of the Space Station moves forward, it will be easy to map the identified functions to the arrangements. Systems may be added or deleted from a level or levels changed. Such a mapping will not invalidate the analysis of automation possibilities discussed herein.

4.2.1.3 Role of the Executive - An executive, in the sense of a master computer from which all commands originate, will not be needed on the Space Station. The current notion is that each subsystem will provide a service, in response to mission demands. The crew and ground control will initiate missions and the specific subsystems will respond accordingly. As such, there is no need for an executive in a control sense. There is, however, a need for a preferred system whose function is to aggregate system state from subsystem state information. This system could be ground based initially and flown later or could be part of the crew command and control software. A preferred subsystem, such as the status monitoring, caution and warning system, is recommended.

4.2.1.4 Fault Tolerance and Redundancy - An example of the technique expected to be found adequate for most redundancy applications is cross connection. The secondary may be on hot or cold standby. The primary periodically stores a snapshot of its state in the shared memory for checkpoints. When the controller responsible for managing this redundant set determines that the primary is faulty, that responsible controller disables the primary and enables the secondary. Some of the elements to be considered in redundancy and fault tolerance are shown in Table 4-3.

Table 4-3 Redundance and Fault Tolerance Considerations

- o All major subsystems
- o Redundancy of all major subsystem computers
- o Self-checking and correcting
  - Error detection/correction (hamming) for memory transient faults
  - Spare physical memory for permanent memory faults
  - Second microprocessor for state errors
  - Third microprocessor for permanent hardware fault

4.2.1.5 Built-In Test - While fault-tolerant computer architecture will be used in key subsystems, they will not be found in every subsystem. Subordinate processors and systems will have the ability to status what is controlled and to inform the appropriate controllers of errors. Fault-tolerance implies the ability to detect and correct errors within a processor. Built-in-test refers to the ability to detect errors within subsystems. It implies either the existence of a microprocessor tightly integrated with a subsystem or a software program running in a subsystem controller.

4.2.1.6 Smart Sensors (Integrated) - The effect of smart sensors is to allow a partitioning of basic controller functions between the intelligence within the sensor and within the system controller (Table 4-4). This could eliminate the basic controller in some instances, but the viability of this approach depends on the computing capability included with the sensor. Adding computational capability to sensors introduces the potential to eliminate basic controllers entirely. Thus, some savings might accrue.

Table 4-4 Smart Sensors

- o Microprocessors integrated with sensors
- o Pattern recognition in the associated microprocessors
- o Signal conditioning functions in the microprocessors
- o Weight and power savings likely a wash
- o Frees higher level controllers to run other functions - control push-down

4.2.2 Intelligent Automation

4.2.2.1 Mission Templates - It should be possible to rigorously pre-analyze all normal, routine mission elements of the Space Station. The results of this analysis can be captured in tables of states, lists of procedures, and menu based templates. During the execution of mission element, data points obtained at the subsystem level can be compared to the appropriate state vectors and control exercised in accordance with the pre-loaded constraints and rules. The mission template generation and execution process is illustrated in Figure 4-3. There may be significant application of AI technology in designing the minimal state vector/control set to prestore.

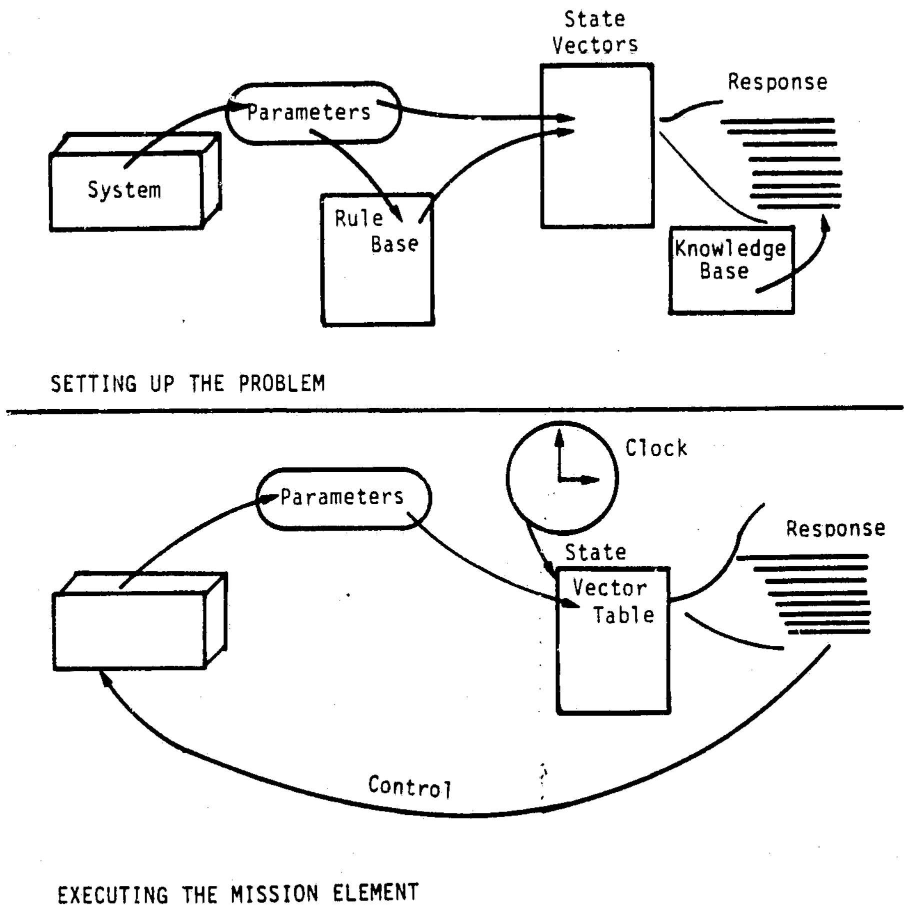


Figure 4-3 Mission Template Generation and Execution

4.2.2.2 Operator System Interface (OSI) - The OSI should use stand-alone capable 32-bit processors in the class of Sun or Apollo. Their existing interface tools are flexible and general, providing multi-windowing and ICON accessible objects, as well as bit-mapped displays.

Some system modeling tools could be hosted on the OSI computers. These could include mathematical models of subsystems or table-oriented subsystem state computers. The class of machines discussed above provide significant computational and I/O capability. Further, data collection and trend analysis software may be hosted on the OSI computer. This would aid in solving the knowledge engineering problems for specific subsystems at a later date. Considerations are summarized in Table 4-5.

Table 4-5 OSI Considerations

- o Use stand-alone capable 32-bit processor (Sun, Apollo)
- o Host some modeling software on MMI computer
- o Host data collection for trend analysis software on MMI computer
- o Weight differences will be negligible
- o Power differences may be become important
- o Data system sizing probably will be adequate
- o Human Factors Friendliness requires additional processing
  - "Modeless" interface
  - Models of human interaction
  - Strive for a graphics (ICONIC) input language

4.2.2.3 Onboard Software Support Environment - The ideal, tailored software environment applicable to the onboard systems probably does not currently exist. It should include a compiler for the language that is to be used for all software executing on the station. It should also include a text editor that is sensitive to the syntax of the language so the editor can help the programmer catch errors and enforce rules for structuring programs. The environment should hide from the programmer any dependencies introduced by the level of controller, which is the target upon which the software is to execute. The host computer, upon which the development environment executes, should provide enough run-time facilities to allow the programmer to debug code without having to download into the target controller until late in the debug phase. Such software development environments are under development for the ADA programming language. Development considerations are shown in Table 4-6.

Table 4-6 Software Development Environment

- o Single HOL for entire space station
- o Single HOL for space station life
- o ADA may be too immature
  - lack support environment
  - compiler development currently lagging
- o Consider "C"
  - good for operating system development
  - tailorable
  - solid support environment, UNIX
  - supports KBS development
- o Require rapid prototyping or testbed aids for preliminary checkout

4.2.2.4 Top Level Advisor - In contrast to the mission template approach to automation, there is need for, eventually, a top level advisor. This system would be a subsystem of the space station and reside on its own interface device to the ODDNET. Likely it would have several computers each with significant amounts of main and peripheral storage, all preferably solid state. If the space station is to be autonomous from the ground, it needs a subsystem whose function is to act as ground surrogate. While mission templates would allow subsystems to know what to do for a mission component, the top level advisor would plan and schedule mission components. Figure 4-4 shows the components of such a system. CPCI refers to a computer program configuration item and CPC to a computer program component.

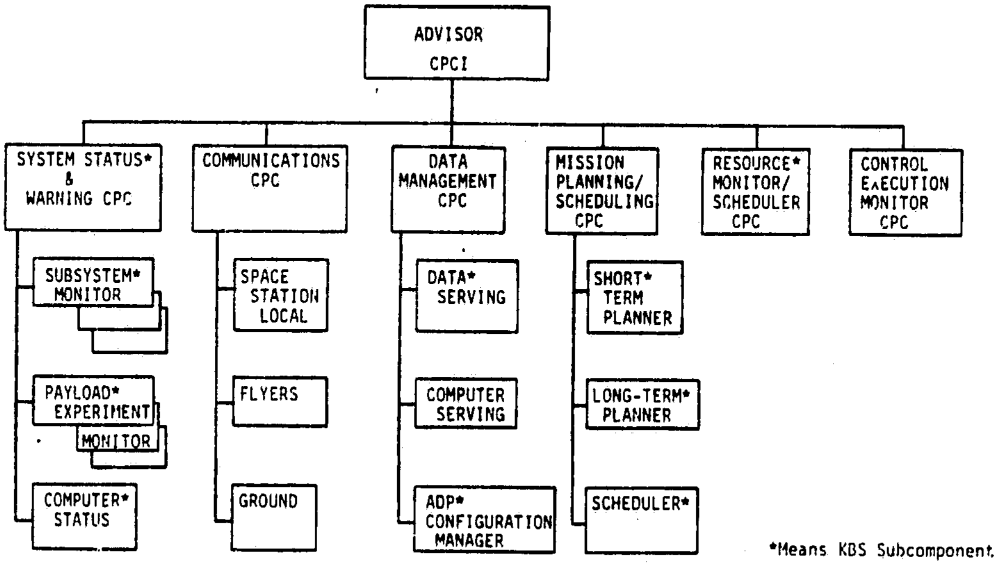


Figure 4-4 Components of Top Level Advisor

4.2.2.5 Knowledge Based Systems Subcomponents - Scattered throughout the space station software will eventually be KBS components. They will be used for system fault detection/isolation and for embedded status monitoring. The fundamental structure will involve a sequence of sensor/actuator, A/D conversion, state comparator, rule base interpretation; and, if necessary, conflict resolution through a knowledge base. At lower levels in the system, very little dependence will occur on the knowledge base. Once fixed, the state comparator and rule base will be accessed most often and this activity is similar to data base access. They will be mechanized as tables within a data base. The KB will run best on a symbolic processing machine. The other components can be run on normal computers. The higher in the functional hierarchy one moves, the more complex and important becomes the KB.

4.2.2.6 Data Base Effects - There are two aspects to data that are generally confused in everyday discourse between humans but which become important in software design. These two aspects are intensional and extensional, as shown in Table 4-7. Intensional data captures the meaning or intent of data objects. It may be considered data about facts. Extensional data focuses on descriptions of processes or world objects. An example of extensional data is a description of a maintenance procedure whereas the intensional data would provide an explanation of why parts of the procedure are being done.

Knowledge based systems focus on the intensional aspects of data and require data bases containing intensional information. Control systems focus on the extensional aspects and require data bases containing extensional information. Both kinds of data base will be present in the space station. It will be important to be able to coordinate between these data bases. More specifically, one cannot expect to use an extensional data base for intensional based inferencing or vice versa. It would be difficult and wasteful of effort to duplicate extensional data within an intensional data base.

Table 4-7 Data Base Effects

NOTE: IN HUMAN ACTIVITIES, WE GENERALLY MIX THESE TWO ASPECTS OF DATA.

INTENSIONAL	EXTENSIONAL
MEANING	DESCRIPTION
DATA ABOUT FACTS	FACTS
META-MODELS	MODELS
EXAMPLE: EXPLANATION OF WHY PARTS OF THE PROCEDURE ARE BEING DONE	EXAMPLE: DESCRIPTION OF A MAINTENANCE PROCEDURE

4.3 AUTOMATION ASSESSMENT

4.3.1 Comparison of Automation Techniques

Figure 4-5 shows each of the automation techniques considered. Generally, the hard automation techniques can all be implemented in the near term. Some of the intelligent techniques which focus on use of conventional software approaches but requiring extensive analyses of the problem domain are ready. In a future time frame (5-10 years) the knowledge based techniques could be ready as well as highly integrated sensors with extensive pattern recognition software. Much of the hard automation approaches apply to low level system components while the intelligent approaches affect higher level components. Technology risk for the hard automation techniques is low and becomes high for the top level advisor.

But there are roles for each automation approach, and the knowledge based techniques should not be ignored just because they involve some technical risk. Payoff is in the areas of fault tolerance/redundancy, built-in test, mission templates, top level advisor, and KBS subcomponents as they directly affect crew workload and autonomous operations. Certainly, the hard techniques should be implemented for near term payoff. The intelligent techniques should be implemented as well and the KBS approaches commenced as soon as possible to drive their maturation.

	Approach	Near Term Implementation	Long Term Implemen	Low Level System Component	High Level System Component	Cost to Implement	Risk of Technology	Directly Impacts Crew Workload	Directly Impacts Autonomous Operations
HARD	Physical Architecture	▲		▲	▲	M	L		
HARD	Control Philosophy	▲		▲	▲	M	L		▲
HARD	Fault Tolerance & Redundancy	▲			▲	M	L	▲	▲
HARD	Built-In Test	▲		▲		L	L	▲	▲
HARD	Smart Sensors	▲	▲	▲		L	L		
INTELLIGENT	Mission Templates	▲			▲	L	L	▲	▲
INTELLIGENT	Operator System Interface	▲			▲	M	L	▲	
INTELLIGENT	S/W Environment	▲		▲	▲	L	L		
INTELLIGENT	Top Level Advisor		▲		▲	M	H	▲	▲
INTELLIGENT	KBS Subcomponents		▲	▲		M	M	▲	▲
INTELLIGENT	Data Base Effects		▲	▲	▲	L	M		▲

Figure 4-5 Summary Comparison of Automation Techniques

4.3.2 Assessment Discussion - The scarring or design aspects needed to accommodate the automation techniques are summarized in Section 3.0. It is clear that the space station must accommodate fault tolerant computers at the subsystem level as well as redundant computers hosting key processes. As fault tolerance makes use of Hamming codes the subsystem computers should be oversized to mitigate the expected performance degradation. The use of peripheral memory accessed through the ODDNET is reasonable. Sizing of that store can become important depending on functions and data allocated to it. This points to the need for extensive performance prediction simulations.

A corresponding issue concerns effective use of timeslicing to provide memory access and subsystem-subsystem communication. There are many aspects to this issue. Depending on how the timeslicing is enforced and designed, the data management system can be biased towards synchronous or asynchronous operation. This in turn could cause significant data use of the bus. The SDPs should accommodate 32-bit processors. This allows use of virtual memory operation and can also serve to mitigate some of the performance degradation caused by fault-tolerant approaches.

A significant overdesign of the bus interface units (BIU) or interface devices (ID) should be provided. Again, significant performance modeling is required to support this analysis. Inadequate sizing of these units (speed) could severely affect throughput in the system.

There should be provision to add at least one major subsystem to the ODDNET after IOC. This is envisioned as the top-level advisor. Within the functional architecture of the space station, functional encapsulation or bounding to the maximal extent should be enforced. This will minimize data flow in the system and allow easier maintenance and upgrade of the software.

The KBS components will need a ground-based development machine separate from mission control computers. This machine should run LISP and/or PROLOG in firmware and host the necessary development support tools. The KBS, when stable, will be moved onto target architectures which will run on the ground. Extensive use of mission templates onboard may drive up peripheral memory requirements so that RAM discs and other solid state local storage is inadequate. Further, hosting mathematical modeling and/or data collection and organizing software on the machines could impact peripheral memory requirements. Local disc or bubble memory peripheral storage may be needed.

The issue of integrating KBS with standard software and data bases is important. Stand-alone "expert systems" cannot be afforded nor are they needed. KBS techniques must be exploited in conjunction with conventional techniques, viewing each of these as merely ways of encoding intensional knowledge.

The issues involved in adequate development support cannot be ignored. The investment in tooling is crucial, as it allows management of complex software. Note that 1) solution of problems in constructing tools should occur well in advance of the need date of the tools, and 2) that such tools when constructed can be applied throughout American industry. Refer to Volume 2 for details concerning the development support needs.

4.4 TECHNOLOGY DEVELOPMENT PLAN

4.4.1 Staged Implementation (Top Level Advisor)

It would be plausible to consider a staged approach to providing the ultimate configuration of space station data management systems.

Initially all knowledge based systems will be under development on the ground in a machine optimal for development of such software, possibly in approximately 1990. The ground personnel would provide the functions previously described to be performed by a top level advisor.

The next logical step would be to host the various top level advisor and subsystem KBS on their target architectures. The subsystem components will be hosted on board as elements of the Standard Data Processors (SDPs). The top level advisor would likely require several computers sharing a local data bus. One of these computers would likely be a symbolic processor much like a SYMBOLICS 3600. An additional likely computer for the top level advisor would be a data base machine such as an IBM 500. It is an open question whether large peripheral storage of data necessary for the top level advisor is best kept locally or accessed through the ODDNET. This issue would be resolved after the peripheral storage requirements are established. The functions running on these machines on the ground would perform as experiments. Ground personnel would still be prime for such missions elements.

The next step would move the subsystem components on board during the next three years, to be in place by about 1995. During such time, the crew would monitor closely the activities of these components. During this period careful attention will be paid to the standard mathematical optimization and modeling software supporting calculations of schedules, docking maneuvers, resource expenditure, etc. Ground personnel would still be prime. A key question will be to what extent versions of these models can be integrated with the top level advisor. It is desirable to have this conventional planning and predicting software available to allow mathematically trying out KBS systems.

A short time after this stage, (1996), it should be possible to move the top level advisor's target architecture onboard the space station as a separate subsystem being off the main space station data bus. It would require its own interface device and SDP. During this time it would be run as an onboard experiment; ground personnel would still be primary for the top level advisor missions.

By 1998, it should be reasonable to expect the onboard crew to perform planning, scheduling, and status monitoring functions with the help of the top level advisor. This date could be significantly improved upon from, say, 1996 if there are no development problems nor any significant knowledge engineering problems.

Finally, by 2000, the space station onboard systems would include fully integrated top level advisors and subsystem components. These would function in the mode of supporting the human crew to the extent they wished and managing the space station when cut off from ground or without crew. Preliminary analyses show that there should be little impact on data communications within the space station through inclusion of these systems - presuming adequate local data storage accessibility, without tasking the main data bus.

4.4.2 Top Level Advisor Automation Approach

The top level advisor will consist of several portions that could ultimately be implemented as shown in Figure 4-6. The figure lists the top level advisor element in the far left column, its proposed computer processor needs, the degree of complexity of the automation process, what form that automation will take, and some typical comments at the far right.

Component	Location	Automation Level	Automation Basis	Comments
– System Status & warning	– computer processor – symbolic processor	H	expert system	Responsible for aggravating and inferring system state from subsystem states. Note : there may be one inference engine for these parts
Subsystem monitor 1, 2, ..., n	– parrallel processor – symbolic processor	M	expert system components	Note : "a distributed expert system" Active, full blown expert system lower in architecture
payload/experiment monitor 1, 2, ..., n	– parrallel processor – symbolic processor	M	expert system components	
computer status	– computer processor – symbolic processor	M	expert system	
– Communications Local flyers ground	– computer processor – signal processor	L	———	High speed existing technology
–Data Management	Data Computer	M	Semantic Linkers	Note: a large blackboard with utilities
– Mission Planner Short term Long term	– Symbolic processor – computer processor	H H	Planning Deep Reasoning	
– Mission Scheduler	– parrallel processor – computer processor – symbolic processor	M	– Planner – Optimization Techniques	
– Resource Monitor	– data processor – computer processor	L-M	expert system	tied to system status & warning
– Resource Scheduler	– Parrallel processor – Symbolic perocessor	M	– Planner Optimization Techniques	
–Control Execution Monitor	– computer processor	L	———	

Figure 4-6 Attainable Automation Levels

4.4.3 Cooperating KBS Components

Figure 4-7 points out both where advances in techniques for making use of various artificial intelligence and conventional software techniques in a cooperative manner are required and where some cooperation may occur. Except for natural language interfaces, the components column of the figure, orders the technologies by speed of execution. It is noted where complexity and size factors impact the components. The technology needs, where known, appear in the right-hand column.

	Technology	Components	Complexity	Size	Needs
Slower ↓	Expert System	Heuristics (rule base)		X	search speed
		World MOdel (K base)	X		KB mgmt/heterogeneous representation
		Inference engine			
		data base			
	Planners	Rule base			
		Knowledge base	X	X	
		Inference engine	X		computational speed
		data base		X	access speed/I/F to HOL (speed) (semantics)
	Deep Reasoners	Rule base	x		
		Knowledge base	X	X	K Engineering tools
		Data base	X	X	I/F to HOL
		Inference engine	X		
	Learning Systems & Prediction	Rule base	X	X	Cognitive Paradigms
		Knowledge base	X	X	Domain paradigms
		Data base	X		Many components cooperating engines
		Inference engine	X		
	Natural Language	Rule base		X	
		Parser			KEngineering tools
		Knowledge base	X		
		data base		X	
		inference engine			Speed of processing

Figure 4-7 Structural Attributes of AI Technology Base

One can envision how these technologies could cooperate. The learning and prediction systems could run in "background" mode to the deep reasoners, forming hypothetical world models and long-range predictions. The deep reasoners could run in a similar support mode for planners. The deep reasoner could pre-analyze options and validate candidate plans. This would require a loose coupling between the two. Planners could perform a similar function for expert systems by embedding their results in a time and event ordered structure and therefore evaluating those results.

4.4.4 Time Phasing of Needs

If both product, e.g., systems onboard space station, and development process support needs are arranged by time, one can get an idea of the extent to which some of the automation approaches may be implemented.

Figure 4-8 shows this arrangement, focusing on key examples. Initially, proof of concept expert systems, planner experiments, and deep reasoner experiments are all running on the ground. In the mid-1990s at least one onboard symbolic processor and some onboard expert systems for fault detection/diagnosis are anticipated. At about 2000, large stable expert systems, fast planners and some learning systems, all onboard, are expected. There will be several symbolic processors and extensive cooperation between the KBS components. By IOC, test aids for distributed systems, and KBS, plus space station specific VLSI design aids, and a KBS development support environment are needed.

		IOC		FOC
Product Needs	KBS	– proof of concept expert systems – planner experiments – deep reasoner experiments	– expert systems – slow planners – deep reasoners	– large expert systems –fast planners – semantic linkers – fast deep reasoners – learning systems
	Architecture	some distribution	– symbolic processor	– several symbolic processors – extensive distribution
Development Process Support	Tools	– test for distributed systems – test for KBS – VLSI design aids	– semantic linkers – intelligent V&V	
S/W development	Laboratories	– KBS development environment – VLSI Transition laboratory		

Figure 4-8 Overall Placement of Automation Needs by Time

Well before IOC a stable comprehensive software support environment for the selected space station language is needed. This is another reason to consider alternatives to ADA. ADA may be ready in 2-3 years for system development but it is unlikely a comprehensive support environment will be ready for 5 years or more. In the mid-1990s, semantic linkers and intelligent validation and verification tools are needed. This is all quite feasible.

5.0 ASSEMBLY AND CONSTRUCTION (A&C)

During the parallel parts of the SSAS effort, space station automation features and definitions were achieved along with identification of corresponding assembly and construction support equipment. A brief definition for each concept was generated by collecting and organizing relevant data for all four reference structures as to basic configurations, assembly construction scenarios and functional activities. In addition, a spectrum of A&C elements were defined for large space structures and the evolutionary shift in the assembly and construction process from man intensive to machine intensive.

Assembly and construction support equipment (ACSE) characteristics were established by assessing a finite set of generic processes that applied to one or more of the four reference large space structures. The functional flow shown in Figure 5-1 provides a task sequence and references the paragraphs herein where each step is discussed.

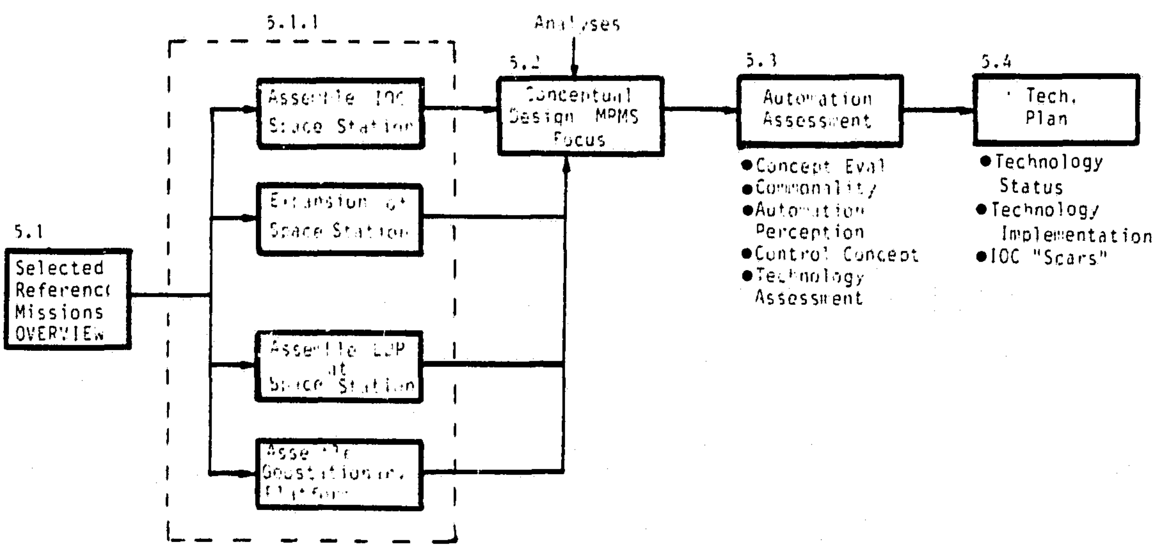


Figure 5-1 Functional Flow of ACSE Assessment Process

5.1 FUNCTIONAL CHARACTERISTICS

The initial step used in developing ACSE functional characteristics was to review and select a representative assembly and construction mission set that would encapsulate both near- and long-term technology needs for a wide range of potential users. The objectives in guiding the selection process were to produce a conceptual configuration and system description that could be both manageable and broad enough to uncover and display major construction and assembly functional issues where automation could have a considerable impact. The detail desired should be top level but sufficient to typify major technology drivers involved in evolutionary changes required over an operating period of 10 to 20 years.

The major focus was placed on starting with the IOC Space Station buildup and on specific areas where automation could play a beneficial role in operational productivity and safety. Using this approach, four categories and specific missions within each were identified as shown in Table 5-1.

Table 5-1 Selected A&C Mission Model

MISSIONS	YEAR
o ASSEMBLE IOC SPACE STATION	1991
-- Power tower or strongback & common modules	
o EXPAND SPACE STATION	1992-1994
-- Add satellite servicing facility	
-- Add OTV hanger and service facility	
o ASSEMBLE LARGE SPACECRAFT	1997
--Assemble LDR at Space Station (LM-3)	
o ASSEMBLE GEOSTATIONARY PLATFORMS	2000
--Advanced Large Commercial Communication Sys. (LM-7)	
LM -- Landmark Mission	
LDR -- Large Deployable Reflector	
OTV -- Orbital Transfer Vehicle	

Features of the mission model concepts address NASA's role in initiatives to exploit and explore space over an evolutionary period of time. Characterization of the major features include visibility to an extended operational time span, using a starting point where considerable resources have already been expended, using operational orbits where both manned and unmanned activities have been identified and verified, using basic structural configurations that are compatible with a number of generic type large space structures, and using missions that have been evaluated from both a deployable and erectable standpoint.

As a summary of the assembly and construction model's implications for long-term technology applications and needs, it serves potentially as a "quick look mission set" in the form of an assessment tool. Its use in this effort was to develop or identify commonality trends, starting with the IOC Reference Configuration and going out through construction of a geostationary (GEO) platform. This time flow has a direct utility to technology planning with possibly a much greater cost impact on technology implementation, i.e., integrate or bypass. The introduction here of a very limited number of missions and system concepts used to illustrate the application of derived technology utilization and needs was a function of the time available to do the study. However, general results from many of the prior relevant studies that have examined specific missions in considerable detail indicate that the mission uniqueness and state-of-the-art implementation have the greatest impact on design conceptualization.

5.1.1 A&C Mission Scenarios

The majority of effort expended on these four missions was focused on the IOC Space Station buildup with considerable lesser effort directed at the other three.

The basic options available to the mission designer is the selection between deployable and erectable or some mix of both. Program impacts of these options are many and in some cases very significant. Primary selection drivers are based on transportation costs, material density and costs, cargo bay stowage efficiency, degree of on-orbit versus ground fabrication, flight crew versus ground personnel time and quantity and complexity of orbital construction support equipment. Where special equipment is identified, it, in turn, has special functional requirements. This equipment may have to be assembled, positioned, set up, controlled, monitored, serviced and maintained with specially-trained personnel or servicer equipment located at the construction site. The special equipment identified to perform these types of functions has been classified as Assembly and Construction Support Equipment (ACSE). Present indications are that many diverse support equipments will be required, and although the specific equipment may be dependent on the nature of the large space structure system to be constructed, the basic principles of construction are such that much of the support equipment is common. This equipment commonality factor was stressed throughout the study effort, along with its adaptability toward technology transparency.

Seven Shuttle flights shown in Figure 5-2 have been identified to make the basic IOC Space Station operational. The structure utilizes a combination of deployable and erectable structures with the majority of the booms and keels deployed automatically.

Figure 5-3 illustrates a typical section of an automatically deployable Box Truss structure (A) along with an example of an erectable "Nested Tube" (B) structure.

Advantages and disadvantages between these two examples are many and conflicting, e.g., packaging for delivery to orbit and on-orbit operational support have opposite advantages and disadvantages for the two examples show in Figure 5-3.

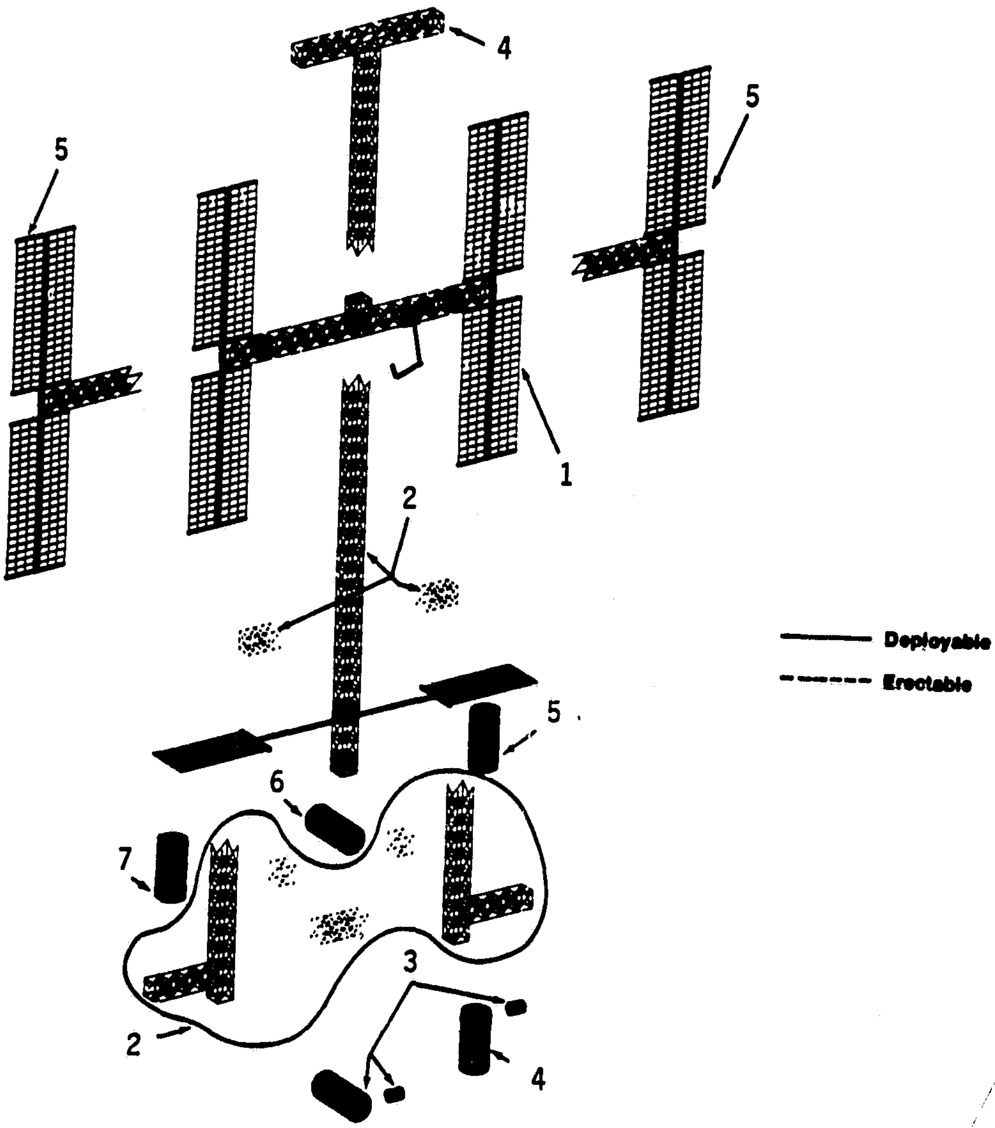


Figure 5-2 Erectable/Deployable Structure on Space Station

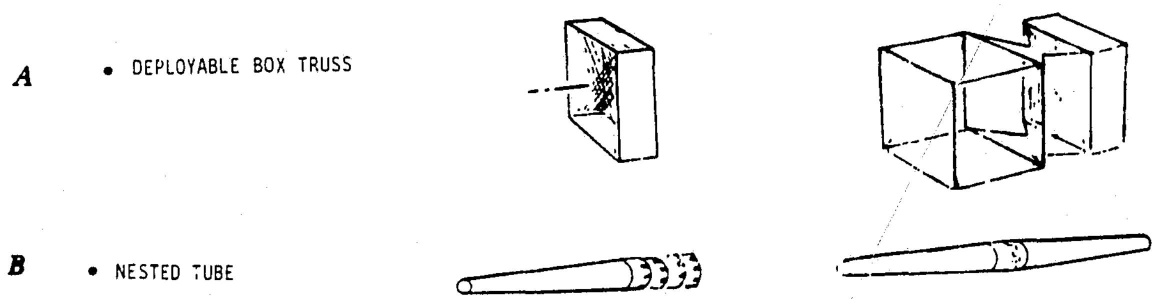


Figure 5-3 Examples of Deployable and Erectable Structures

In the Space Station reference documentation, a mobile remote manipulator system (MRMS), shown in Figure 5-4, is the major piece of assembly and construction support equipment used to move people and material over the Space Station structure. The basic unit consists of a crawling mechanism and a Shuttle remote manipulator.

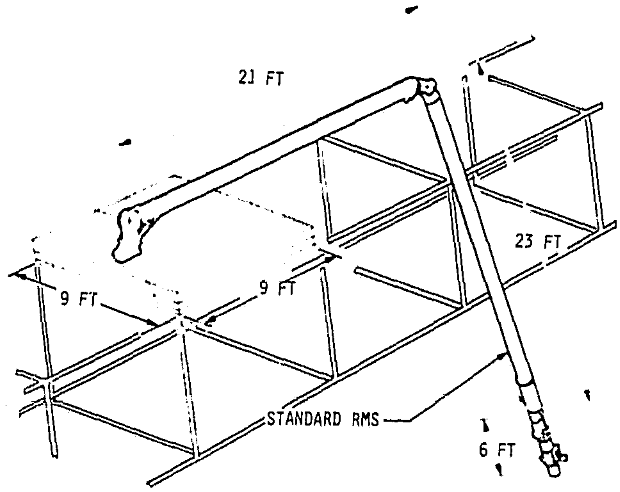


Figure 5-4 MRMS Reference Configuration

The scenarios and functional activities discussions on the remaining three representative A&C missions are presented in the technical report.

5.1.2 ACSE Commonality

An initial listing of common, generic ACSE is shown in Table 5-2. This list is a combination of items identified in the four reference missions, with duplications combined and less significant items omitted. Many of the potential candidates are obviously significant and require much further detailed analysis.

Table 5-2 Primary ACSE Candidates

1) SHUTTLE REMOTE MANIPULATOR (RMS)	11) UNIVERSAL TOOL STORAGE UNIT
2) MOBILE REMOTE PLATFORM	12) PORTABLE & MOBILE LIGHTING/ CAMERA UNIT
3) MOBILE REMOTE MANIPULATOR SYSTEM (MRMS)	13) PORTABLE CONTROL BOX/PENDANT
4) MRMS WITH 2-20 FT ARMS (RMS DERIVATIVE)	14) SPECIAL FUNCTION MANIPULATORS (5-DOF OR LESS)
5) TELEPRESENCE WORK EFFECTOR (EVA ANALOG)	15) CAROUSEL MECHANISM (SATELLITE ASSEM. FIX)
6) MOBILE FOOT RESTRAINT (MFR-SHUTTLE)	16) STRUCTURE DEPLOYMENT AID
7) CLOSED-CHERRY PICKER	17) ALIGNMENT & SURFACE ACCURACY TOOLS (GROSS)
8) UNIVERSAL DOCKING (BERTHING) UNIT	18) ALIGNMENT & SURFACE ACCURACY TOOLS/SYSTEM (FINE)
9) FASTENERS (INHERENT IN DESIGN)	19) CHECKOUT TOOLS
10) FASTENER TOOLS (CLAMP, WELD, RIVET, ETC.)	20) PORTABLE DEPLOYABLE SUN SHADE
21) SPECIAL PURPOSE END EFFECTORS (MANIPULATOR EXCHANGE)	

5.2 CONCEPTUAL DESIGN FOCUS ON MRMS

The Mobile Remote Manipulator system (MRMS), sometimes referred to as the Assembly and Transport Vehicle, is a multipurpose logistics device outfitted with a space crane (Shuttle RMS). As shown on Figure 5-4, it plays an important function in the buildup of the Space Station IOC and is the primary logistic tool on the station. The system is a tool to transport modules and/or payloads from the Shuttle cargo bay and position them for attachment to the Space Station truss structure. The combination of crane, astronaut and Manned Maneuvering Unit (MMU) are utilized in locating, latching and deploying the structure segments. The same procedure is repeated for the radiators, the keel extensions and the lower boom. Subsequent usage is necessary for maintenance, repair and servicing of the station and future spacecraft. It is also necessary for Space Station growth and assembling spacecraft.

5.2.1 MRMS Evolution

Figure 5-5 shows a summary of the anticipated MRMS program evolution as it applies to an automation assembly growth of Space Station.

All of the original IOC capabilities will also be available throughout this span. In 1993 two 20-foot arms will be added and additional control capabilities incorporated, as shown. The Telepresence Work System (TWS) will be incorporated, to complement or at least partially replace the EVA need, in this 1995-1997 time frame. Ultimately, the system will evolve to operate under teleautomation to further reduce the level of man-intensive supervision of the system.

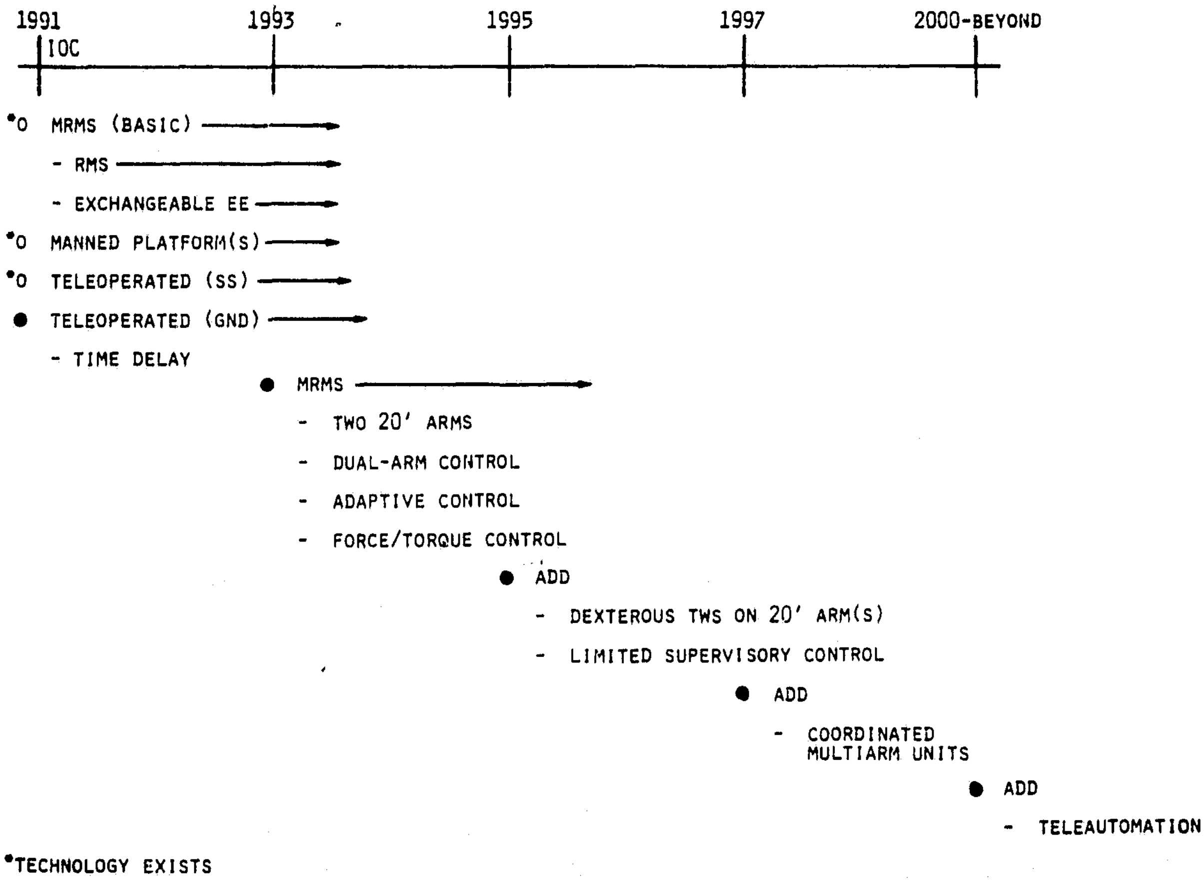


Figure 5-5 MRMS Program Evolution

5.2.2 Dual Astronaut Positioning Arms

The first major growth modification anticipated of the MRMS is the addition of two 20-foot arms to the payload platform layer. The size of the basic platform is approximately nine feet square. It consists of three layers as shown in Figure 5-6. An artist illustration of this concept is shown in Figure 5-7.

The bottom layer consists of a square track arrangement that rides on guide pins attached to the truss nodes. The flat tracks are connected on the corners by "switches" that rotate 90°. The switches are aligned to permit motion over the guide pins in two orthogonal directions. The central element is the push/pull drive mechanism. It consists of a drawbar, with locking rods, connected to the MRMS by a rack and pinion drive. To pull the MRMS in a desired direction, the drawbar is extended forward one bay to the next set of nodes and locked by driving the lock rods into the nodes. The corner switches are aligned parallel to the movement of the vehicle. By actuating the electric motor, the MRMS is pulled by the drawbar along the tracks. To reverse directions, the MRMS pushes itself. The vehicle is always captive to the truss structure by having four-point support maintained at all times. By repeating the process, the platform is translated longitudinally in an "inch-worm" fashion.

Also required are Mobile Foot Restraint (MFR) positioning arms. Astronauts in EVA suits are positioned within their work envelope by these movable positioning arms. Control of the positioning arms and all features of the MRMS optionally resides with the EVA astronaut(s). These two positioning arms will be used on opposite sides of the space crane platform. The positioning arms have the freedom to translate along one side of the top layer. This capability greatly expands the work volume of the positioning arms as well as the astronaut. It also provides the option to have the astronauts work as a pair in a dual-arm mode.

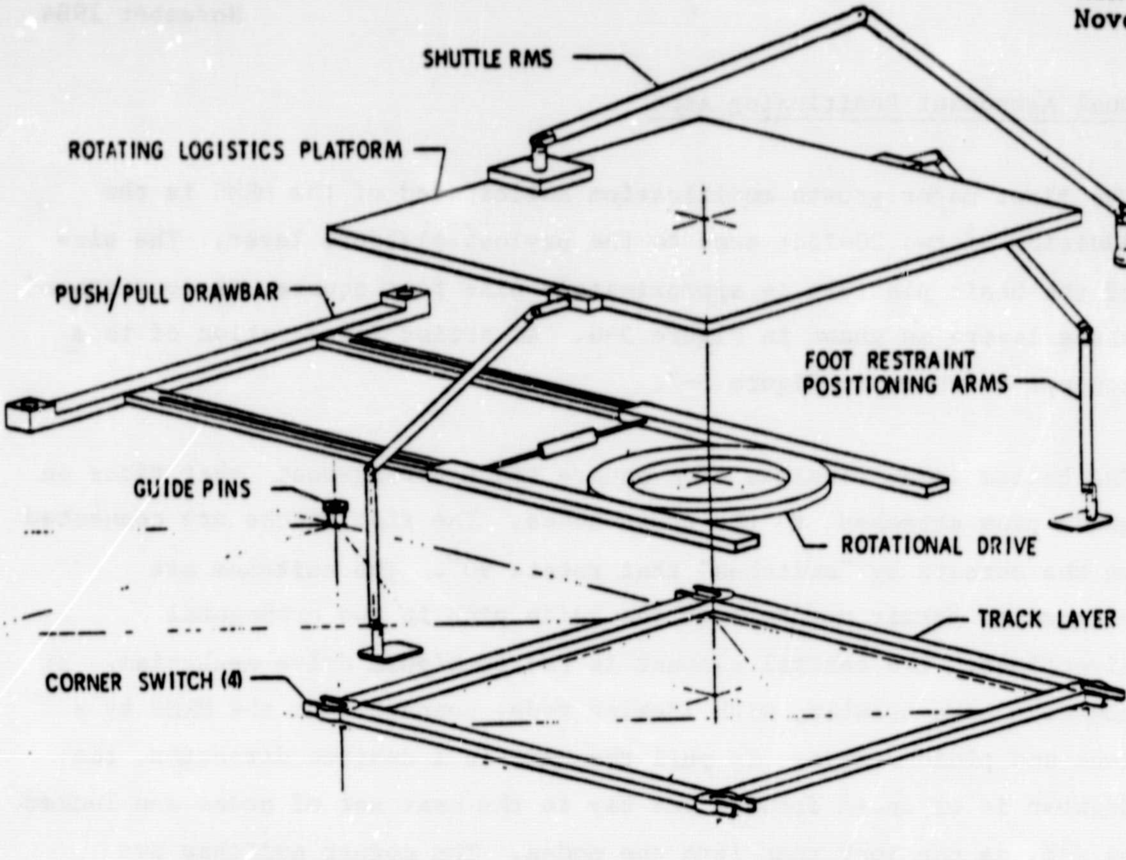


Figure 5-6 Mobile Remote Manipulator System Elements

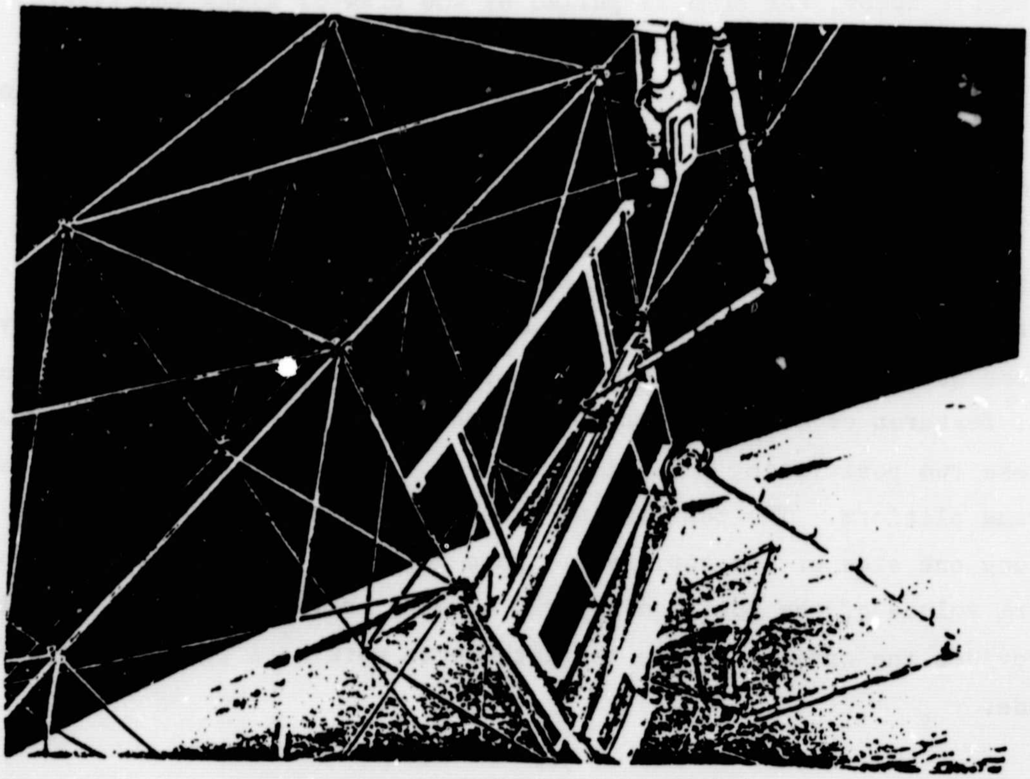


Figure 5-7 MRMS Artist Concept (Second Generation)

The MRMS will have a self-contained, rechargeable power supply. Depending on the work and the mission, the platform will be adaptable in terms of special storing devices and cradles for miscellaneous hardware.

5.2.3 Telepresence Effector Concept

The second major growth modification to the expanding MRMS is the addition of a dexterous two armed EVA analog that can be transported around the station or crawl over the structure. The EVA astronaut or his replacement is an integral part of assembly work and is needed to accomplish the finer, precision tasks. There has been a considerable amount of discussion on the usage of EVA astronauts. The major problem is the high cost of supporting a man, not to mention the risks involved. An alternative to man will be a TWS (Telepresence Work System) at the end of the positioning arms, as shown in Figure 5-8. The TWS has the same or greater capabilities than man, yet reduces the amount of support equipment and preparatory work. An artist illustration of this advanced concept is shown in Figure 5-9.

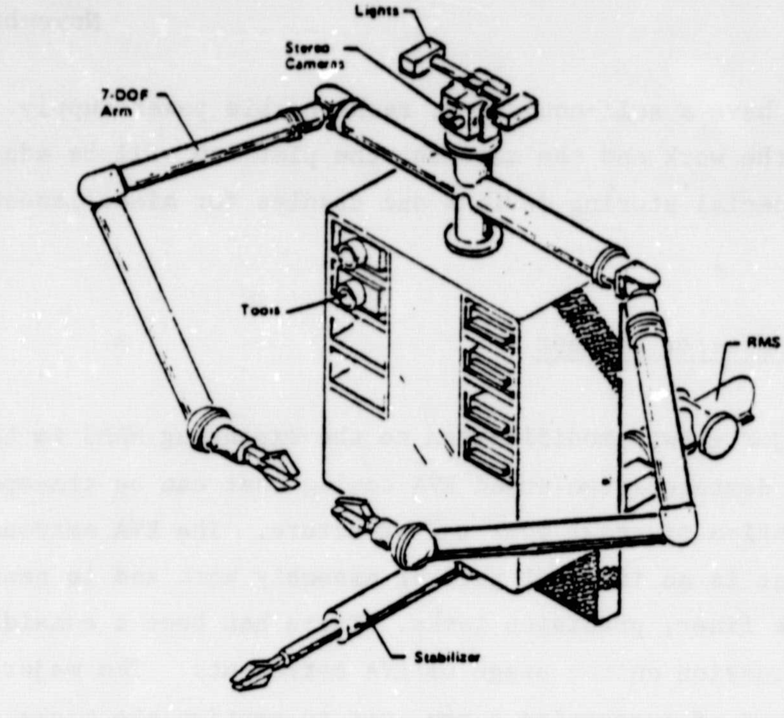


Figure 5-8 Telepresence Work System

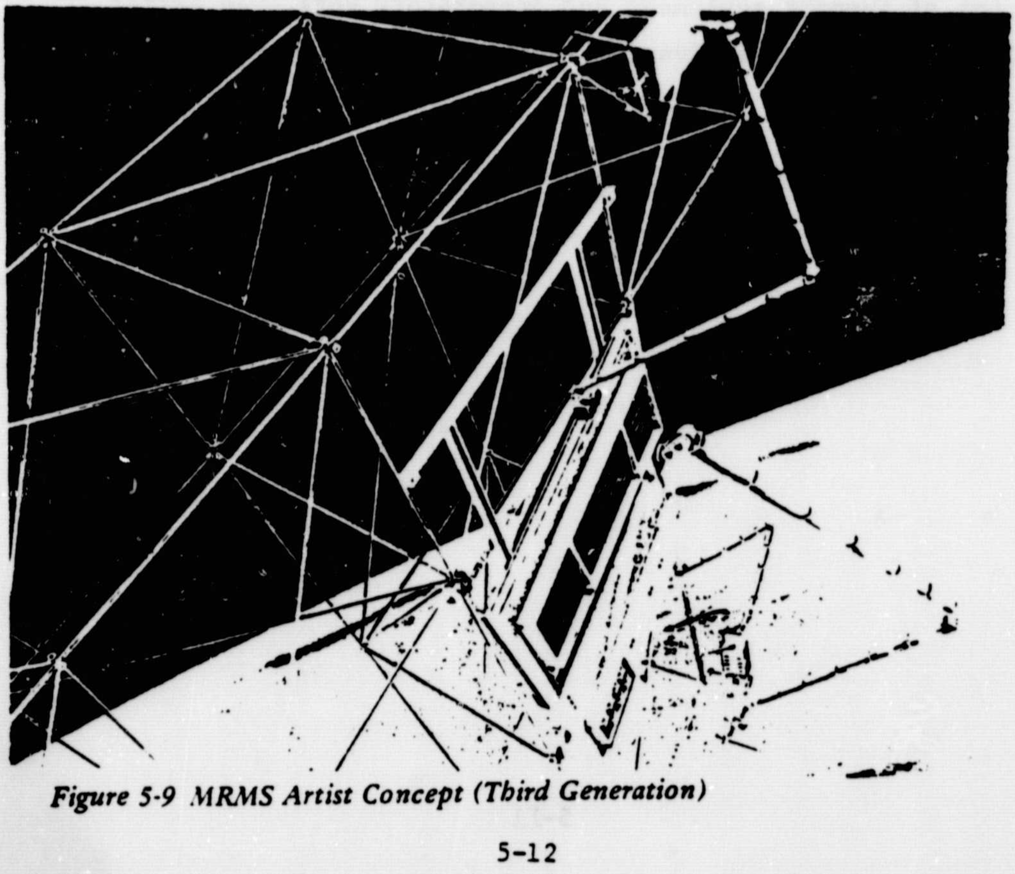


Figure 5-9 MRMS Artist Concept (Third Generation)

5.3 AUTOMATION ASSESSMENT

Implementation and evolution of automation on both the system and subsystem levels is required to enable operational productivity in the initial as well as growth versions of the station. Increasing levels of automation over operational periods of 10-20 years will be driven by several factors: growth of the physical station, growth of the station operational complexity, increasing information workload, enhancements in computer capabilities, transition from a facility housekeeping priority mode to a payload intensive operation environment, and to a more failure/maintenance conscious mode as the station ages. As indicated above, productivity is the major driver and results in a basic guideline to try and automate as many of the systems, subsystems and payloads as possible.

Productivity as it applies here could take the form of reduced risk of human error, human safety, reduced crew time spent on laborious or monotonous tasks, thus freeing them for tasks requiring their unique capabilities, operating with reduced ground support crew and operating closer to optimum system performance efficiencies.

Activities that make up these tasks in the area of assembly and construction include items such as material handling, joint fastening, beam adjustment and many others. The need for space automation in manned and unmanned space vehicles is really the need for solutions that use automation in whatever fashion or combination necessary to complete a job. The space operations philosophy to date has had humans with hands-on capability performing a large number of the automatable jobs. Past implementation of automatic features consisted initially of a bottoms-up approach in which single components of automation were developed, followed by linked components of automation which were eventually combined into more complex systems progressing towards integrated solutions.

The emphasis of this study is automation; however, the IOC space station will use the unique capabilities of man in the form of hands-on and remote control. Understanding and appreciation of these man/machine interfaces are necessary to define the automation features and the degree of change with time. A simple model used to indicate a reference baseline is shown in Figure 5-10.

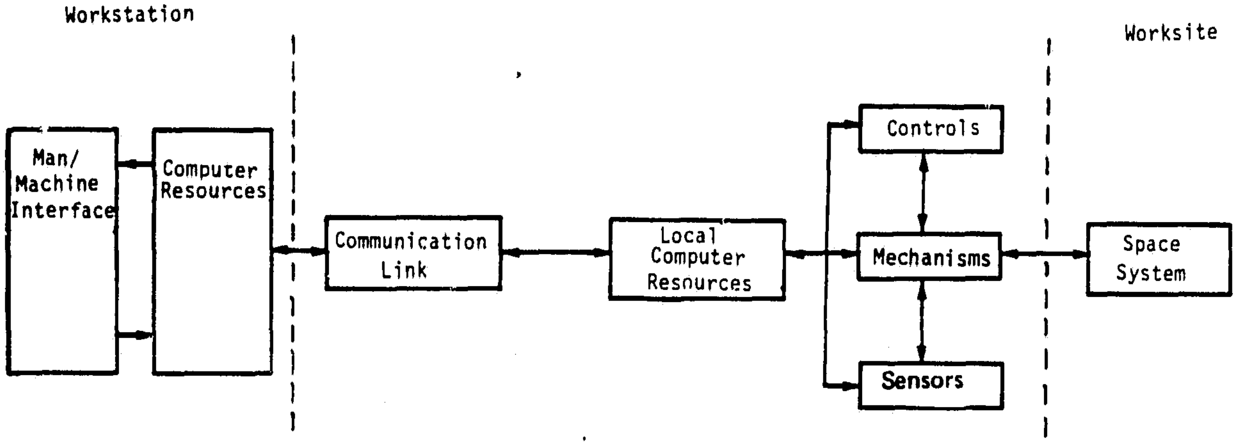


Figure 5-10 Human Interactive Automation Model

The area on the far right labeled spacecraft worksite and the mechanical hardware represents the space station structural components and the mobile remote manipulator system (MRMS) that were discussed in the prior section. The key to making this hardware operate comes under the direction of the man/machine (computers) combination. A proposed step partitioning in this area is shown in Figure 5-11. The capability to go directly from EVA/IVA hands-on to autonomous control can be accomplished using todays technology or conventional automation. This involves the extension and amplification of man's physical capabilities. However, to include the incorporation of man's mental capabilities requires a far more progressive approach, similar to that shown in Figure 5-11.

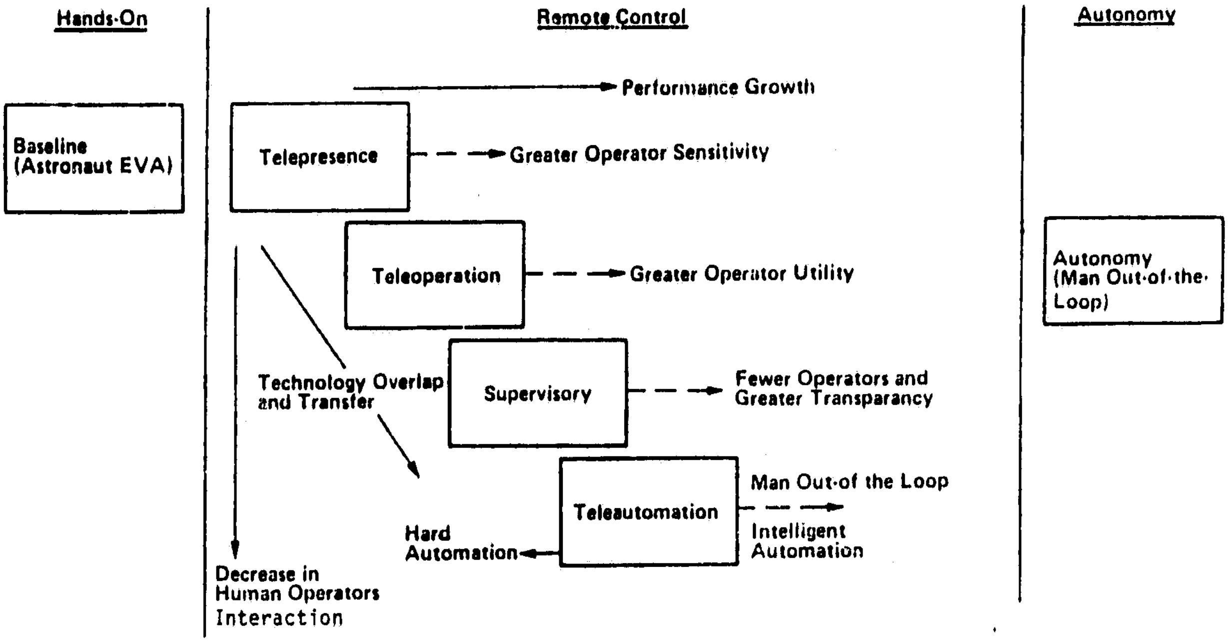


Figure 5-11 Remote Operations Transition Overview

Shown on this schematic is a logical partitioning of capabilities in transitioning from an intensive hands-on mode to an on-orbit autonomous mode. Terms used in establishing specific steps can be considered a subset of remote control. Concise distinctions defining these evolving concepts are vague in many respects but do contain some specific capabilities that provide unique differences.

For example, telepresence is the most human intensive control mode in this group, but it also provides fine dexterity at the worksite with minimal operator training. This capability is extremely useful where the remote human operator has an in-depth knowledge base relevant to the worksite, but little or no experience in teleoperation. Teleoperation provides for the reverse of telepresence in that the operator is skilled at receiving displayed data at the remote workstation and providing commands in response to displayed signals. Technology in the form of sensory perception has a considerable overlap or potential for technology transfer from one concept to the other. Sensors must be selected where the data feedback signals are compatible with either direct display through the video screen or to the computer and adaptive control software. Both supervisory and teleautomation modes as defined here provide a progressively decreasing level of operator interactions.

Using the steps developed and shown in Figure 5-11 and the basic philosophy flow of slowly transferring the human operator's physical interactions and mental capabilities from them to machines can be illustrated through the control environment. For purposes of this study, the control system evolution phase is divided into four major stages as displayed in Figure 5-12. Each stage in this control concept is represented by different shades in sequential time periods. A brief discussion of each stage is presented below:

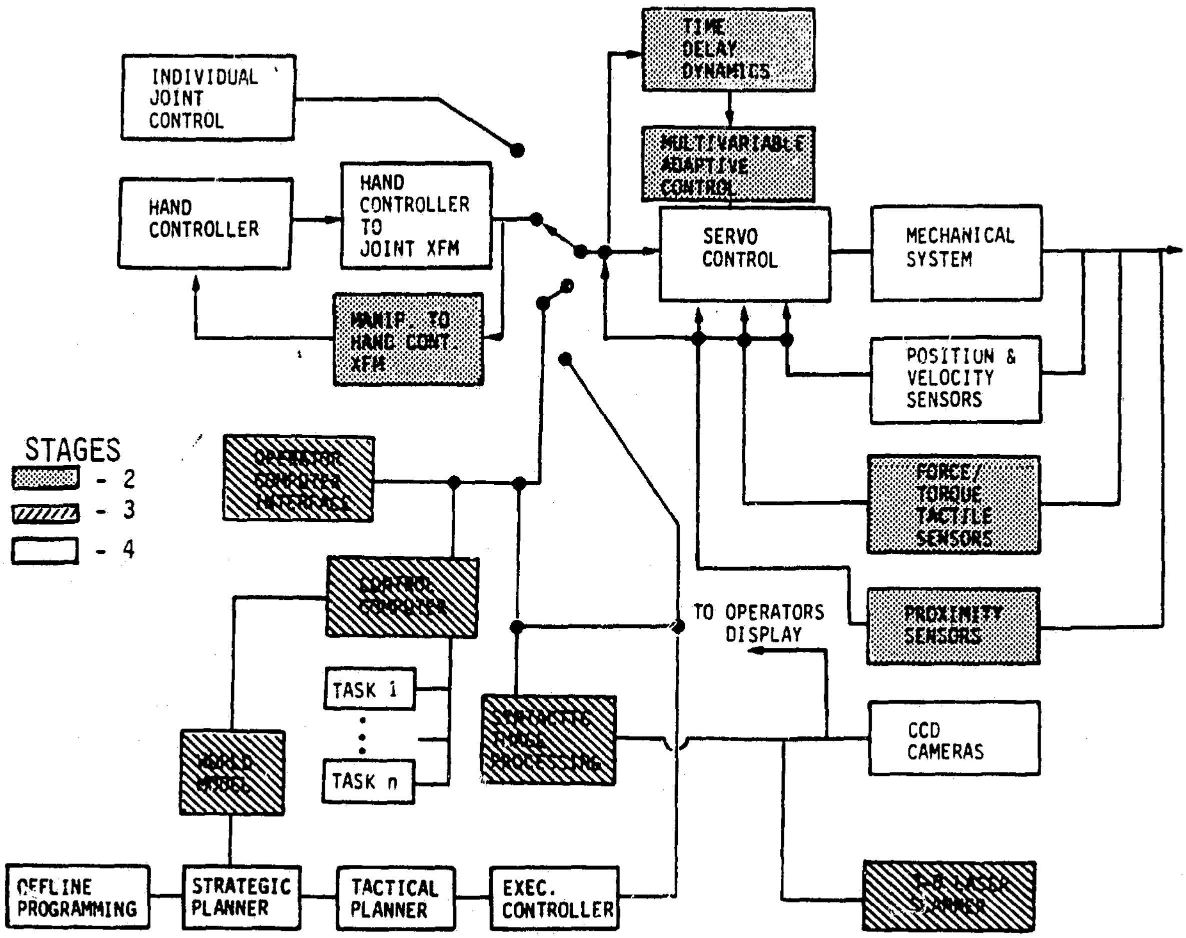


Figure 5-12 Remote Control Automation Evolutionary Stages

Stage 1

In the first stage, all manipulator actions are based upon controller inputs. Manipulator position is a direct function of hand controller position. The prime method for operator sensing is through indirect vision (TV). Typical hand controllers used here include switches, exoskeleton and replica types.

Stage 2

In the second stage of evolution, additional sensing of worksite activity is achieved through force and tactile sensors. The output of these sensors can be monitored by the operator through graphic displays or directly through the hand controller. In addition, the operator is aided by more advanced control laws that incorporate force information as well as adaping to load changes. These advanced laws facilitate the control of two arms by one or two operators.

Stage 3

The third stage marks the beginning of the use of intelligent automation techniques. For single segments of a given task, the operator will have the capability for initiating a "supervisory" mode in which the computer has the responsibility for executing the given task. The computer notifies the operator of task status, exception or fault conditions and task completion. Stereo vision or scanning laser data are processed and used in control algorithms to provide range data.

Stage 4

In the final stage of evolution, the operator specifies a class of tasks to be performed. The computer plans the task, including order of activities, tool selection and exception handling. The operator is notified only when workaround techniques fail. Visual data is used to a higher degree in both planning and execution.

Figure 5-13 shows the overall control system evolution based on a time phase consistent with the simple mission model representing assembly and construction trends. The major evolutionary steps follow a logical waterfall schedule based on a sequential need priority and a technology development estimate.

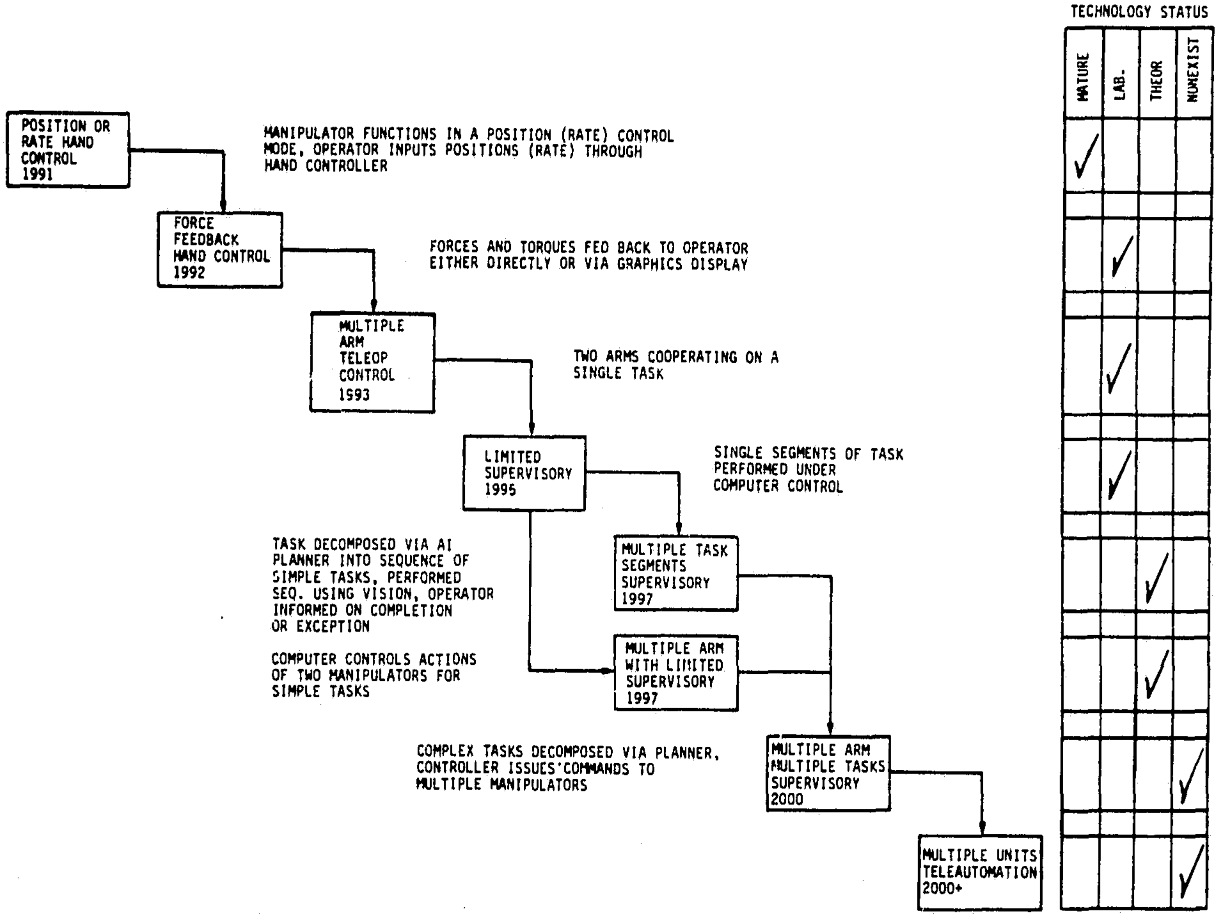


Figure 5-13 Control System Evolution

A technology assessment matrix was prepared using the information generated in Figures 5-5 and 5-13. Figure 5-14 summarizes this data and identifies the projected primary and ancillary technology drivers needing additional study, research, development and verification. The order in which they are listed reflects a priority ranking for development. This was done as part of the technology assessment effort where the priority ranking technique used depended on a simple comparison procedure. Each key technology was compared against a set of priority parameters.

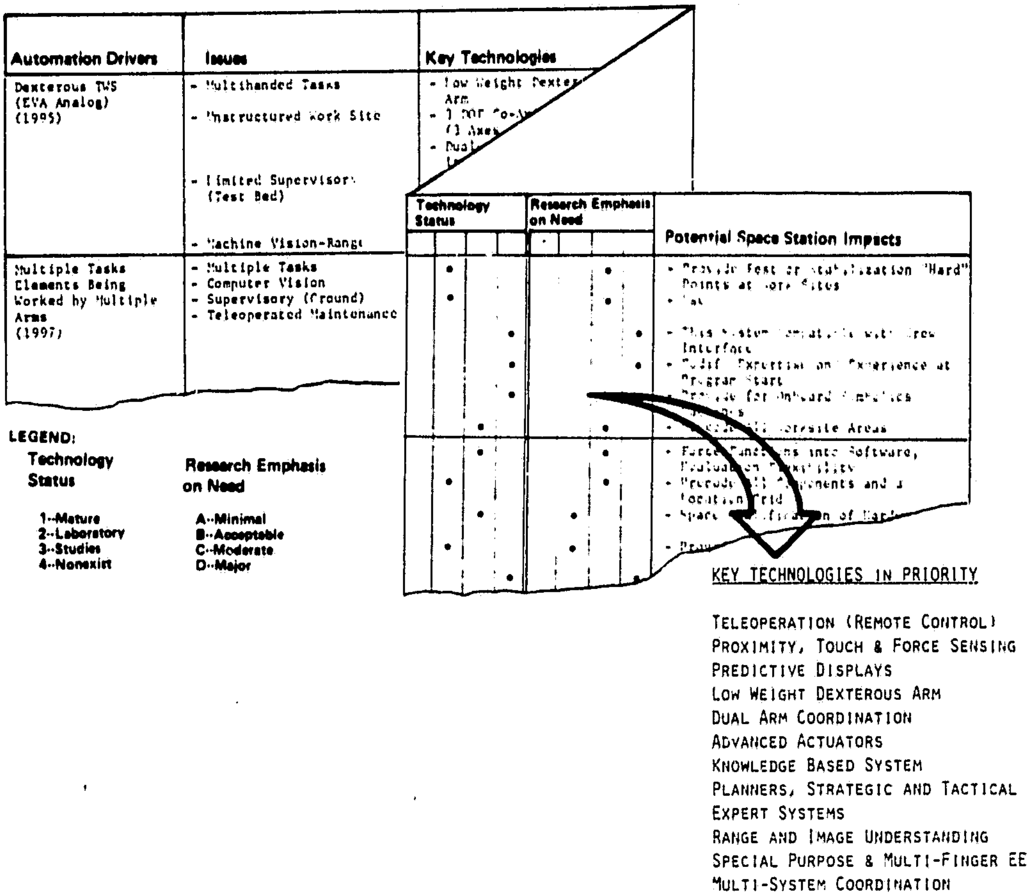


Figure 5-14 Automation Technology Assessment

The process used was to separate the least-preferred features from the most preferred features. A value of merit was assigned where the number "1" indicated the most preferred and went sequentially higher through to the least preferred. A final priority ranking is presented in Table 5-3 that shows a numerical tally of all the individual rankings with the lowest value having the top priority. This was a very quick look approach in that no weighting factors were applied. Each of the nine preference ranking parameters carried the same weighting factors, whereas in more complex assessment methods different weights might be applied to each comparison parameter.

Due to the vagueness in this area, and in some cases a lack of comparison data, the results were intended to show trends rather than exact conclusions.

Table 5-3 Technology Priority Comparison Matrix

SELECTED TECHNOLOGY GROUP / PRIORITY RANKING CRITERIA	Human Productivity	Existing SRT Efforts	Application Frequency	Risk Consideration	Development Cost	Benefits	Prior SRT Efforts	Near-Term Development Need	National Interest	Final Priority Ranking
Predictive Displays	9	1	6	2	2	8	N/A	3	11	3
Proximity, Touch & Force Sensors	10	6	5	1	1	5		1	9	2
Teleoperations (Remote Control)	5	5	2	3	3	1		4	10	1
Advanced Actuators	6	4	4	4	6	11		2	8	6
Low Weight--Dexterous Arm	7	3	1	5	5	10		5	7	4
Dual Arm Coordination	8	2	3	6	7	6		6	5	5
Machine Vision (Range & Image Under.)	3	11	11	9	10	7		9	2	10
Knowledge Based Systems	2	8	7	10	11	4		7	4	7
Expert Systems	1	10	9	8	8	2		8	1	9
Special EE & Multi-Finger EE	11	7	8	7	4	9		11	6	11
Planners, Strategic & Tactical	4	9	10	11	9	3		10	3	8
Multi System Coordination	N/A									12

5.4 TECHNOLOGY DEVELOPMENT PLAN

A cost effective and technically feasible automation development plan must consider a number of different disciplines and time related impacts. Some of the major items of considerable importance in generating a development plan include an understanding of the technology status, a sequential approach towards technology implementation, and a logical evolution that provides options as a function of risk, safety and costs. The key technologies used in generating the plan are those identified in Table 5-3 of the prior section. Table 5-4 shows the application of these key technologies to the generic list of ACSE.

Table 5-4 Technology and Equipment Matrix

PRIMARY SUPPORT EQUIPMENT CANDIDATES	Predictive Displays	Proximity, Touch & Force Sensors	Teleoperations (Remote Control)	Advanced Actuators	Low Weight Dexterous Arm	Dual Arm Coordination	Machine Vision (Range & Image Under.)	Knowledge Based Systems	Expert Systems	Special EE & Multi Finger EE	Planners, Strategic & Tactical	Multi System Coordination
1) Shuttle Remote Manipulator (RMS)	●	●	●									
2) Mobile Remote Platform	●	●	●									
3) Mobile Remote Manipulator System (MRMS)	●	●	●	●			●					●
4) MRMS with 2 20 ft Arms (RMS Derivative)	●	●	●	●	●	●	●	●	●	●	●	●
5) Telepresence Work Effector (EVA Analog)	●	●	●	●	●	●	●	●	●	●	●	●
6) Manned Foot Restraint (MFR shuttle)		●	●									
7) Closed-Cherry Picker		●		●	●	●		●		●	●	
8) Universal Docking (Berthing) Unit		●					●					
9) Fasteners (inherent in design)			●	●						●		
10) Fastener Tools (clamps, weld,rivet etc)		●	●							●		
11) Universal Tool Storage Unit		●										
12) Portable & Mobile Lighting Camera Unit		●	●	●			●	●	●		●	
13) Portable Control Box-Pendant						●		●				●
14) Special Function Manipulators (5 DCF or less)	●	●	●	●	●		●			●		●
15) Carousel Mechanism (satellite Assem Fix)	●		●	●						●		
16) Structure Deployment Aid		●								●		
17) Alignment & Surface Accuracy Tools (Gross)	●				●		●	●			●	
18) Alignment & Surface Accuracy Tools System	●				●		●	●	●		●	
19) Checkout Tools (Mechanical,Elect.,&Data)	●	●	●				●			●	●	
20) Portable Deployable Sun Shade	●		●									
21) Special Purpose End Effectors (Manipulator Exchange)		●	●	●		●	●			●		●

The integration of these technologies into the assembly and construction support equipment development will be consistent with standard aerospace hardware development programs. However, early hardware development should take advantage of the NASA protoflight concept of early flight testing of systems and subsystems. This reduces the number of test hardware units, reduces the extent of ground testing and makes use of the Shuttle test bed concept where hardware is tested in a structured space environment, then returned for post-test inspections and analyses. With this programmatic philosophy, all subsystems will be divided into manned and unmanned elements. These manned elements include items such as the MRMS personnel and material transporters and the MFR (mobile foot restraint). Any item with direct human interaction or where crew safety could be at issue will receive more extensive ground testing to demonstrate flight worthiness.

The unmanned elements, such as manipulators, docking devices, mobile transport platforms, lighting aid, alignment package, etc., will initially be evaluated from the Orbiter payload specialist station with the elements being captive within the cargo bay. The Shuttle remote manipulator system and EVA manned maneuvering unit will be utilized in these evaluations.

After completion of proof-of-concept and subsystem tests, the various elements will be assembled on a priority step basis (greater system complexity) and ground tested to verify all interfaces. The new elements added into the system will then be functionally verified as a system through Space Station test bed Shuttle sortie flights, using task panels and structure mockups for operational simulations. This verification process will ensure the operational demonstration can be operated efficiently as part of an evolvability growth plan.

After completion of the flight subsystem tests, the elements will be assembled and checked to verify all Space Station interfaces. Any inconsistencies will be updated and factored into the flight hardware fabrication cycle.

A summary development and demonstration plan schematic is presented in Figure 5-15 that follows the various key technologies through the major fabrication and test cycles. This plan has been generated using five primary phases in the development and demonstration of selected assembly and construction support equipment (ACSE): 1) design study, 2) proof of concept, 3) prototype or protoflight units, 4) Shuttle flight test bed, 5) systems integration, and 6) space flight operations verification.

6.0 TECHNOLOGY PROJECTIONS

The overall emphasis of this study was to project into the future and forecast technology requirements needed to adapt to the anticipated evolutionary growth of the Space Station. Many of these technology requirements were discussed in the previous sections, along with development plans. This section presents a summary of the technology developments for both system automation (or architecture) and assembly and construction, emphasing manipulation and associated technologies.

The technology time phased summary for both areas is shown in Figure 6-1. The center area of the figure represents the control element, which is common to both manipulation and system architecture. The anticipated time frames for development of ground and flight capabilities and future sophisticated capabilities are shown.

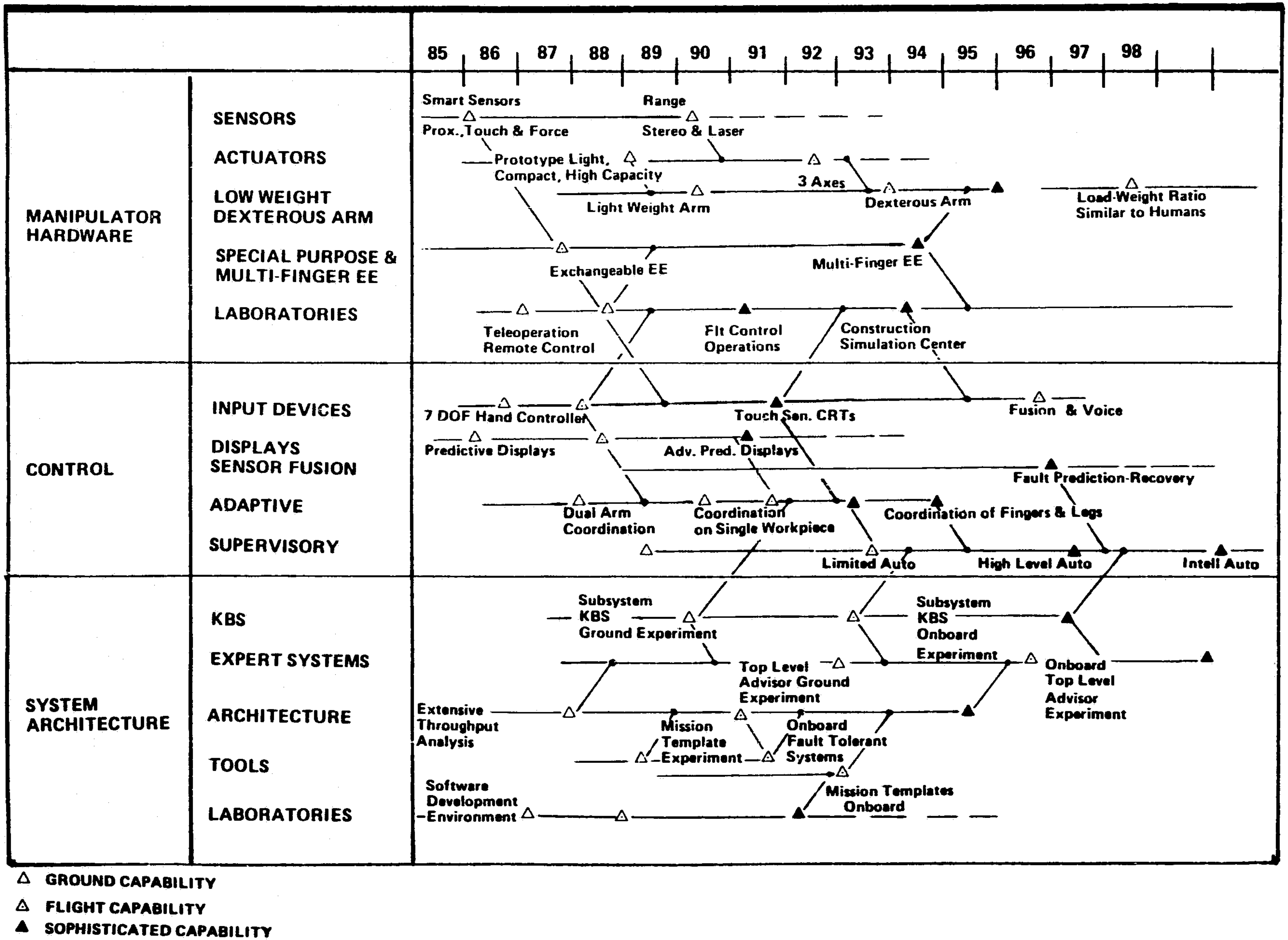


Figure 6-1 Technology Time Phase Summary