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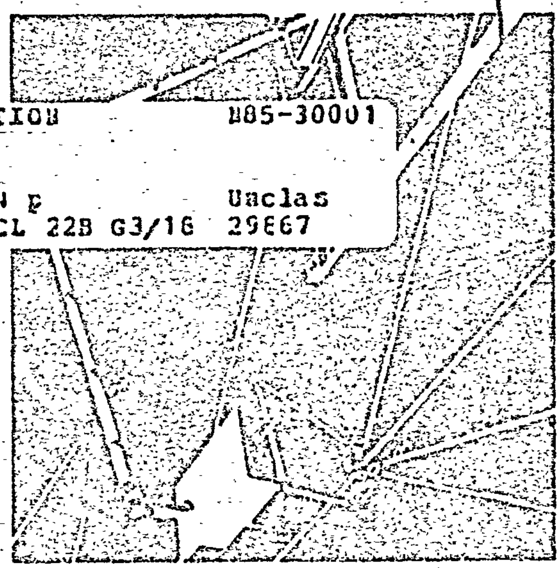
Task 5.3

Volume II | Final Report | November 1984

Technical Report

Autonomous Systems and Assembly

Space Station Automation Study



MCR 84-1878
November 1984

FOREWORD

This final report, prepared by Martin Marietta Denver Aerospace, provides the technical results of the Space Station Automation Study. The report is submitted in two 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 C. Marshall Space Flight Center of the National Aeronautics and Space Administration.

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1.0 INTRODUCTION

1.1 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. Many of the activities projected can be characterized as ones that can be programmed in advanced and are better suited for automated systems.

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 drive 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, it 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 Initial Operational Capability (IOC) Space Station for later adaptation to evolving technology.

The challenge is to define a Space Station that combines the proper dynamic mix of man and machine over an extended period of time, while retaining a high degree of backup capability.

1.2 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.

1.3 GENERAL STUDY APPROACH

The initial step taken by NASA in organizing the SSAS was to form and convene a panel (Figure 1.3-1) of recognized expert technologists in automation, space sciences, and aerospace engineering to produce a Space Station automation plan.

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.

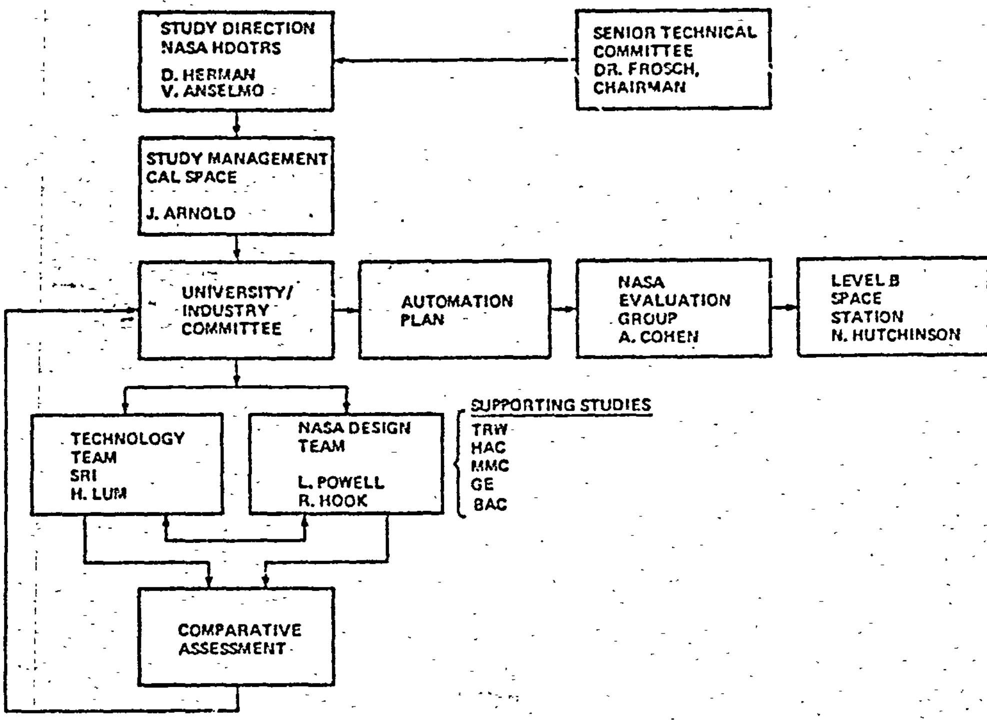


Figure 1.3-1 SSAS Organization

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 1.3-2. The fifth contractor, BAC, was assigned to investigate and report on man-machine interfaces.

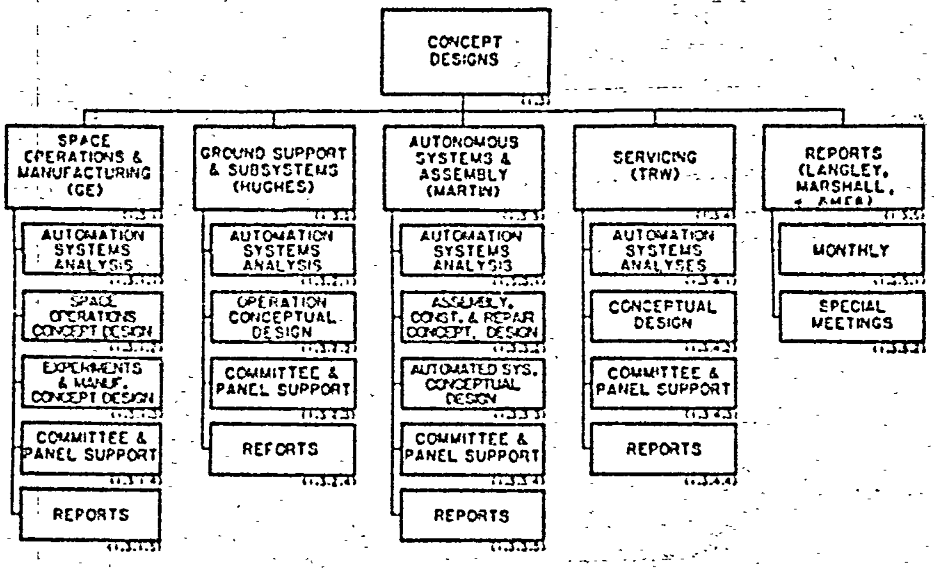


Figure 1.3-2 SSAS Work Breakdown Structure

1.4 STUDY OBJECTIVES, GUIDELINES AND APPROACH

1.4.1 MMC Objectives

The first phase of the Space Station Automation Study was conducted over a period of four months. Martin Marietta's part in this study 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 this effort are:

1) Define through analysis the potential ultimate 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).

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

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

1.4.2 Guidelines

The guidelines used to bound this study are listed below:

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

2) The associated lead time needed to prepare the technology base and to perform the necessary advanced development activities was estimated to be 4 to 5 years.

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

4) The Space Station mission requirements identified by NASA/LaRC, dated 7 June 84, would be used as a representative mission model where practical.

5) 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.

1.4.3 MMC Study Approach

Figure 1.4.3-1 shows the MMC study task flow broken down into five main thrusts for the assigned areas of responsibility: 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, Reports and Sustaining Engineering.

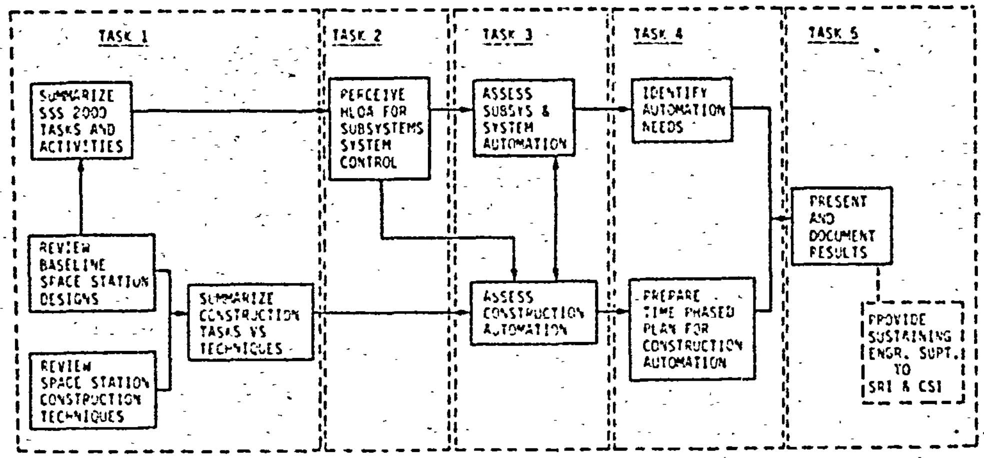


Figure 1.4.3-1 Approach to Space Station Automation Study

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

Figure 1.4.3-2 shows the study schedule, starting in July, with the major effort being completed in mid-November. It represents the considerable overlapping required of the four major tasks. The fifth task, as shown, covers presentations and documentation and information transfer with NASA, Stanford Research Institute (SRI), and California Space Institute (CSI). As shown, the major portion of this effort was completed in four months. During this four-month period, four Technical Interchange Meetings (TIMs) were held, with a fifth meeting held at NASA to present final reports.

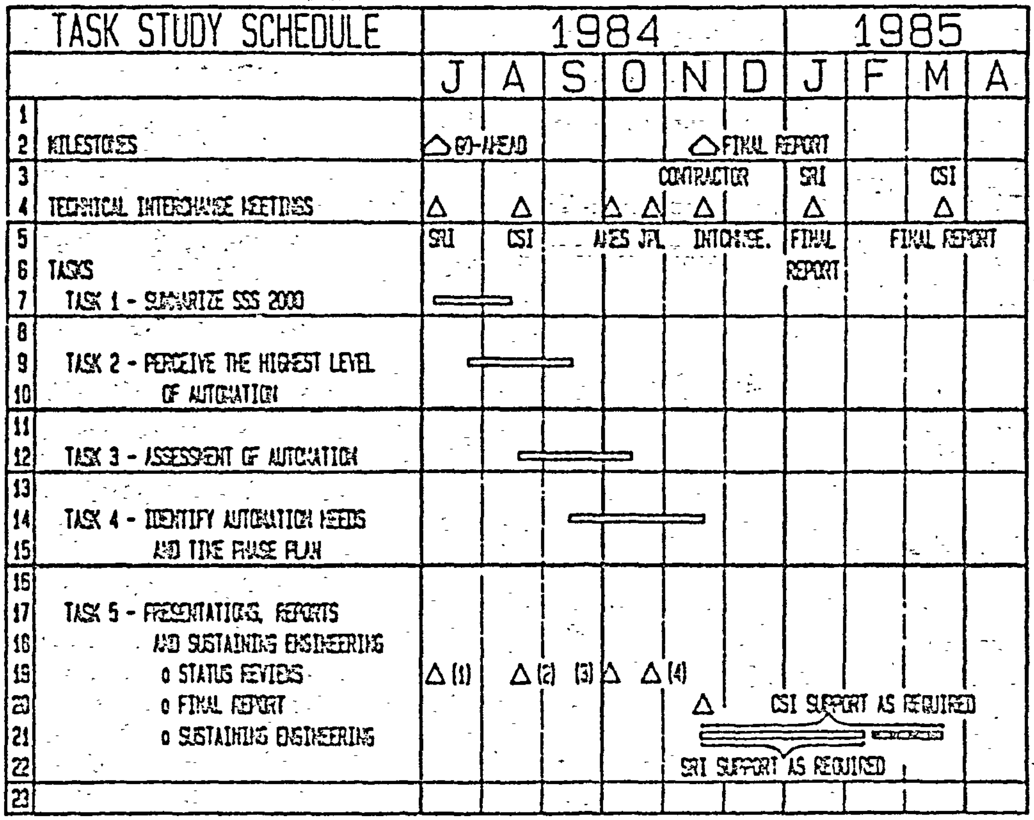


Figure 1.4.3-2 Study Schedule

1.4.4 Task Descriptions

As shown in the Study Flow Plan, 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 and provide meaningful results.

The basic approach was further structured in a matrix format in which both the automated systems and construction/assembly activities were directed through each of the five major tasks in a parallel manner. A brief summary description of the activity covered in conducting the major task(s) effort(s) is presented below.

MMC first conducted a review (Task 1) of the NASA/LaRC mission model, dated 7 June 84, that included a number of missions out through the year 2000. Specific features looked for included the increase or decrease in mission types and number of space vehicles and any related impacts on system and subsystem performance growth. An assessment was also made of proposed large space systems likely for future space planning. Rather than do an exhaustive coverage of all space construction and assembly missions envisioned, it was quickly determined to concentrate on a set of four representative construction mission scenarios. These scenarios encompassed the more relevant aspects of construction from a standpoint of commonality, standardization, and technology evolvability. They also include concepts that span a time phase leading up to 2000 and beyond.

Two of the selected reference missions are identified as Technology Development Missions (TDMs), previously investigated under the NASA/MSFC contract NAS8-35042, to which this Space Station automation study effort was added (Task 5.3). Details of the future mission goals and the construction reference mission scenarios are presented in Sections 3 and 6, respectively.

The next step (Task 2) in the flow approach was to define top-level concepts that featured the highest level of automation that could be perceived. Using the baseline of functions and activities identified in Task 1, the study tried to identify the highest level of automation that can be perceived for both automated systems and construction techniques.

The perception process can be described as one of thought and design concept extension, projection, and forecast. This includes going from human intensive to human out of the active loop.

An important part of the perception process included identifying techniques which would improve or enhance man's productivity in space. In addition, the approach must encompass the maximum practical degree of automation in operations, construction, activation, monitor and control, fault detection, fault isolation, and fault remedy.

In the Task 3 approach, the impact of technology on automation applications was analyzed. Using concepts developed in Task 2, the study analyzed automation functions as they applied to various types of operator controllers, i.e., facility buildup, product fabrication, information handling, and equipment maintainers. Much of the technology information developed for this task was based on a number of different sources such as our existing advanced automation technology data base, information supplied by SRI International, and current literature on advanced automation.

Various levels of automation were compared with current state-of-the-art and a projected IOC configuration. Projection techniques for selected time slices were applied against the near-term product development and emerging automation technology to identify gaps, voids, or deficiencies in the projected technology.

The last step (Task 4) in this approach was to organize the identification of hardware and software elements in such a manner as to facilitate technology implementation or development. The projected missions were examined and a time-phased need plan developed. The plan shows the time at which levels of automation should be increased, or made available, to support the long-range Space Station missions and objectives.

A fifth task was generated and maintained to track and document study reports, handouts, and presentations. This task also provides for the sustaining engineering needed to communicate with NASA, Stanford Research Institute and California Space Institute during the second phase. The major outputs of this study are:

1) Orientation Meeting - Presentation on study approach and expected results.

2) Technical Interchange Meetings (TIMs) - TIMs were scheduled on a monthly basis; the evolving final report output status was presented at each of these meetings.

3) Final Presentation and Report - At the fifth month, a final presentation at the NASA/JSC location. Study results through this period were documented in a final report.

1.4.5 MMC Work Breakdown Structure

A work breakdown structure was generated to encompass and integrate the tasks described in Paragraph 1.4.4 above. The structure further breaks the individual tasks down to levels which are more descriptive of the study effort. The structure also provided a meaningful outline for visibility of the final report contents.

As shown in Figure 1.4.5-1, there are four major elements. Elements 1.1 and 1.2 provide the baseline and reference data applicable to both 1.3 and 1.4, which are the two major study activities, system automation and assembly and construction, respectively. These major activities are further decomposed as shown.

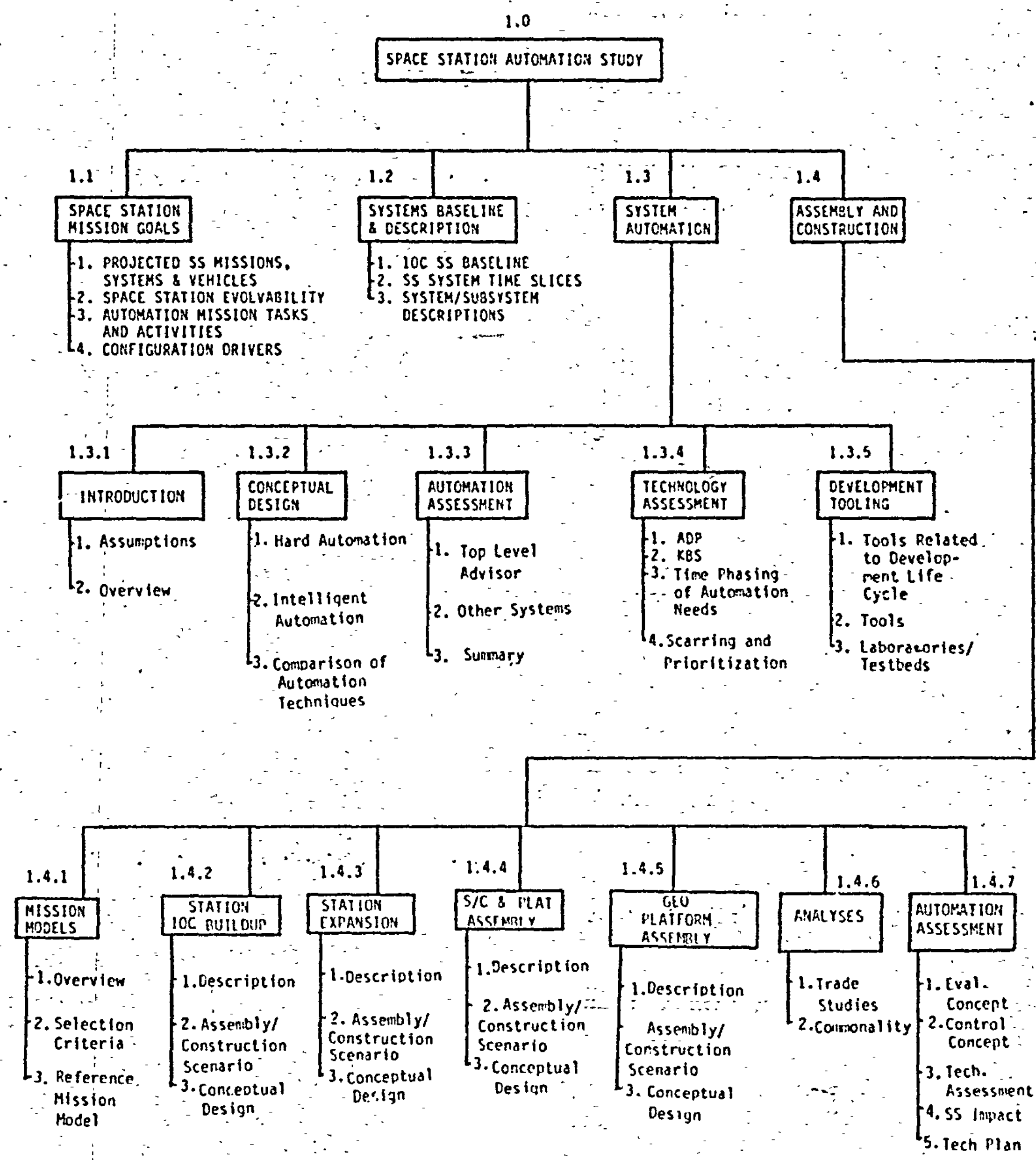


Figure 1.4.5-1 Space Station Automation Study

1.5 SOURCE DATA AND TERMINOLOGY

1.5.1 Source Data

As stated in the guidelines above, during the performance of this study maximum use was made of related space automation studies. These reference sources are listed in Appendix A.

1.5.2 Terminology Descriptions

For familiarization, the following is intended to provide a brief overview of the meaning of selected automation and remote control terminology as used herein. It is not intended to impose a precise definition of these terms but simply to facilitate the communication process.

1) Artificial Intelligence: A discipline that attempts to make computers do things that, if done by people, would be considered intelligent.

2) Automatic: A general term used to define self regulating of motions and operations of machines.

3) Autonomy: Independence of a flight system from direct real-time control by the ground.

4) Hard Automation: Conventional automation using some form of numerical control (NC) or standard algorithmic control scheme.

5) Flexible Automation: Refers to advanced automation systems that can cover a wide range of applications with inherent reprogrammability.

6) Telepresence: The ability to transfer a human's normal functions (e.g., manipulation, tactile, etc.) to a remote site and receive human sensory feedback (e.g., visual, force reflection, etc.) that provides a feeling of actual presence at the worksite.

7) Teleoperation: Remote manipulation in which humans provide the control signals based on responses to efficient information feedback.

8) Supervisory: A control mode using a mix of human and machine (computer) control in which the operator uses high-level commands when instructing the computer to perform complex multiple activity sequences.

9) Teleautomation: The capability to interact with and modify a remote automated system and carry out a predesigned function or series of actions, after initiation by an external stimulus (e.g., offline programming and remote data base updating).

10) Remote Control: The capability to control from a remote location. The terms Telepresence, Teleoperation, Supervisory Control, Teleautomation, and Augmented Control as used in the literature are generally regarded as different examples or subsets of Remote Control.

1.5.3 Acronyms and Abbreviations

A listing of the acronyms and abbreviations used herein is contained in Appendix B. Those in common usage or which are considered obvious are not included.

2.0 SUMMARY

2.1 GENERAL

This section provides a general summary of the study results by reference to the applicable sections, tables, and figures herein where the pertinent data is contained. Refer to Volume I, Executive Summary, for the compilation of this data into an integrated, concise reference source. Note that this study involved two distinct areas: system automation and assembly and construction. Herein, these areas have been addressed separately.

2.2 SYSTEM AUTOMATION

2.2.1 Overview

The ultimate attainable level of automation for the Space Station in the year 2000 was established (Section 5.1.2). The elements to be implemented are reflected in Figure 5.1.2.1-1 and further defined in Section 5.2. Summary conclusions are contained in Section 5.1.2.3. Figure 5.2.3-1 shows a summary comparison of the automation techniques (hard versus intelligent).

2.2.2 Assessment

Automation assessment data are in Section 5.3. The projected evolution is shown in Figures 5.3.1.1-1 through 5.3.1.1-6, supplemented by descriptive text in the corresponding paragraphs. The power, Environmental Control and Life Support System (ECLSS) and Guidance, Navigation, and Control (GN&C) subsystems are contained in Section 5.3.2.

2.2.3 Scarring and Prioritization

Scarring and prioritization are discussed in Section 5.3.3 and summarized in Table 5.3.3.1-1. Time phasing is contained in Section 5.3.3.2.

2.2.4 Development Support

Development support needs, which refers to development tools and aids, are discussed in Section 5.4.

2.3 ASSEMBLY AND CONSTRUCTION

2.3.1 Overview

The four major mission categories involved in this study, and the associated reference mission models, are described in Section 6.1. The mission categories include 1) Space Station IOC buildup, 2) Space Station expansion, 3) large spacecraft and platform assembly, and 4) geostationary platform assembly. Each of these are subsequently addressed in Sections 6.2, 6.3, 6.4, and 6.5, respectively. Each of these sections provides a description, scenarios, and conceptual design data.

The Mobile Remote Manipulator System (MRMS) basic design features and evolutionary considerations are contained in Section 6.2.3 and 6.2.4, respectively. Trade studies related to the MRMS are in Section 6.6.1.

2.3.2 Assessment

Commonality of the assembly and construction support equipment required for different mission tasks and scenarios is addressed in Section 6.6.2 for subsequent utilization in the automation assessment. The automation assessment is reflected in Section 6.7. Figure 6.7.2-1 shows enhancement techniques for remote control automation. Control system evolution is in Figure 6.7.2-2 and the automation technology assessment in Figure 6.7.3-1. An overall automation summary is contained in Section 6.8. A development plan is discussed in Section 6.8.3.

2.3.3 Scarring and Prioritization

Priorities are discussed in Section 6.8.2 and reflected in Table 6.8.2-1. Scarring projections are in Table 6.8.4-1.

3.0 SPACE STATION MISSION GOALS

Long-range planning is a keystone to successful productivity, cost effectivity, and life cycle cost improvements. Performance of long-range planning requires the capability to look into the future and make logical estimates and projections based on trends and forecasts of what the future could be like. While many people inherently possess the ability for credible forecasting, others develop varying levels of proficiency using different techniques. These techniques include projecting trends, model-making, collective prophecies, content analysis, Delphi technique, etc. (20)

The approach used on this task was to first break it down into four subtasks: 1) projected Space Station missions, systems, and vehicles; 2) Space Station evolvability thrust; 3) automation missions tasks and activities; and 4) configuration drivers.

3.1 PROJECTED SPACE STATION (SS) MISSIONS, SYSTEMS, AND VEHICLES

This section discusses those study themes considered necessary in responding to the expectations that are most likely to be generated by the space utilization society in regard to automation in space in the next one to three decades.

First, the understanding of what direction advanced automation will take requires an overall view of future mission trends and spacecraft population numbers. The initial missions investigated included the Space Station Mission Requirements identified by NASA/LaRC dated June 7, 1984. One forecasting technique used to start this effort was that of "Projecting Trends." In forecasting, it is reasonable to assume that present trends will continue for a while, but not indefinitely. In other words, one trend must be corrected by other trends or facts.

Missions identified in the LaRC reference Space Station mission model (27) are summarized in Figure 3.1-1 as to mission categories by number and year of launch. As can be seen in this figure there is a general trend for missions to reach a peak during the mid-1990's and a considerable decrease out through the year 2000 time frame. This trend is realistic since very few follow-on or new missions were identified in this model. Most of the missions investigated could be identified with science, technology or near-term commercial. Any benefits such as new manufacturing or material processing facilities would not be identified until after specific processes are identified and verified along with a long range growth plan, assuming successful results of the initial laboratory tests.

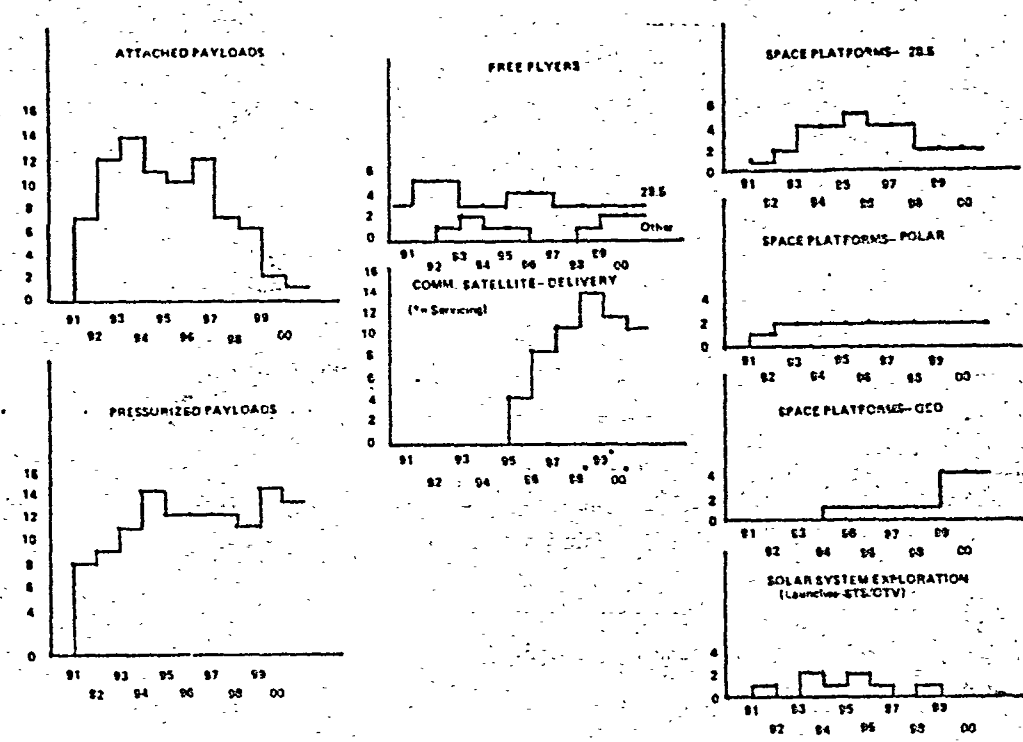


Figure 3.1-1 Mission Model–Summary

Since this information did not provide adequate data needed to show any trend toward core system robustness or conservativeness, a second approach was used. This second forecasting technique depended on "collective prophesies" in which a group of knowledgeable engineers engaged in a brainstorming session that reviewed the mission categories listed in Table 3.1-1. These areas were evaluated as to their future trend relative to activity predictions or frequency levels as a function of time. Results of this forecasting technique are shown in the table, where number one indicates a lower or decrease in mission activity from that of the first decade (91-00) to that of the second decade (00-10), number two indicated a similar level of activity and number three indicates a projected increase in activity after the year 2000. This information is useful since it indicates areas where future technology maybe beneficial. For example, using the information developed in Figure 3.1-1 and Table 3.1-1, a logical growth projection for many of the most common Space Station (SS) elements resulted. Table 3.1-2 shows the results of this analysis of the mission model and indicates an active growth period through the year 2000 and beyond. This growth is shown in Table 3.1-2 by the indicated time slices. Data beyond year 2000 are projections; the other data are from the LaRC mission model.

Table 3.1-1 Future Space Station—Projected Missions by Category

SCIENCE AND APPLICATIONS:	
ASTROPHYSICS	2
EARTH SCIENCE	1
SOLAR SYSTEM EXPLORATION	2
LIFE SCIENCES	1
MATERIALS SCIENCES	3
COMMUNICATIONS	3
TECHNOLOGY DEVELOPMENT	
MATERIALS & STRUCTURES	2
ENERGY CONVERSION	2
CONTROLS & HUMAN FACTORS	3
SPACE STATION SYSTEMS OPERATIONS	2
COMPUTER SCIENCE	3
PROPULSION	1
COMMERCIAL MISSIONS:	
MATERIALS PROCESSING	3
EARTH & OCEAN OBSERVATION	2
COMMUNICATION SATELLITE DELIVERY	2
COMMUNICATION SATELLITE SERVICING	3
INDUSTRIAL SERVICES	3

ESTIMATED LEVEL OF ACTIVITY

1. LOWER
2. SIMILAR TO 91-00
3. HIGHER

Table 3.1-2 Space Station System Time Slices

MISSIONS	(IOC) 1991	1995	(GROWTH) 2000	BEYOND 2000
SPACE STATION -				
ATTACHED PAYLOADS	7	10	1(10)	(10-15)
PRESSURIZED PAYLOADS	8	12	13	(10-15)
FREE FLYERS -				
28.5° INCL	5	4	3	(3)
OTHER	-	1	2	(2)
SPACE PLATFORM				
28.5° INCL	1	5	2	(3)
POLAR	1	2	2	(2)
GEO	-	1	4	(4)
SOLAR SYSTEM EXPLORATION	1	2	0	(2)
OMV MISSIONS	17	10	17	(15-20)
OTV MISSIONS	-	5	18	(18)

(NOS. IN PARENS. ARE SPECULATION; OTHERS ARE FROM MISSION MODEL)

Referring back to Table 3.1-1, mission categories where obvious growth is projected comes under the following areas:

1) Communications (all phases),
2) Material sciences and processing,
3) Satellite services, and
4) Technology, i.e., controls and human factors and computer sciences.

3.2 SPACE STATION EVOLVABILITY CANDIDATES

The most relevant items in the previous list that addresses the nearest of the future growth missions are communications, material sciences and processing (space manufacturing) and satellite servicing. Some of the more relevant information collected on these missions is discussed in the following paragraphs relative to automation opportunities. The last item (item 4 above), technologies needed for space system exploration, will be discussed under far-out future missions.

3.2.1 Communications

Communications satellites in the United States are growing so fast that orbital slots for satellites operating at current frequency bands could be exhausted by 1990. Current assignments of these slots are made by the Federal Communications Commission (FCC). Most of the slots at C band (4-6 GHz) and Ku band (12-14 GHz) are gone. The next highest of the radio frequency bands allotted by international agreement to communication satellites is the Ka band (17-30 GHz).

Present communications satellites are now being used primarily to transmit long-distance television programs from remote locations. During the coming years, analysts predict they will be increasingly used for such emerging applications as providing long-distance data links between computers and tying remote corporate offices together into central networks.

Satellites making up this system are parked in geosynchronous orbit (22,300 miles) and positioned along an arc approximately 67° to 143° west longitude. Within this arc, a number of individual satellites can operate in a common frequency band, without interference from each other's ground station, as long as they maintain a certain minimum separation distance in orbit. Presently this separation distance is three degrees for C-band satellites, two degrees for Ku-band satellites and one degree for proposed Ka-band satellites.

Although orbital space slots for C and Ku bands will soon be full, further enhancement may be possible. For example, orbital spacing could be decreased by increasing ground station antenna size. This provides only temporary relief and confirms the need for near-term development of Ka-band technology and systems to meet the continued-projected future growth of commercial satellite communications.

Following references from Appendix A are sources of further information: 3, 14, 22, and 47.

3.2.2 Space Manufacturing

Another area of considerable commercial interest is "Space Manufacturing." The term "Space Manufacturing" is broadly used to indicate the use of space to produce a salable product that someone is willing to buy. The capability to meet this criteria depends to a great extent on availability of low-cost mission support systems. A sample of these systems that could be very influential in providing cost effective operations include new launch systems, manned or unmanned processing facilities, free-flying transport vehicles, smart sensors, and large power supply systems. Along with these, component modularizations, electronic advancements, space manipulators, resupply capabilities, remote control and flexible automation all lead to a re-emphasis on space manufacturing. (4)

The desire for space manufacturing is well documented, along with the use of Space Station as a test bed to conduct early proof-of-principle experiments. However, the next step would look at increased production techniques which would require space manufacturing facilities to be designed to function first in a pilot plant mode and finally as a production facility.

The use of space for materials processing has been limited to small research experiments on Apollo, Skylab and ASTP. With the operational availability of the Shuttle and Spacelab, some small-scale laboratory operations have been conducted. Any experiments flown on Shuttle/Spacelab are limited by crew safety considerations and a desire to keep the cost down. Once the process has been verified, full scale pilot plant operations would be developed. Visionaries have indicated in various speeches and papers that space manufacturing/materials processing opportunities appear almost unlimited. The general public and even potential users who have heard and read these words take it for granted as a routine happening that will evolve in the normal passing of time.

In general, this is not true; it usually takes a concerted effort with R&T expenditures to conceptualize and verify the feasibility necessary to interest commercial investments needed to make it happen.

The effort proposed here is an attempt to provide potential users a low-cost approach through the sharing of space and support equipment within a basic manufacturing/processing (M/P) facility. A systems approach is necessary to identify the overall flexibility needed to support a majority of the M/P functional requirements. Some of the more common features that take advantage of various space attributes include: Zero gravity (weightlessness and near-perpetual motion), near-perfect vacuum (acoustic isolation, offgassing, no thermal convection, etc.) perpetual reservoir (waste products dump, heat sink, toxic and hazardous materials disposal), and solar energy (electrical, heating and cooling provision). Typical generic support features that must be provided include equipment holddown fixtures, material handling mechanisms, monitoring (vision) systems, centrifuge device, pressurization capability, computational processing, data handling, remote control, automation and spacecraft docking for receiving raw materials and removing finished products.

Areas critical to Space Station, where material processing growth is required, includes micro-gravity control, crew safety hazards, venting of toxic or contaminated waste, and direct versus indirect human interaction. In the direct or indirect human interaction, the spacecraft designer must consider the overall space requirement for crew safety which is one of the more restrictive design parameters. This affects the location and degree of crew participation when planning for any space manufacturing mission. From all initial indications, a multi-mission pilot plant concept could be unmanned with an MMU/EVA option. To make this a viable option, the basic facility would have a high degree of automation with manual override through remote control. The typical tradeoff here would be the cost effectivity between providing the autonomous equipment versus the life support system and man-rating the facility.

Impacts on Space Station as a result of material processing growth appears to be in the area of using the Space Station as a setup and checkout station and as a remote operations-support center.

Collectively, the space attributes of weightlessness, vacuum, disposal reservoir and solar power should benefit space manufacturing considerably. Opportunities appear to be limited with a best guess for full scale commercial pilot plant operations some time in the mid to late 1990s. Present efforts indicate the first commercial operations would most likely take place in selected electronics products and pharmaceuticals. However, historically, the capability to predict future products has not been too good, and the probability is greater for new products not even anticipated today.

3.2.3 Satellite Servicing

Satellite servicing is a term broadly used to indicate some type of support functions provided to spacecraft, i.e., deploy/retrieve, resupply/refuel, maintenance/repair, etc. These capabilities will be more demanding for future missions than the basic STS systems possesses, such as the Remote Manipulator System (RMS), the Remote Extravehicular Mobility Units, i.e., Orbital Maneuvering Vehicle (OMV), Orbital Transfer Vehicle (OTV), etc., and the Manned Maneuvering (MMU). Much of the early activities projected for these systems are covered by the TRW contract report and include tasks such as those required for development, flight testing, operations verification, and first generation orbital operations. These capabilities can be divided into satellite services at or near the orbiter, and those remote from or beyond the orbiter capabilities.

Shuttle and Space Station servicing capabilities depicted by TRW in their parallel report provides the evolutionary development of the first type of service systems as presently defined. Beyond the initial capability of satellite placement and limited retrieval of free-flying spacecraft, there is a projected need for cost effective servicing at remote locations from the orbiter.

The evolution of satellite service capabilities remote from the Orbiter/Space Station is considered in the future mission category and will depend on development of a flexible or intelligent servicer concept. This unit as conceptualized would be attached to and transported by an OMV and OTV to either medium earth orbit (MEO) or geosynchronous orbit (GEO). Obviously, this aspect of manned orbital operations will be dominated by remotely controlled (teleoperation/teleautomation) systems for servicing tasks that are beyond the crew hands-on capability provided by Space Station and EVA.

The automation impact on Space Station to support this type of future mission falls into two primary areas: system control and logistics support. The servicing option which may be pursued to acquire an intelligent servicing capability can vary over a wide range of remotely controlled servicing techniques. These include from a hardware standpoint the degree of "hard" to "flexible" automation and from a human interaction standpoint, the degree of "telepresence" to "teleautomation".

A principal objective of an intelligent servicer is to provide flexible servicing to a number of different satellites at their operational location. In many cases this is the cost effective approach when compared to returning the malfunctioning satellite back to the Space Station. Flexible servicing is differentiated from conventional servicing by provision of the onboard capability to adapt to a varying satellite work site environment. To accomplish this requires sophisticated vision systems, smart sensors systems, adaptive control modes, "expert" system software, and an executive controller employing artificial intelligence techniques. Potential "scars" that are indicated to implement an intelligent servicing capability includes a more complex control station, i.e., knowledge based systems (KBS), massive memory, and advanced data processing. In the logistics area, potential "scars" include the capability to service and load an intelligent servicer at a lower component Orbital Replacement Unit (ORU) level. Important issues related to implementation of servicing include degree of worksite structure, standardization, modularization, commonality and operability.

Following references in Appendix A are sources of further information: 34, 38, 41, and 42.

3.3 FAR-OUT FUTURE MISSIONS

The last of the mission goals investigated were those that featured missions conceived to address those issues that seem to impact life here on Earth. Information reviewed include everything from wishful thinking to in-depth analysis of massive solar power satellites to extraterrestrial exploration.

One other forecasting technique used to provide an insight into this area was a derivative of "content analysis." This technique is patterned after intelligence-gathering methods used during World War II, when allied forces discovered the value of reading newspapers from small German towns, which reported food shortages and other problems that revealed situations behind the enemy lines.

The study group used in this effort scanned a number of newspapers, magazines, periodicals, conference papers and other sources. A summary of selected issues collected from these sources is shown in Table 3.3-1. This table presents three sample groupings with some of the more relevant issues listed.

Table 3.3-1 Long-Term Opportunities for Future Space Missions

- SAMPLE OF TERRESTRIAL PROJECTIONS:
  - INCREASING ENERGY DEMANDS
  - INCREASING COMMERCIAL COMMUNICATION NEEDS
  - SAFE DUMPING OF TOXIC WASTE
  - DEPLETION OF RAW MATERIALS
  - OVERPOPULATION AND SHORTAGE OF FOOD
  - INCREASING URGE TO EXPLORE AND MIGRATE INTO SPACE
- EXAMPLES OF EVOLVING SPACE POLICY:
  - EXPLOIT SPACE FOR COMMERCIAL BENEFITS
  - MONITOR TERRESTRIAL EVENTS
  - CHARACTERIZE THE GLOBAL FUNCTIONING OF THE EARTH
  - SURVEY THE UNIVERSE AND STUDY PLANETARY BODIES
- TYPICAL EXTRATERRESTRIAL FORECASTS:
  - EARTHLINGS VENTURE TO MOON
  - MINING AND PROCESSING OF MOON MATERIALS
  - MANNED LAUNCHES FROM MOON INTO SOLAR SYSTEM
  - COLONIZATION OF EARTH'S SOLAR SYSTEM

The first grouping shows issues identified in various literature sources where there is a major world concern. Although many of these concerns are real, changing trends have a considerable impact on modifying future projections. When these concerns are investigated with the use of space to help resolve them, a number of new space initiatives have resulted that in many cases boggle the mind. Just a brief sample of new opportunities includes concepts such as space colonies, solar power satellites that convert the sun's continuous energy to supply electric energy at the Earth surface, mining and processing of raw materials, i.e., iron, silicon, aluminum, titanium, oxygen and others, from the moon or from asteroids and the possible use of space to dump hazardous waste.

The second grouping, examples of Evolving Space Policy, are listed to show the wide span of differences required in growing or evolving a space station that supports existing objectives versus futuristic objectives.

The last group indicates a scenario that could lead to future colonization of space. In fact, a three-day symposium on figure space programs sponsored by NASA and held in Washington on October 29, 1984, addressed many of these same items. A basic theme of this symposium was the feasibility of returning to the moon again, this time to establish permanent colonies. A scenario proposed included moon people raising their own food, mining minerals, producing rocket fuel and conducting 3- to 6- month exploratory sorties of the lunar surface (see references 11, 48, and 49).

According to NASA administrator James Beggs, establishing a permanent lunar base, or bases, is the next logical step to man's conquest of space. It could easily be accomplished in the years 2000 to 2010, Beggs said, after NASA deploys its Earth-orbiting space station. "I believe it highly likely that before the first decade of the next century is out, we will, indeed, return to the moon," Beggs told the symposium. Beggs said the lunar base could be used as a springboard to send astronauts to explore Mars and several asteroids (small planets) in orbit between Mars and Jupiter later in the century.

One of the major objectives in all manned missions, where extended periods in space are planned, is the closure of all life support system functions. In the aggregate of closing these functions, growing ones own food in space is by far the most complex and challenging and as a result the last one to be addressed.

Boeing has conducted a study for NASA's controlled ecological life support system program at Ames Research Center that investigated the economics of space inhabitants growing their own food. As part of this study they looked at NASA planning forecasts for the next 50 years. From this forecast examination, six typical missions were selected for reference purposes. The six reference missions include:

1) A low earth orbit (LEO), low-inclination space station,
2) A LEO, high-inclination space station,

3) A military command post in an orbit at about 132,000 miles altitude,
4) A lunar base,
5) An asteroid base, and
6) A Mars surface-exploration mission.

The interest and importance in this technology area made it a prime candidate for major modifications and overall facility growth. Considerable "scarring" could be considered in this area to accommodate future automation.

3.4 SUMMARY

A summary of the evolutionary functions associated with various long range missions and objectives of permanent manned presence has provided an insight to an optional sequential buildup of a space based infrastructure.

The potential candidates for automation are many and complex. It is logical that these elements along with control options be developed on a technology priority and cost effective basis. A low risk approach should make maximum use of ground and flight R&D experimental testing. A logical sequence of space vehicles first uses the shuttle orbiter as a mini-R&D test bed and then progresses to the space station as a larger test bed facility, and finally as an operations center for space activities relevant to supporting both co-orbiting platforms and other platforms in LEO, GEO and beyond. A general summary of space station evolvability drivers are shown in Table 3.4-1. In order to attain these basic goals, an ever increasing level of space crew productivity is required. Early awareness of automatible functions, that support an increase in productivity, is mandatory to allow for pre-emptive automation transparency.

Following references from Appendix A are sources of further information: 1, 2, 4, and 25.

Table 3.4-1 Space Station Evolvability Drivers

- TEST BED FOR COMMERCIAL PRODUCTS
- TEST BED FOR HUMAN MIGRATION INTO SPACE
- TEST BED FOR ROBOTICS PERFORMANCE GROWTH IN SPACE
- A SERVICING FACILITY FOR FREE-FLYING SPACECRAFT
- ASSEMBLY/CONSTRUCTION OF LARGE SPACE SYSTEMS
- A STAGING BASE FOR SATELLITE LAUNCHES UP TO GEOSTATIONARY AND BEYOND
- A LOGISTICS BASE FOR TRANSPORTING CREW AND MATERIALS TO MANNED GEOSTATIONARY PLATFORM

4.0 SYSTEM REFERENCE AND DESCRIPTION

4.1 IOC SPACE STATION REFERENCE

The purpose of this section is to provide a Space Station reference data base for the study team and to familiarize them with a current configuration. The Space Station definition as now conceived consists of both manned and unmanned elements with an Initial Operating Capability (IOC) early in the 1990s. Much of the data developed and summarized here was taken from reference 24.

4.1.1 Mission Tasks and Activities

To accomplish the diverse set of missions outlined in the prior Section 3.0 and to accommodate the complex equipment and payloads, a highly involved set of mission tasks and activities could be generated. Many of these are reflected in the later Sections 5.0 and 6.0 as related to the specific study elements of system automation and assembly and construction, respectively. The top-level mission tasks and activities, in terms of general capabilities and resources, are summarized as follows:

1) Provide a capability to assemble, maintain, and repair satellites, payloads, and space platforms

2) Provide pointing control with an accuracy of $\pm 10°$ and a stability of $\pm 0.02°/sec$.

3) Provide the following resources:
   - o Power
   - o Thermal
   - o Telemetry, command control, and timing
   - o Onboard data management
   - o Equipment calibration capability

- o Dedicated crew support
- o IVA and EVA support
- o Pressurized volume

4.1.2 General Requirements

The general, top-level requirements applicable to the IOC Space Station are identified below. These requirements are oriented toward the system evolvability, primarily with respect to automation, and reliability. The requirements hierarchy will expand and encompass all subtier elements as the system development begins. Requirements related to the system automation and construction and assembly are identified in Sections 5.0 and 6.0 herein, respectively.

A number of the significant general requirements are as follows:

1) Indefinite operational lifetime

2) Common design, hardware and software, with maximum standard interfaces

3) Provide for modular growth

4) Accommodate or incorporate new technology into existing systems

5) Autonomy from ground control

6) Maintain the Space Station critical operations during unmanned periods

7) Design critical systems to be fail-operational/fail-safe/restorable as a minimum

8) Shelf life of 10 years minimum

9) Redundant functional paths and redundancy management

4.1.3 IOC Configuration

The IOC configuration currently envisioned and baselined for this study is commonly referred to as the "power tower." The general configuration is shown in Figure 4.1.3-1.

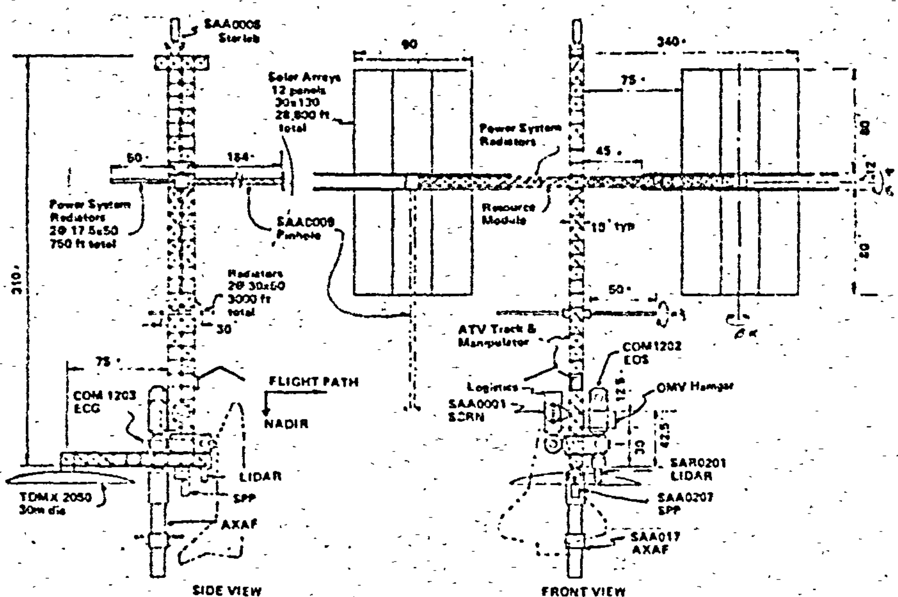


Figure 4.1.3-1 Power Tower IOC Configuration

The design characteristics are summarized in Table 4.1.3-1.

Table 4.1.3-1 IOC Space Station Characteristics

1. Station Configuration	Power tower with 5 modules (2 habitation, 2 laboratories, and 1 logistic)
2. Orbit	28.5°, 270 nau. miles
3. Crew Size	6 (with growth capability)
4. Logistics Support	Logistics module with 90-day resupply
5. Servicing Capability	1 OMV, 1 OTV (ground serviced)
6. Platforms	1 co-orbital, 1 polar orbit
7. Electrical Power	75 kWe (25 housekeeping, 50 payloads)
8. Reboost	Thrust level 100-300 lbs, 90-day cycle

4.2 SPACE STATION SYSTEM

4.2.1 System Elements

The Space Station, including the timeframe beyond IOC, will consist of a number of interrelated elements. The initial capabilities and growth of any of these elements must be compatible with the capabilities and requirements of the other elements. The major elements and their characteristics are summarized as follows:

1) STS (Space Transportation System)

2) Space Station
   - o Habitation modules
   - o Laboratory modules
   - o Logistics modules
   - o Pressurized payloads

- o Attached payloads
- o OMV and kits
- o OTV and kits

3) Free Flyers
   - o 28.5° inclination
   - o Other orbits

4) Space Platforms
   - o 28.5° inclination
   - o Polar orbit
   - o GEO

5) Ground Support Equipment and Facilities

6) Communication Network

4.2.2 Mission Model Analysis

Analysis of the referenced mission model data (Section 3.0) identified the quantities of the major system elements as a function of time, beginning at IOC and supporting the long-term buildup. In some areas, the IOC elements are perhaps overly optimistic. For example, the number of space platforms and free flyers appears to be more realistic in the growth phase. At any rate, the data are shown in Table 4.2.2-1 for four selected time slices. As noted, the numbers in parenthesis are projections while the other data were derived from the mission model.

Table 4.2.2-1 System Time Slices

VEHICLES	(IOC) 1991	1995	(GROWTH) 2000	BEYOND 2000
STS	1	1	1	(2)
SPACE STATION	1	1	1	(2)
SPACE PLATFORMS	2	7	4	(4)
FREE FLYERS	5	5	5	(5)
OMVs	1	(1-2)	(2)	(3)
OTVs	1	(1-2)	2	(3)

(NOS. IN PARENS ARE SPECULATION)
(OTHERS ARE FROM MISSION MODEL)

4.2.3 System Expansion Impacts

As the Space Station system expands from the IOC configuration, there will be a considerable impact on the levels of operations management and system control. Factors contributing to this expansion are as follows:

1) Additional Payloads
2) Additional Modules
3) Increased Levels of Servicing
4) Increased Levels of Maintenance and Repair
5) New Construction and Assembly Tasks
6) Increased Operational Complexity

Each subsystem will, in turn, be impacted by increased levels of support activity and operations management. These subsystems must have a sufficient design margin for small increases in system incremental growth and design flexibility for add-on capabilities to accommodate the projected overall growth. To summarize, the major subsystems are as follows:

1) Power

2) Data
3) Thermal
4) ECLS
5) Communications
6) Fluids Management
7) Structures and Mechanisms
8) EVA

The major impact considerations for three of the subsystems, power, data management and environmental control and life support, are shown in Table 4.2.3-1. The remaining subsystems are covered in greater detail in a parallel report prepared by Hughes Aircraft Company.

The selection of these three subsystems was based on the projected advancements required and thus would probably include more opportunities for advanced automation.

Table 4.2.3-1 Subsystem Impact Considerations

- ELECTRICAL POWER SYSTEM
  - -- INTERFACES, DISTRIBUTION, CONTROL AND PROTECTION
  - -- INCREASED LEVEL OF LOADS MANAGEMENT
  - -- POWER GENERATION - EXPANDED CONTROL
    - - EXPANDED MONITORING
    - - EXPANDED MANAGEMENT
- DATA MANAGEMENT SYSTEM
  - -- ADDITIONAL DATA INTERFACES
  - -- INCREASED DATA TRAFFIC
  - -- INCREASED DATA MANAGEMENT
    - - HANDLING
    - - ROUTING
    - - STORAGE
    - - TRANSMISSION
- ECLS
  - -- ADDITIONAL MODULES AND/OR CREW MEMBERS WILL INCREASE THE RESOURCE REQUIREMENTS
    - - POWER
    - - DATA
    - - THERMAL
    - - CONSUMABLES
    - - FLUIDS MANAGEMENT
    - - LOGISTICS
    - - INCREASED HEALTH MAINTENANCE ACTIVITY

4.3 SPACE STATION SUBSYSTEMS

For the purposes of this study, three major Space Station subsystems were examined with a fourth one added half way through the study:

1) Electrical Power
2) Environmental Control and Life Support (ECLS)
3) Data Management
4) Guidance, Navigation and Control (GN&C)

As stated earlier, the remaining subsystems will be examined in a parallel report by Hughes Aircraft Company.

4.3.1 Electrical Power

4.3.1.1 Requirements and Functions - The major electrical power system requirements, or functions, are as follows:

1) Provide 75 KW at end of life for IOC
2) Provide 300 KW for growth (2000) configuration
3) Provide power source for eclipse or dark side periods
4) Provide power generation, conversion
5) Provide power distribution and control
6) Adequate redundancy
7) Protection against single failure in primary busses
8) Circuit protection

The major automation requirements for the electrical power system are as follows:

1) Automated routine management and control of power system

2) Automation of routine resources management (all power-related consumables)

3) Automated fault detection and isolation

4) Automated redundancy management

5) Automated reverification of power system

6) Automated management and control shall be accessible to crew and/or ground. Manual override control shall be available for TBD functions.

7) Appropriate alerting of marginal conditions provided to crew

8) Accessible and complete "audit trails" for automated actions taken

9) Use "natural" or "high order" computer language

10) Provide for automatic or manual initiation of system validation or reconfiguration

11) Automated monitoring and protection of power interfaces to protect against payload failure of misuse of resources

12) Design to allow for implementation of artificial intelligence as technology permits

13) Provide capability to permit or accommodate the automation of on-line operational mission management

4.3.1.2 <u>Power System Baseline</u> - The power system baseline consists of the solar arrays, power generation modules, conditioning, and control and distribution assemblies. A typical system configuration is shown in Figure 4.3.1.2-1.

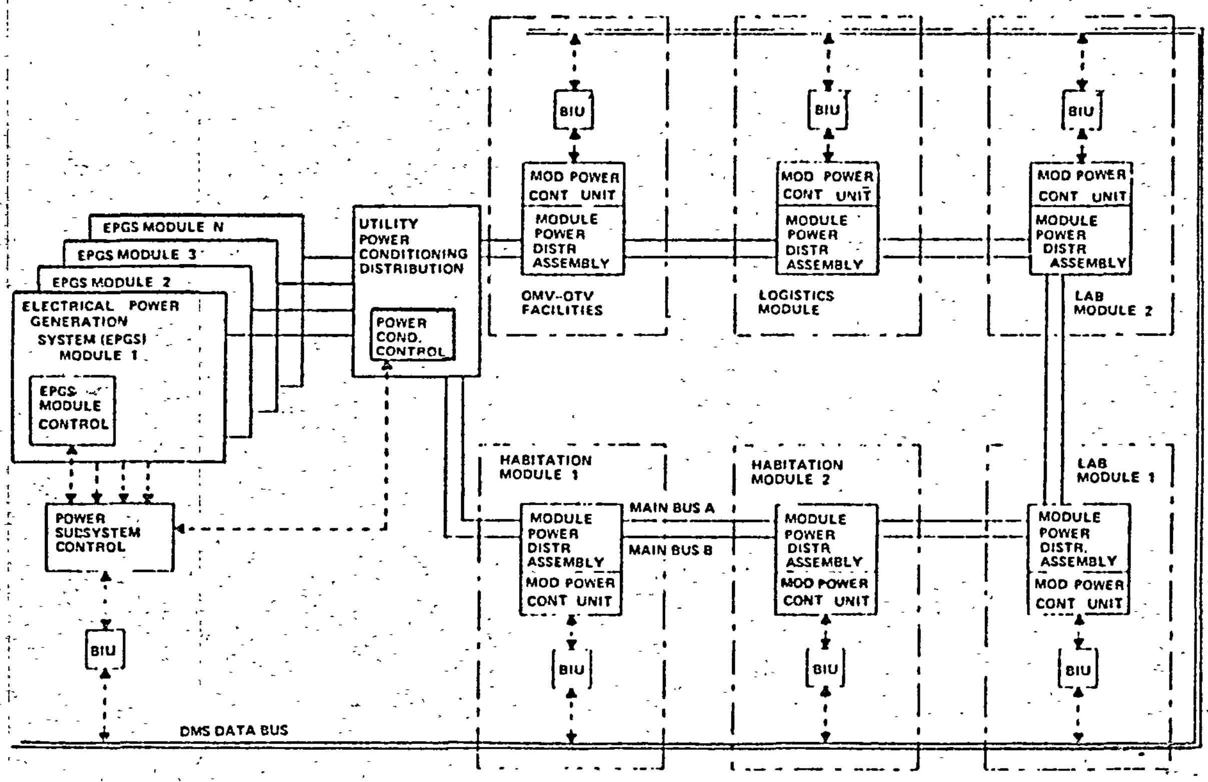


Figure 4.3.1.2-1 Electrical Power System Configuration

4.3.1.3 Growth Characteristics - The electrical power system is expected to provide approximately 75 KW at IOC and evolve to approximately 300 KW for the year 2000. Many changes will probably occur during this growth period. An approximate timeframe for the change or modification is shown in Table 4.3.1.3-1.

Table 4.3.1.3-1 Electrical Power System Time Slices

	(IOC) 1991	1995	(GROWTH) 2000	BEYOND 2000
POWER GENERATION & CONVERSION (SOLAR PLANAR SYS)	• AUTOMATIC SOLAR SEGMENT MANAGEMENT OR AUTO PEAK POWER	• LARGE SOLAR CONCENTRATOR (1996) • LASER POWER TRANS/RECEPT/CONV (1997) • POWER SYSTEM TECH. (1996)		
ENERGY STORAGE	• BATTERY MANAGEMENT CHARGING & RECONDITIONING	• AI/EXPERT SYSTEM • INTEGRATE WITH ADDITION OF REGENERATIVE SYSTEMS (EG FUEL CELLS)	• AUTONOMOUS	
POWER DISTRIBUTION AND CONTROL	• LOADS SCHEDULING & MANAGEMENT AI/EXPERT SYSTEM	• EXPANDED	• EXPANDED AS REQUIRED	
SUN ACQUISITION AND POINTING	• AUTONOMOUS			
POWER MEASUREMENTS	• EXTENSIVE PERFORMANCE MONITORING • MAIN DRIVER IS FAULT DETECTION & ISOLATION	• EXPAND OR MODIFY WITH POWER SYSTEM CHANGES		
FAULT DETECTION	• AUTOMATIC DETECTION • REPROGRAMMABLE LIMITS • SYSTEM ALERTS			
FAULT PREDICTION	• TREND ANALYSIS	• PREDICT IMPENDING FAILURES WITH AI/EXPERT SYSTEM (E.G. INJECT STIMULUS SIGNAL; MEASURE RESPONSE)		
FAULT ISOLATION	• AUTO IDENTIFICATION OF FAULT ORU • GREATER DIAGNOSTICS ON DEMAND			

Table 4.3.1.3-1 (concl)

	(IOC) 1991	1995	(GROWTH) 2000	BEYOND 2000
FAULT RECOVERY	• AUTO SWITCHING OF REDUNDANCY FOR SELECTED FAIL-OPERATIONAL MODES • FAIL-SAFE OPERATION WITH OPERATOR SUPERVISION TO RECOVER OR RECONFIGURE			
VERIFICATION OR CHECKOUT	• MANUAL OR AUTOMATIC INITIATION		• EXPANDED TO MATCH SYSTEM CONFIGURATION	
UNMANNED SS	• FULL AUTONOMY CRITICAL FUNCTIONS WITH GROUND BACKUP TO ENABLE REVISIT		• EXPAND WITH SYSTEM CONFIGURATION	

4.3.2 Environmental Control and Life Support System (ECLSS)

4.3.2.1 Requirements and Functions - The major ECLSS requirements, or functions, are as follows:

1) Six crew members
2) 90-day resupply
3) 28-day safe haven
4) No overboard waste dump; waste products returned to earth
5) Indefinite life with onboard maintenance
6) Minimize crew and/or ground involvement
7) Fail operational fail safe
8) Modular design for growth and new technology; minimum scar
9) No hazardous fluids within pressurized modules

The ECLSS functions are dependent on the kind or type of module being utilized. The applicability of the ECLSS function relative to the type of module is shown in Figure 4.3.2.1-1.

REQUIREMENT BY MODULE

ECLS FUNCTIONS PERFORMED	HAB. #1	HAB. #2	LIFE SCIENCES	MATERIALS LAB	LOGISTICS
AIR TEMPERATURE CONTROL	X	X	X	X	X
O_2/N_2 PRESSURE CONTROL	X	X	X	X	X
VENTILATION	X	X	X	X	X
MONITORING	X	X	X	X	X
WALL THERMAL CONTROL	X	X	X	X	X
NOISE CONTROL	X	X	X	X	X
ODOR/CONTAMINANT CONTROL	X	X	X	X	X
FIRE CONTROL	X	X	X	X	X
LIGHTING	X	X	X	X	X
PARTICULATE FILTRATION	X	X	X	X	X
BACTERIAL/MICROBAL CONTROL (AIRBORNE)	X	X	X	X	X
HUMIDITY CONTROL	X	X	X	X	X
ELECTRONICS CONDITIONING	X	X	X	X	X
POTABLE WATER SUPPLY	X	X	X	X	
HANDWASHING	X	X	X	X	
GALLEY SUPPORT	X				
SAFE HAVEN SUPPORT	X	X			
EXPERIMENTS CONDITIONING			X	X	
ANIMAL AIR FILTRATION			X		
ANIMAL AIR ODOR/CONT. CONTROL			X		
ANIMAL AIR HUMIDITY CONTROL			X		
ANIMAL AIR MONITORING			X		
ANIMAL AIR TEMPERATURE CONTROL			X		
ANIMAL DRINKING WATER SUPPLY					
ANIMAL FOOD SUPPLY					
EVA SUPPORT (AIR LOCKS ONLY)					

Figure 4.3.2.1-1 ECLS Function by Module

Figure 4.3.2.1-2 depicts the module arrangement used for the reference configuration. This arrangement provides a "racetrack" configuration, i.e., each module (except the Logistics Module) has two exits. There is a high degree of module commonality, particularly among the four modules in the racetrack. This results in the fewest number of module types being required. This arrangement also provides a minimum total number of elements and a minimum number of interfaces between elements. Penetrations around a radial port and the opposite axial port permit passage of major utilities.

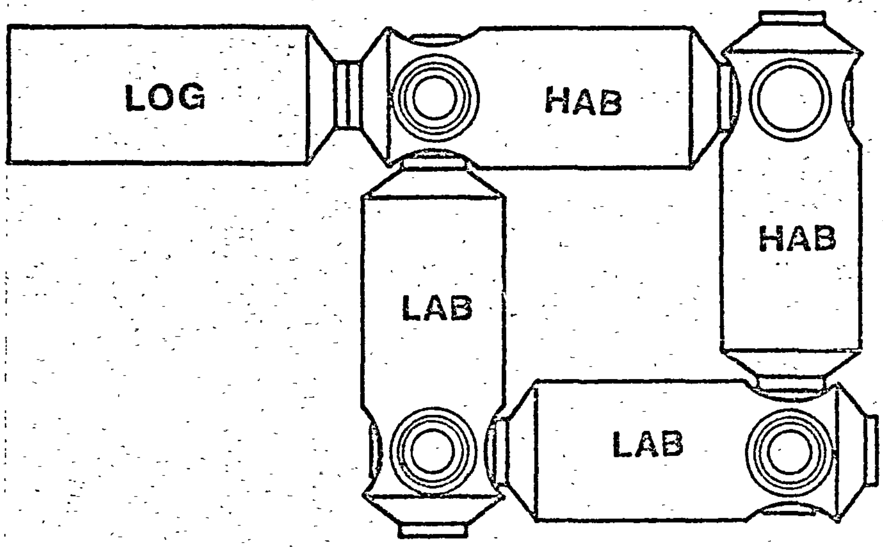


Figure 4.3.2.1-2. Reference Module Arrangement

Line definition for the ECLSS includes two 4-in.-diameter lines penetrating through the bulkheads, and expanding to 6-in.-diameter ducts. Air flow on one line provides supply to the module, while the other line is used for collecting exhaust air. Internal utilities entering/exiting through the two bulkhead panels include dual 1-1/2 in.-diameter coolant supply and return lines, dual 1-in.-diameter lines for drinking water, for waste liquid water, condensate water, and wash water. Also included are dual 3/8-in.-diameter O_2 supply and 1/2-in.-diameter N_2 supply lines. Traffic through the Laboratory Modules is low, with the majority of traffic being in the two Habitation Modules. Traffic considerations and interface/integration considerations seem to make it preferable to have the Logistics Module and Orbiter berthed to the Habitation Modules, and to have the pressurized payload modules berthed to the Laboratory Modules.

4.3.2.2 <u>ECLSS Baseline</u> - The IOC ECLSS baseline consists of a variety of equipments and consumables. Common Equipment (CE) is located in all major modules. Other modules are outfitted in accordance with their major function. The types or kinds of equipments and consumable are listed in Table 4.3.2.2-1.

Table 4.3.2.2-1 IOC ECLSS Baseline

<u>COMMON EQUIPMENT (CE)</u>	<u>AIRLOCK SUPPORT EQUIP (ASE)</u>	<u>HEALTH & HYGIENE (H&H)</u>
Sensible Heat Exchanger Pkg	Pump/Accumulator	Commode w/Urinal (2)
	Escape Sys (Balls & POS)	Shower (2)
Vent Fan Pkg & Filters	EVA Suit I/F & Regeneration Sys	Handwash
O_2/N_2 Control		Hot Water Heater
Cabin Dump & Relief	<u>RESUPPLY & STORAGE (R&S)</u>	Cold Water Chiller
Air Distribution Bus	Normal O_2 Supply	
Cold Plates	Normal N_2 Supply	<u>AIR REVITALIZATION EQUIP (ARE)</u>
Water Pump Pkg } Not in	Potable Water Supply	Humidity Control Pkg
Freon Pump Pkg } Log Mod	Bulk Freezer Storage	CO_2 Removal
Interface H/X	Waste Water Treatment & Storage	Contaminant Control
Fire Detection & Suppression	Trash Compactor, Storage & Odor Control	Atmospheric Monitor
		Odor Removal
Water Distribution Sys	CO_2 Storage	CO_2 Compressor/Liquifier
Gas Distribution Sys	Fecal Waste Bulk Storage	
		<u>ECLS CONTROL & DISPLAY (C&D)</u>
<u>SAFE HAVEN EQUIP (SHE)</u>	<u>GALLEY</u>	
Emergency CO_2/RH/Trace Contamination Control	Refrigerator/Freezer	
	Oven	
Emergency O_2	Trash Compactor	
Emergency N_2	Handwash	
Emergency Potable Water		
Shelf Stable Food		

The present space station life support systems (for air, water, waste, and food) are classified as either "open", i.e., resources are all supplied from storage-ground resupply with no regeneration, or some degree of "closure", i.e., used resources are regenerated. The IOC concept as shown in Figure 4.3.2.2-1 for this study has a partial closure of the water management system and regenerative CO_2 removal system while all the others are open. Advantages of closing the life support system reside in the considerable opportunities for reducing logistics weight and volume.

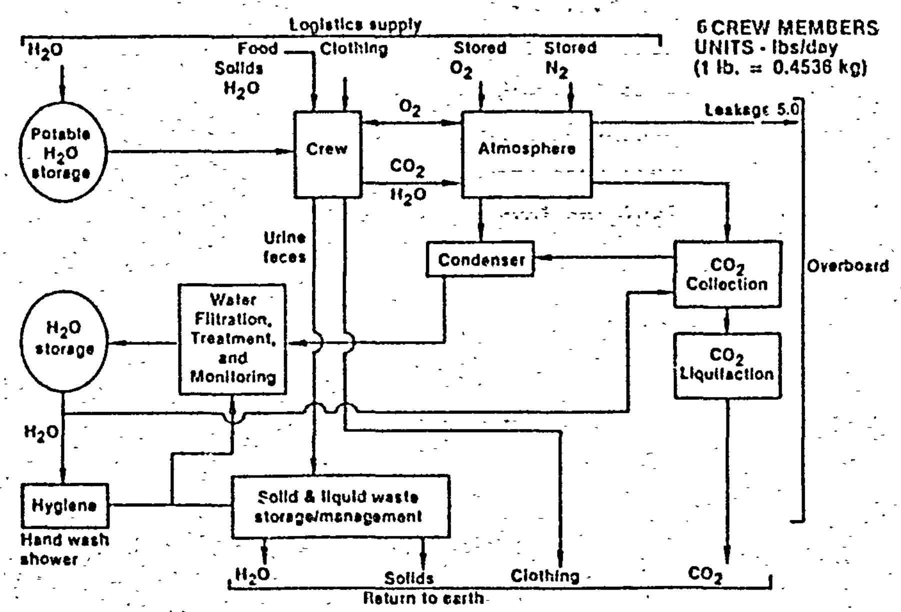


Figure 4.3.2.2-1 ECLSS Functional Flow Diagram

4.3.2.3 Growth Characteristics - The successful evolution of the ECLSS from the IOC to Space Station 2000 and beyond must include a consideration of the significant factors at the outset. The system must satisfy the initial requirements but must be able to accommodate the expected changes that will occur. Growth potential is, therefore, a factor in the evolution criteria. The evolution criteria would include the following factors:

1) Technology Status/Risk
2) Operational Support Crew and Ground
3) Growth Potential
4) Ilities Considered
5) Logistics
6) Safety/Complexity
7) Economic Benefits--Lower volume, lower weight, lower power

The quality and quantity of consumables required to support the life functions constitute a major logistics problem for a long-term Space Station. Reclamation, reconstitution, recovery, and regenerative systems offer opportunities to alleviate this problem. However, budgetary limitations, technology maturity, performance, verification time, and control complexity all combine to drive the degree of closure and the implementation timing. ALthough considerable savings can be realized at each logical step of partial closure, the technologies and subsystems needed to obtain such savings require a large number of additional systems, subsystems, components, sensors, and instruments. To provide efficient system performance requires a large number of subsystem interfaces, and careful balancing of interacting chemical processes. (6) Parallel processing options exist for carbon dioxide removal, water reclamation or gray water processing, oxygen generation, i.e., water electrolysis or CO_2 reduction, and contaminants removal. The important issue here is to start with a concept that is technologically transparent to options that will be added in the future to close on a step-by-step basis all LSS functions, even through the food cycle with progressively high productivity features. A proposed evolution of the closed loop approach for the major LSS elements is summarized in Table 4.3.2.3-1.

Table 4.3.2.3-1 Evolutionary Loop Closure Approach

FUNCTION	1980 OPEN	1991 SEMI-OPEN	2000 SEMI-CLOSED	BEYOND 2000 IDEAL-CLOSURE
CO_2 CONTROL	$LiOH/CO_2$ ABSORB.	REGEN. CO_2 REMOV. CO_2 LIQ./STOR.	REGEN. CO_2 REMOV. CO_2 LIQ./STOR.	REGEN. CO_2 REMOV. CO_2 REDUCTION
POTABLE WATER	RESUPPLY	RESUPPLY	WATER PROCESSING	TOTAL WATER PROC.
O_2 SUPPLY	RESUPPLY	RESUPPLY	RESUPPLY	O_2 GENERATION
N_2 SUPPLY	RESUPPLY	→	→	→
WASH WATER	RESUPPLY	PARTIAL PROC.	TOTAL PROCESSING	TOTAL PROCESSING
FOOD	RESUPPLY	→	→	GROW FOOD

4.3.3 Data Management System (DMS)

4.3.3.1 Requirements and Functions - The major data management system requirements or functions are as follows:

1) Provide sufficient data processing for each subsystem

2) Provide command and status indications to/from all subsystems

3) Provide ancillary data and resource coordination to customers
   - o Interfaces for payloads
   - o Multiplex customer data streams up to 300 megabps
   - o Transmit to ground through TDRSS or TDASS
   - o Support near-term mission planning and scheduling and provide information to customers

4) Provide fully interactive data work stations of a common design as the man/machine interface
   - o Data communication shall be visible through the data work station
   - o Provide crew total commanding capabilities and data verification into each subsystem
   - o Protect the system from accepting erroneous commands that effect crew safety or damage equipment
   - o Provide data work station hard copy capability
   - o Design for low noise levels

5) Provide a crew training support capability for subsystems

6) Provide real-time support for data storage of 1200 gigabits

7) Provide a single time and frequency reference for all SS elements and customers (payloads)

8) Provide a common data format for data transactions between space station program elements

9) Support checkout capability of subsystems and redundant components

10) Support checkout and launch of OMV and OTV

11) Support operation of remote manipulation and instrument pointing

12) Employ data security techniques/unauthorized access

13) Provide data communication access by crew or ground for subsystem monitor and control

14) Support maintenance by providing for all command and data transfer to be stored with capability to purge

15) Provide for data transfer between subsystems through a data network that can support a (300) MBPS rate (TBR)

16) Provide automatic fault handling for customer interfaces

17) Design for enhanced maintainability of software life cycle

18) Provide capability for crew to modify, generate, add or delete application software in real-time with the system on line

19) Design for RFI compatibility

20) Design for bit error rate of 10^{-6} (TBR)

21) Design to be "user friendly" with prompts and help function

The end-to-end data management system involves the full spectrum of the Space Station program. An overview of the major elements is shown in Figure 4.3.3.1-1.

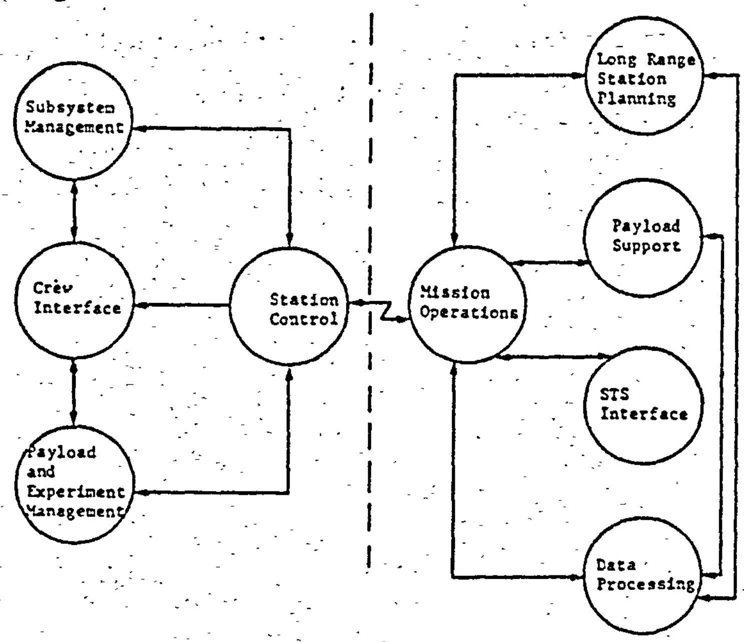


Figure 4.3.3.1-1 End-to-End Data System Functions

The major automation requirements for the data management system are as follows:

1) For unmanned periods of operation, maintain critical operations

2) Automated routine management and control of DMS

3) Automated fault detection and isolation

4) Automated redundancy management

5) Automated reverification of DMS

6) Automated management and control shall be accessible to crew and/or ground. Manual override shall be available for selected functions.

7) Appropriate alerting of marginal conditions provided to crew

8) Accessible and complete "audit trails" for automated actions taken

9) Use "natural" or "high order" computer language

10) Provide for automatic or manual initiation of system validation or reconfiguration

11) Automated monitoring and protection of data interfaces to protect against payload failure

12) Design to allow for implementation of artificial intelligence as technology permits

13) Data utilities shall be self-managing with allocation of data systems resources being largely automated and transparent to the user

14) Provide for administrative data processing services to support automation of on-line operational mission management.

4.3.3.2 Data Management System Baseline - The data management system must be designed to satisfy a number of system-level requirements. The architecture of the system will provide the structure in which these requirements will be met. Figure 4.3.3.2-1 illustrates the tradeoff between centralized and distributed system architectures.

	Growth Capa-ability	Modu-larity	Bus Traffic	Maintain-ability	Reli-ability	Adapt-ability	Auto-mation/ Autonomy	Hardware Cost	Soft-ware Cost	Compu-tational Speed
Central-ized	Con-strained	Poor	Moderate-ly Low	Moderately Complex	Low	More Complex	Diffi-cult	Moderate	Mode-rate	Limited
Distrib-uted	Easy	Excel-lent	High	Simpler	High	Simple	Simpler	High	High	No Hard Limit

Figure 4.3.3.2-1 Data Processing Architecture Factors

Figure 4.3.3.2-2 illustrates the implementation of distributed architecture and the link between the spaceborne and ground data system.

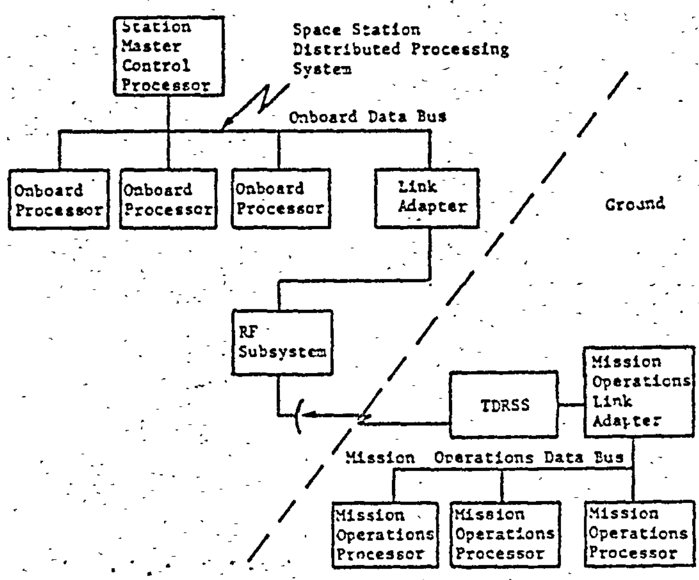


Figure 4.3.3.2-2 Space Station System Data Management Architecture

One data management system concept, utilizing a dual ring-bus configuration, provides a means to link together all data elements of the Space Station as shown in Figure 4.3.3.2-3.

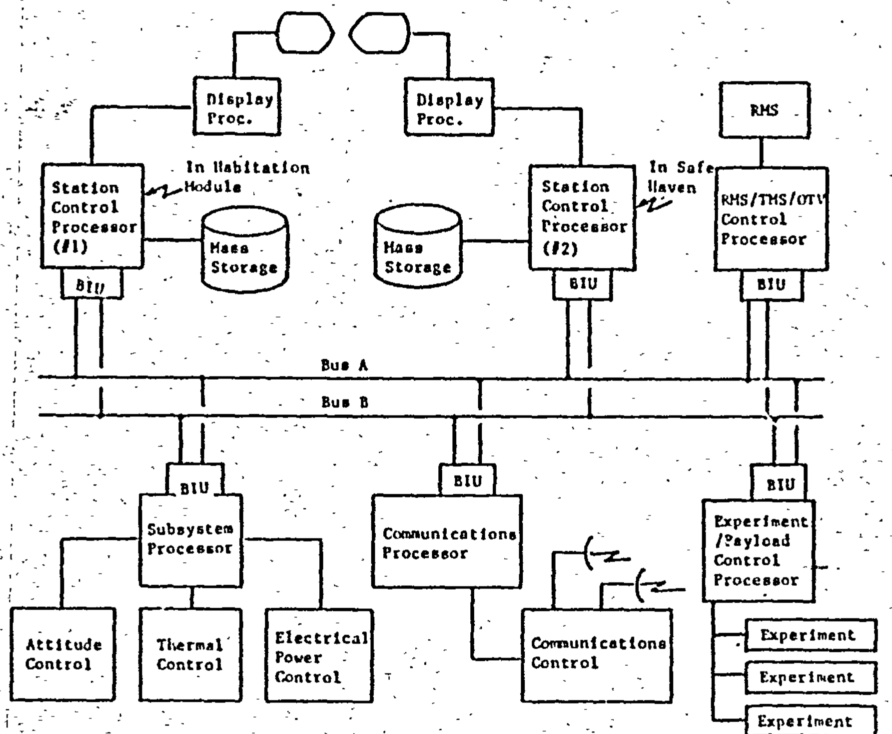


Figure 4.3.3.2-3 Data Bus Concept

4.3.3.3 <u>Growth Characteristics</u> - The data management system attributes will include flexibility and adaptability. Growth changes anticipated may include modular expansion, increased processing speed, fault tolerance, and increased data storage capability as shown in Table 4.3.3.3-1.

Following references from Appendix A are sources of further information: 7, 8, and 50.

Table 4.3.3.3-1 Data Management System Time Slices

	(IOC) 1991	1995	(GROWTH) 2000	BEYOND 2000
DATA ACQUISITION	• EXTENSIVE USE OF REMOTE I/F UNITS		• EXPANDED PRIMARILY BY MODULAR ADDITIONS	
DATA PROCESSING	• NETWORK RATES UP TO 300 MBPS • 100 MOPS		• SAME • 2000 MOPS	
FAULT TOLERANT COMPUTERS	• TBD		• VHSIC	
MASS MEMORY	• TBD (1.2×10^3 GIGABITS)		• TBD (1.2×10^4 GIGABITS)	

5.0 SYSTEM AUTOMATION

5.1 INTRODUCTION

5.1.1 Goals and Assumptions

5.1.1.1 Goals of Automation - There are several goals for automation on the Space Station, as shown in Table 5.1.1.1-1. Automation may reduce crew workload or, stated another way, could allow more complex tasks to be performed by the crew at constant work levels. This points towards the ability of the Space Station to support more numerous and/or more complex payloads, both of which relate directly to an earlier return on the government's investment.

Automation could allow the Space Station to be less dependent upon ground telemetry, tracking, and control (TT&C). This would allow the Space Station to survive if cut off from the ground for an extended (90-day maximum probably) period of time. Many factors could influence the likelihood of this cut off. The range of events over the 30-year expected life of Space Station includes limited nuclear war somewhere on the globe and natural disaster befalling ground mission control. But further, this decreased ground dependancy could allow select payloads to be flown during Space Station development before a full crew staffed the 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. The goal of automation therefore would be to hold the Space Station ground personnel costs to approximately those of the STS. This would be a cost saver for the government and again lead to an earlier return on investment for the government.

Table 5.1.1.1-1 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
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

A somewhat more removed but no less significant reason for automation is that the problems to be solved by industry in order to achieve desired levels of autonomy have high payoff in non-Space Station arenas. The tooling (software and hardware) which will never fly on Space Station but which will be crucial to Space Station mission success through its making possible flying other hardware and software is important.

The Space Station data processing system is a key focal point as recipient of automation.

5.1.1.2 Migration of Ground-Based Missions to Space - It is almost intuitive that there will be a migration during the Space Station life of missions currently thought of as ground based to space. The reasons for this are founded in a desire to keep the number of ground personnel to manageable levels and to increase the productivity of the crew. In order to accomplish this, the Space Station as a system must become more functional. It is a natural step for manned space missions to take advantage of the increasing sophistication of hardware and software. Consider man as an information processor, performing cognitive processing at a variety of levels of sophistication. As the capability to automate parts of this cognitive processing becomes mature, the human can focus on the less mundane levels. Examples of mission elements which can move to space are simple trend analysis, some fault isolation, and some aspects of planning. With the complexity of the flown system on the increase as well as its scope, we can anticipate that the ground mission functions will increase in difficulty as well. As the mission allocation migrates, so will its corresponding system elements such as hardware and software.

It can be assumed that the state of the art in computers and software will lead the technology flown on Space Station by no more than 10 years. This implies that an IOC station will have onboard Automatic Data Processing (ADP) equipment approximately equal to that available today to the research community. A representative example would be a hardened, standalone, 32-bit processor with Winchester drive and bit-mapped, multi-window display. It can be anticipated that the FOC station would have at least hardened symbolic processors and active, intelligent DBMS.

5.1.1.3 Evolution of Artificial Intelligence - Artificial Intelligence (AI) is a broad area of research activity today which promises high payoff. Herein, AI is referred to as providing "flexible" or "intelligent" automation. AI has been much discussed in relation to the Space Station, and there are two overriding points to make.

First, AI is an evolving set of techniques, support tools, and methods. Of these, the methodology is the least mature. AI will undergo evolution as the Space Station evolves. This joint variation makes planning AI inclusion in the later stages of Space Station difficult. There is considerable current interest in AI throughout the world, and its maturation may be counted on. If we err towards being too conservative in our planning to exploit AI and the field evolves within the next ten years, the current planned Space Station may be much less cost effective with respect to what is available from the state of the art much sooner than 30 years.

Secondly, there is an important difference between a research orientation towards AI and an engineering orientation towards it (see Table 5.1.1.3-1). AI offers deep opportunities for research. That orientation is at odds with what may be called standard system engineering methodology. The engineering approach would identify required functions that a system must possess and then allocate them to hardware, software, or human. Exploitation of AI would modify the software allocation to include a special type of software--knowledge based systems (KBS). In defining and developing KBS components of a major system, the developers have the freedom to allocate functions to humans which are insufficiently mature. Such KBS are referred to as using "mixed initiative." It may be possible to construct a fully intelligent expert system to function as an advisor to a human. However, the construction of a system using symbolic manipulations and sizable amounts of human input may be quite feasible. Further, by bounding the problem's context, e.g., "build something to plan Space Station orbit boost" vs. "build a planner for Space Station" vs. "build a generic planner for space systems," it is moved into the realm of engineering. Embracing the notion of an engineering approach to KBS inclusion in Space Station may allow earlier inclusion of at least placeholder AI technology in Space Station and avoid the risk discussed in the previous paragraphs.

Table 5.1.1.3-1 Problems in Approaching KBS Components

Research	Engineering
Method need not be visible	Method must be visible
Artistic method	Structured method
Everything allocated to H/W-S/W	Freedom in functional allocation
Stand alone	Part of larger system
Key resource is people	Key Resource is tooling

5.1.2 Overview

5.1.2.1 The Study Approach - It is attempted to establish the ultimate attainable level of automation for the Space Station in the year 2000. While somewhat unclear, this point in the evolution of the Space Station becomes an important study tool. The expected IOC 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:

- The computer and software across the subsystems was a key accommodator of automation.
- 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 ADP which perform mission elements, now thought of as ground-based and complex, are what provides the context for the stepping from IOC.
- These portions of the ADP deal with planning and scheduling, and caution, warning, and status monitoring.

Therefore, this functional component of the ADP was analyzed, establishing a logical stepping from IOC towards it, and considered what technology could improve its feasibility. An additional reason for this approach is that it complements what is available through the literature.

The approach may be summarized by the following set of sequential study objectives:

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

Figure 5.1.2.1-1 shows that this portion of the study considers 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 KBS techniques. The elements of that column are some key issues discussed below. While the study addresses issues other than these, those shown are considered important.

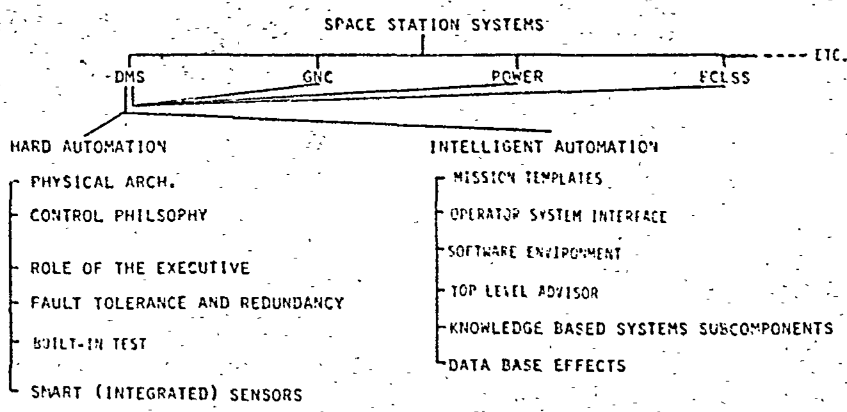


Figure 5.1.2.1-1 Elements To Be Implemented on Space Station ADP

5.1.2.2 Issues in the 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.

5.1.2.3 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 decisionmaker. Interactions between crew members and systems will change.

Research is therefore necessary to (1) define the proper roles of and interactions between crew members, on-board systems, and external systems and personnel; (2) establish criteria on how crews may best cope with complex systems, and how these systems should be configured; (3) determine how complex decisionmaking can best be accomplished in multi-crew environments, particularly under stress; (4) develop a better understanding of the causes and effects of crew errors, and effects of fatigue and desynchronosis on performance and judgment; (5) assess the acceptance of new ideas and technologies and determine how best to indoctrinate crews into their use and acceptance; and (6) correlate behavior patterns and psychological profiles with incidents and accidents.

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. Research is necessary to (1) define and evaluate alternative computer-graphic display formats for each mission phase or flight profile segment; (2) determine the merits of using pictographs for various control and monitoring functions; (3) establish guidelines for use of aural information transfer; (4) establish and evaluate multi-sensor image concepts; (5) determine how the characteristic differences between cathode-ray tubes and flat-panel displays may influence their selection for use in operational systems; (6) establish guidelines for specifying physical characteristics of display media; and (7) establish guidelines for interfacing with on-board systems.

c) Subsystem Status Monitoring/Caution & Warning - As shown in Table 5.1.2.3-1 , one additional function per subsystem is anticipated and one corresponding additional computer to process that function. We anticipate the need for symbolic processors among these additional computers. Communications system sizing will likely be adequate if local storage either through RAM discs or Winchester based peripherals is provided. We should design the system so as not to preclude the inclusion of 32-bit processors in the SDPs.

Table 5.1.2.3-1 Subsystem Status Monitoring/Caution and Warning

- o One additional function per subsystem
- o One additional computer per subsystem—GNC, POWER, ECLSS, etc
- o Symbolic Processor is a subcomponent of these computers
- o Communications system sizing should be adequate if local storage is provided.
- o 32-bit processors associated with the SDPs should not be precluded.

d) Development Support - Beyond onboard needs, we should respect the need for adequate software tooling and laboratories. Some of these are shown in Table 5.1.2.3-2.

Table 5.1.2.3-2 Development Support Needs

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

5.2 HARD AUTOMATION VS. INTELLIGENT AUTOMATION

5.2.1 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.

5.2.1.1 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 (SS) IOC workbook adopts this approach. The ability to have subsystem (e.g., GN&C) 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 5.2.1.1-1.

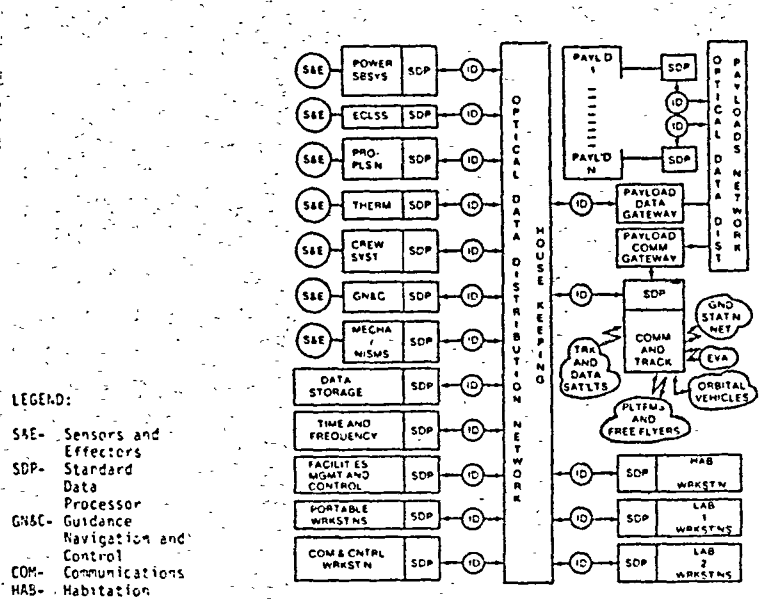


Figure 5.2.1.1-1 Physical Architecture—Information and Management System

The notion of "distribution" is becoming important in analysis of both physical and logical computer architectures. A distributed system offers processing flexibility, expandability without redesign and, generally, size and weight advantages.

Work by Honeywell has resulted in a taxonomy of distributed systems with ten elements. These are shown in Figure 5.2.1.1-2.

1. <u>Loop System with Unidirectional Traffic.</u>
   Disadvantages: bandwidth bottleneck.

2. <u>Complete Interconnection System</u>.

   Disadvantages: proliferation of communication links with processor addition.

3. <u>Central Memory System</u>.

   Disadvantages: memory both a path and storage.

4. <u>Global Bus System</u>.

   Disadvantages: Bus failure is catastrophic.

5. <u>Star</u>.

   Disadvantages: switch failure is catastrophic, bandwidth bottleneck at switch.

6. <u>Loop with Indirect Transfer</u>.

   Disadvantages: node or switch failure is catastrophic.

7. <u>Bus system with Indirect Transfer</u>.

   Disadvantages: System wide bandwidth bottleneck.

8. <u>Regular Network</u>.

   Disadvantages: impossible to add single node .

9. <u>Irregular Network</u>.

   Disadvantages: logical complexity of switching processors.

10. <u>Bus System with Shared Path</u>.

    Disadvantages: path or switch failure may affect multiple nodes.

Note that element 4 in the taxonomy, viewed now as an organization of systems, is the least risky. Certainly, care will have to be taken as far as redundant communication media. This approach has seen success in real time applications. Proper use of distribution increases the survivability of the architecture.

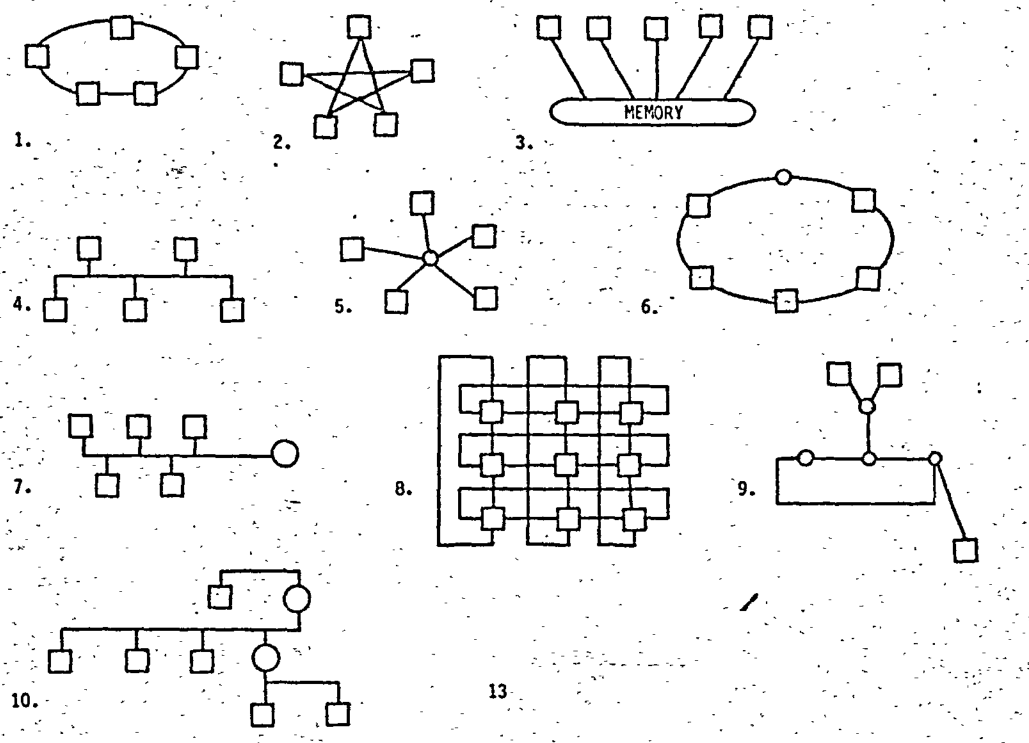


Figure 5.2.1.1-2 Physical Architectures

5.2.1.2 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 here.

5.2.1.3 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 such as, power, GN&C, etc., 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. At each functional level in the Space Station hierarchy, one system in the next level would be responsible for accepting input from the lower levels and to infer the state of that system. This can continue until the ground system becomes the logical step to aggregate system state. If autonomy of space system from the ground is truly desired, then there must be an onboard surrogate for these functions.

5.2.1.4 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. The secondary uses its own data base, which is a replicate of the primary's data base. The secondary begins execution from the state stored in the checkpoint memory.

The only redundant management techniques excluded by the preferred controller connection scheme are function re-allocation and use of a pool of reserve controllers. Both of these techniques require, for example, that all system controllers have access to all data from all systems. So GN&C functions could be swapped with ARG functions because all data from these systems would be mixed together on the same buses. While such connections would provide a lot of capability for functional redundancy, it excludes the opportunity for enforcement of integrity and security. The functions for integrity and security could still be performed, but physical access could not be denied as part of the enforcement policy since the controllers would not be directly in the physical path to the lower level controllers. So function allocation and pooled reserve controllers have been excluded from the available redundancy techniques in favor of the ability to enforce integrity and security checks. Some of the elements to be considered in redundancy and fault tolerance are shown in Table 5.2.1.4-1.

Table 5.2.1.4-1 Redundance and Fault Tolerance Considerations

- All major subsystems
- Redundancy of all major subsystem computers
- 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

5.2.1.5 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. Built-in-test should allow an easier and more accurate determination of system state, less software (test) to be run in higher level onboard computers, and less ground processing dependence. See Table 5.2.1.5-1.

Each of these efficiencies can support additional automation. For example, by freeing computer space which otherwise may have been used, additional software for more involved trend analysis may be run.

Table 5.2.1.5-1 Built-In Test Characteristics

- Supplements fault tolerance and redundance measures
- Status system health
- Periodic execution of diagnostic programs
- Highly integrated microprocessor
- Higher level controller
- Provides indication of fail operational-fail soft-fail safe status

5.2.1.6 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 5.2.1.6-1). This could eliminate the basic controller in some instances, but the viability of this approach depends on the computing capability included with the sensor. If sensors are smart enough to do signal conditioning, this would shift part of the size, weight, and power use out of the controller and into the sensors. This might or might not be an advantage for the total station power budget. Moving signal conversion into the sensors likewise shifts the location of capability without a guarantee of power conservation. However, adding computational capability to sensors introduces the potential to eliminate basic controllers entirely. Thus, some savings might accrue.

The use of the term "dumb" in reference to sensors and actuators is important because these devices require signal conditioning and conversion between analog and digital domains. Consider a controller on a card. Adding two I/O cards changes the capability. Most of the size, weight, and power increase is due to the signal conditioning and signal conversion components. This emphasizes the point that smart sensors and actuators--smart enough to do their own signal conditioning and conversion--could save a lot of the controller size, weight, and power. This may or may not mean a system-level saving for the whole station, and mass have merely shifted the penalty from the basic controller to the sensor.

Table 5.2.1.6-1 Smart Sensors

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

5.2.2 Intelligent Automation

5.2.2.1 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. For each Space Station system (power, etc.), these mission descriptions and corresponding constraints data can be loaded into the appropriate computers. Joint or system states, templates and procedures can be made available at the user interface (command and control) subsystem. Then when a pre-planned mission is scheduled or a mission element is invoked by the crew, the essential sequencing data and crew procedures are already loaded. During the execution of such a mission element, data points obtained at the subsystem level can be compared to the appropriate state vectors and control exercized in accordance with the pre-loaded constraints and rules. The mission template generation and execution process is illustrated in Figure 5.2.2.1-1. There may be significant application of AI technology in designing the minimal state vector/control set to pre-store. Simply having the mission elements described to all appropriate subsystems will enable reduced ground participation in activities. All housekeeping functions and station keeping functions should be describable in this fashion. There is no AI technology used in this mission templating approach. Simple use of current software such as table lock-up and parameter comparisons to intervals will suffice. There is no need for an executive computer in this approach as the subsystems all "know" what they are supposed to do.

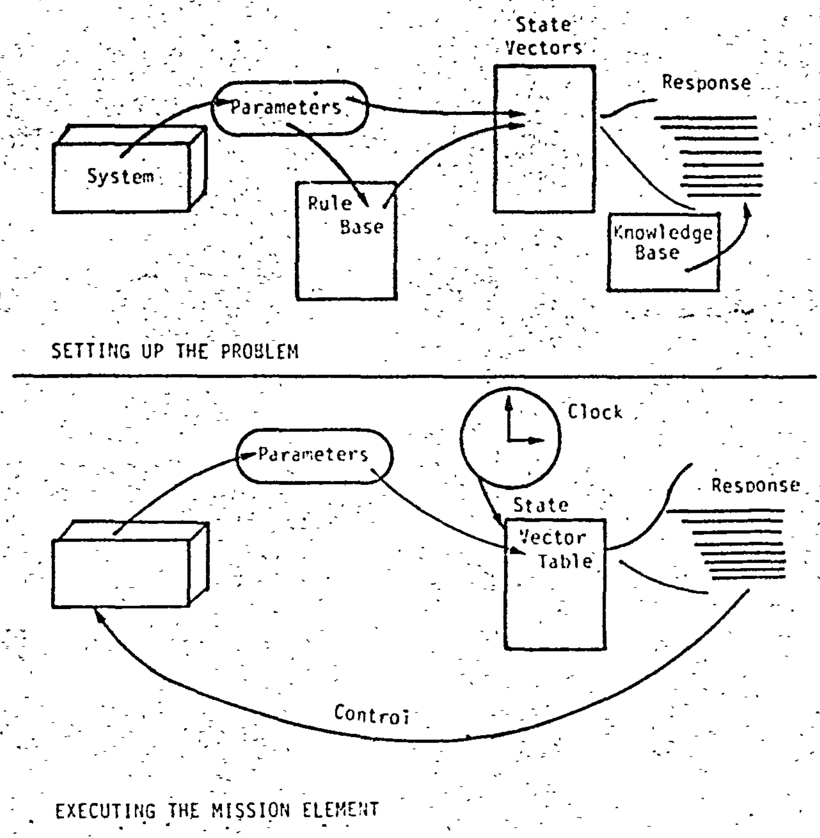


Figure 5.2.2.1-1 Mission Template Generation and Execution

5.2.2.2 <u>Operator System Interface (OSI)</u> - 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.

The hosting of modeling and/or data collection software on the OSI computers will not require significant additional weight (in comparison to a machine to run OSI functions only); however, power consumption, especially for peripheral data storage devices, will increase 10-20%. Data communications through, say, the ODDNET will probably be adequate.

It should be noted that human factor friendliness for an interface costs additional computer processing. Fundamentally, friendliness should be seen as moving functions across tht human-computer functional allocation boundary. More friendliness implies more manipulations in software to create a more essential or more easily assimilatable display.

The move to friendliness emphasizes the use of "modeless" interfaces, that is, interfaces which "know" what the user is trying to do. This does not involve AI except loosely. These interfaces also include models of human interaction as an aid to the interface management software to decide the user's intent. While natural language input is desirable, a purely graphics based input language would be far more easily achievable. This would emphasize menu picks and manipulation of ICONS, all likely through a mouse.

The goals of such interfaces are to communicate information to the user in the most easily usable form as well as enabling a crew member to monitor/control more variables, subsystems, or payloads. The above considerations are summarized in Table 5.2.2.2-1.

Table 5.2.2.2-1 OSI Considerations

- o Use standalone 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 processing
  - "Modeless" interface
  - Models of human interaction
  - Strive for a graphics (ICONIC) input language

5.2.2.3 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.

As a separate issue, the maturity of ADA is in question. Validated compilers are not widely available. This calls into question its choice due to additional risk. A better choice at this time would be the programming language C. Its flexibility and efficiency are well known, and it is particularly suited to operating system software and real-time systems. Its support environment is well known--UNIX--and UNIX supports many AI tools. However, ADA will likely be used if it is available and suitably mature.

The above considerations are summarized in Table 5.2.2.3-1.

Table 5.2.2.3-1 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

5.2.2.4 <u>Top Level Advisor</u> - 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 5.2.2.4-1 shows the components of such a system.

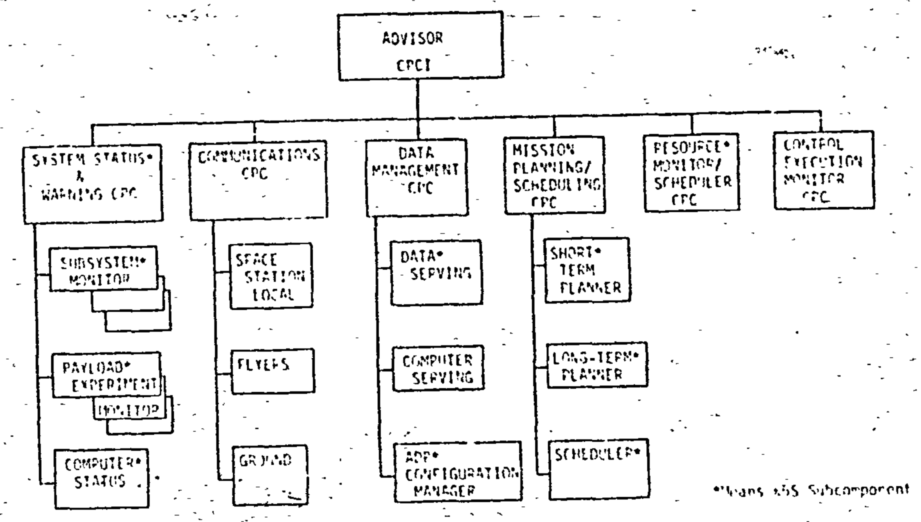


Figure 5.2.2.4-1 Components of Top Level Advisor

a) <u>System Status and Warning</u> is responsible for aggregating the overall system state from the subsystem states. The subsystem monitors and payload/experiment monitors are components of this CPC. The major subsystem state determinations are performed by the subsystem software itself. The computer status component is a preferred subsystem monitor. It accesses status of the core system environment itself. It may cause supplementary heuristics to be invoked or meta-level constraint data within the status and warning master.

b) The <u>communications</u> understanding CPC manages data and message traffic within the space station system. Semantic processing of this traffic is primarily performed at the appropriate other CPCs.

c) The design approach to the <u>data management</u> CPC offers some challenge. It appears that the CPC's internal traffic loads are driven by its design philosophy. A likely role is as follows. The data management CPC corresponds to the operating system functions of a non-distributed system. Additionally it has associated with it a large chunk of fast memory (cache). There will also be a semantic linker running in this CPC whose job it is to aggregate plans, schedule status and projected status of the space station into a coherent whole. This is not to be seen as an executive function with optimizing/modification duties; but, rather, as a means of "pooling" knowledge which will be heterageneously represented. THe data management CPCs mission will include giving knowledge in the appropriate format to the other CPCs. This should minimize CPC-CPC traffic and translation subfunctions within CPCs. Further, queries by the crew to the system will mainly go to the data management (DM) CPC instead of interferring with normal activities of the other CPCs. If the data management CPC becomes instead a relatively dumb peripheral storage controller, the complexity of the KB components of the other CPCs will increase. Further the need for CPC-CPC communication will go up drastically. Note that the role of the DM CPC is as a meta-blackboard for the many KBS components.

d) The <u>mission planner/scheduling</u> will plan and schedule short-term and long-term activities. They will likely generate manby candidate schedules/plans to achieve a approvable complement. Further, other CPCs may need to request running planner and schedules to determine how their actions could impact the master schedule/plan. These requests would result in potential plans/schedules which would then be compared to the currently approved plans/schedules.

e) The resources monitor/scheduler monitors the space station expendables, plans their use, and schedules the plan as well as resupply requests.

f) The control execution monitor's job is to determine if the control instructions prepared and sent out by the various CPC components have ben carried out.

5.2.2.5 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 (Figure 5.2.2.5-1). 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 best be run 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.

It is presumed that these will be a mixture of conventional data bases and KBS data. Only KBS or only conventional data cannot be afforded. The next section speaks to this issue more directly.

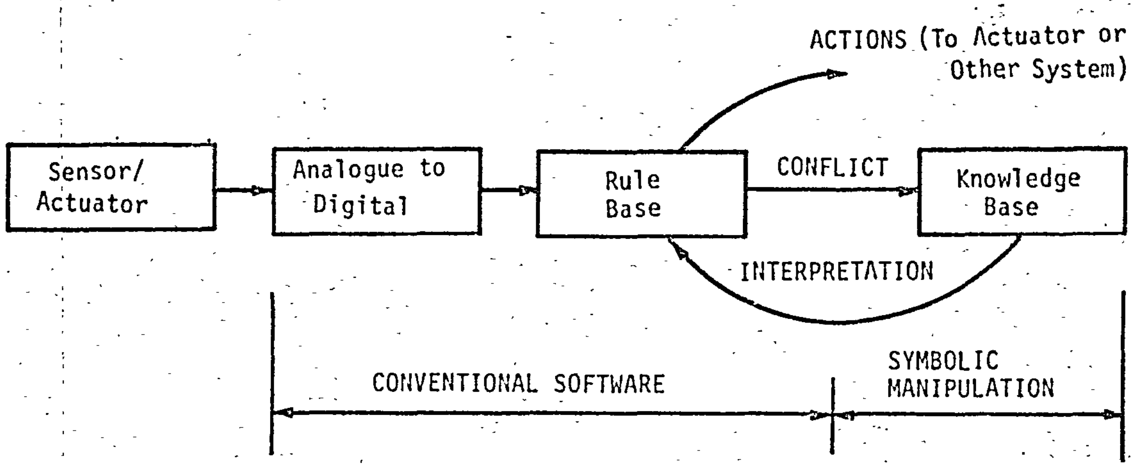


Figure 5.2.2.5-1 Symbolic Manipulation Bounding

5.2.2.6 Data Base Effects - There are two aspects to data which 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 5.2.2.6-1. Intensional data captures the meaning or intent of data objects. It may be considered data about facts. Extensional data focuses on description o 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 5.2.2.6-1 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

5.2.2.7 System Integrity Management - A key function of a top level advisor will be system integrity management. This refers to a level of system state evaluation and control above fault tolerance and redundancy, or power system management. One may imagine a set of layers (Figure 5.2.2.7-1) of space station modes. Each consists of a rigorously pre-analyzed set of responses to various combinations of state conditions which one may obtain. If a mode is in force then a system state would provide one set of stimuli to the subordinate systems which may not be the same as would result if another mode was in force. THis capability would allow minimal housekeeping functions to be performed in a crewless condition while cut of from the ground. In the event crew or ground personnel are available, the top level advisor would function as an advice giver only. There may be some utility to applying AI techniques in the construction of these layers.

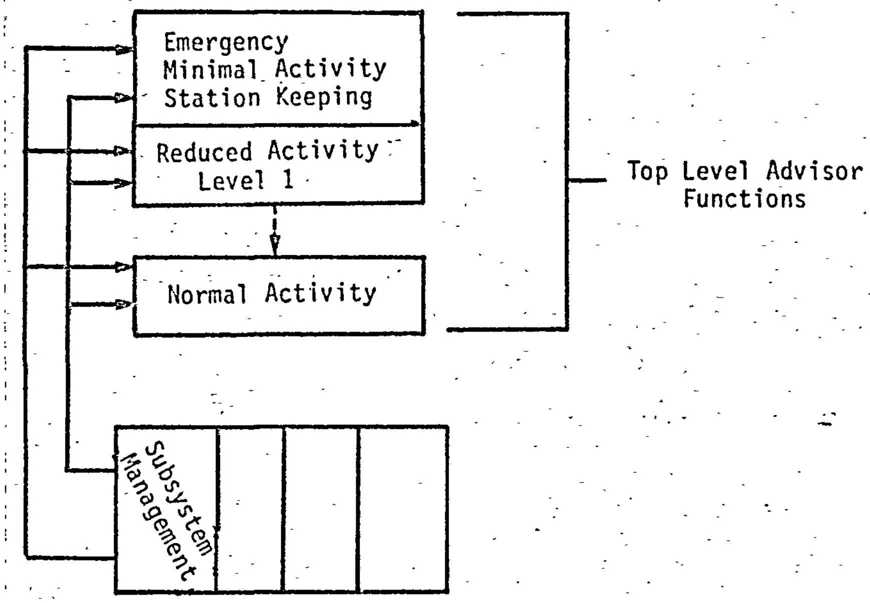


Figure 5.2.2.7-1 System Integrity Management

5.2.3 Comparison of Automation Techniques

Figure 5.2.3-1 shows each of the automation techniques we have discussed so far. 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 further time frame (5-10 years) we foresee that 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. This should not be surprising as the knowledge based techniques automate higher level cognitive processes. The cost to implement column in the figure refers to a per unit basis. Technology risk for the hard techniques is low and becomes high for the top level advisor.

	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 5.2.3-1 Summary Comparison of Automation Techniques

There are roles for each automation approach. We should not ignore the knowledge based techniques 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.

5.3 AUTOMATION ASSESSMENT

5.3.1 Top Level Advisor

5.3.1.1 Staged Implementation - 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. Figure 5.3.1.1-1 depicts such a step, possible in approximately 1990. The ground personnel would provide the functions we have previously described to be performed by a top level advisor. That is, initially, the role of man on th ground will be as it is currently for say, the STS.

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 boards as elements of the Standard Data Processors (SDPs), (Figure 5.3.1.1-2). 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 or the ground would perform as experiments. Ground personnel would still be prime for such missions elements.

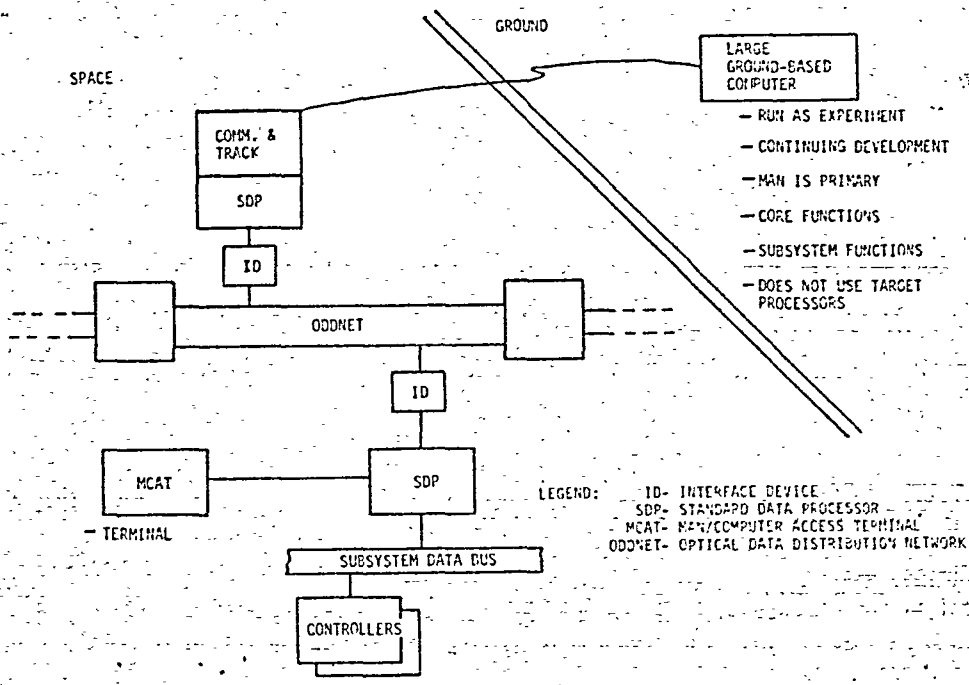


Figure 5.3.1.1-1 System Automation Evolution—1990

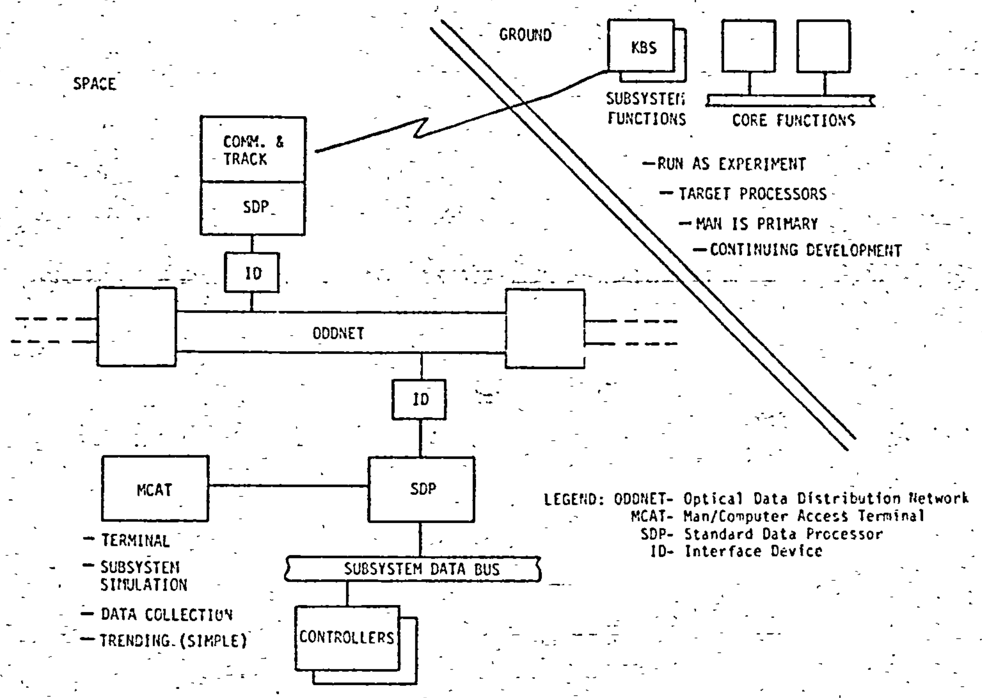


Figure 5.3.1.1-2 System Automation Evolution—1992

The next figure (Figure 5.3.1.1-3) shows that we would move the subsystem components up during the next <u>three</u> years. During such time, the crew would monitor closely the activities of these components. We anticipate much higher confidence in the top level advisor functions during this time even though it would still be run in experiment mode and ground personnel still prime. 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. 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.

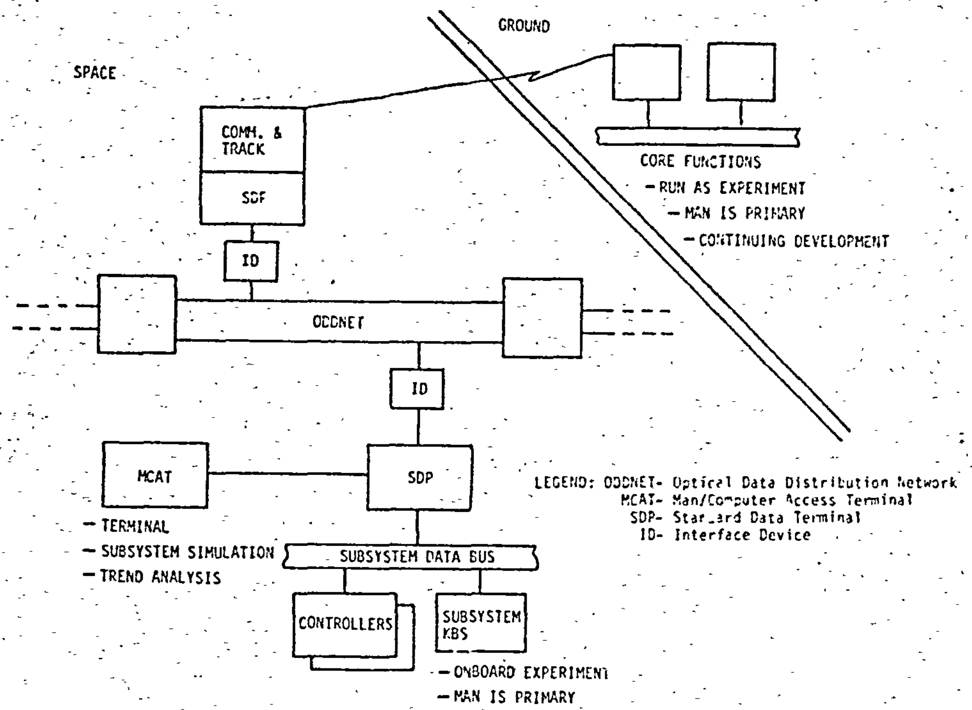


Figure 5.3.1.1-3 System Automation Evolution—1995

A short time after this last stage it should be possible to move the top level advisor's target architecture onboard the space station (Figure 5.3.1.1-4). We should consider it 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. At this time as well, we expect the subsystem components of KBS would become an accepted part of the space station data system.

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 (Figure 5.3.1.1-5). This date could be significantly improved upon from, say, 1996 if there are no development problems nor any significant knowledge engineering problems. By this time, we anticipate that the functionality of the subsystem KBS components could be updated to better reflect procedures and deeper understanding of space station systems.

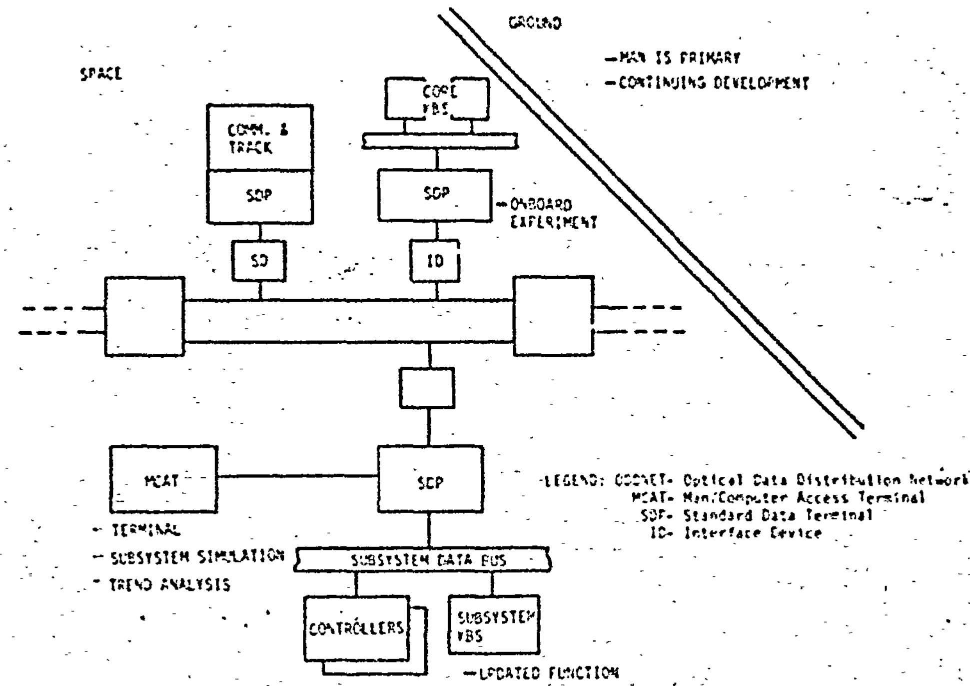


Figure 5.3.1.1-4 System Automation Evolution—1996

C-2

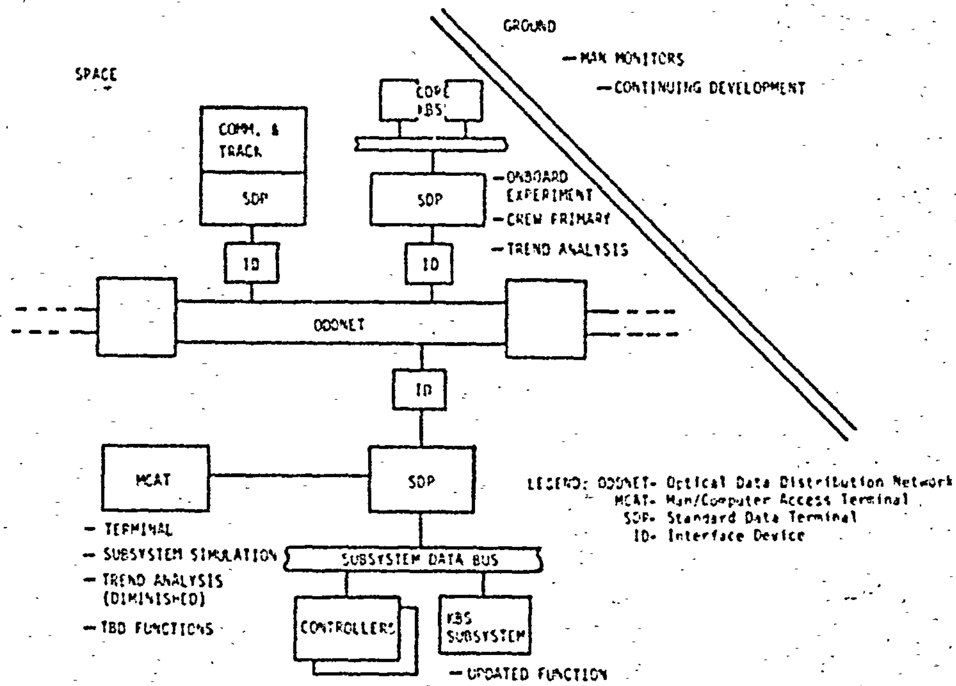


Figure 5.3.1.1-5 System Automation Evolution—1998

Finally, we foresee the space station onboard systems to include fully integrated top level advisors and subsystem components (Figure 5.3.1.1-6). 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 store accessible, without tasking the main data bus.

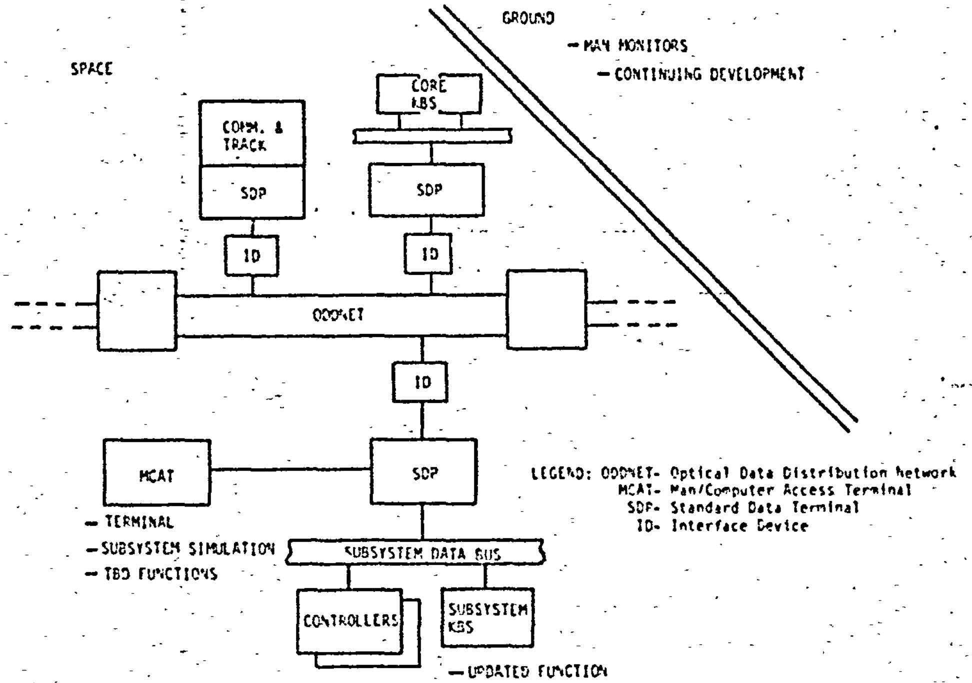


Figure 5.3.1.1-6 System Automation Evolution—2000

5.3.1.2 Top Level Advisor Automation Approach - The top level advisor will consist of several portions as discussed previously. The way each of these could ultimately be implemented is shown in Figure 5.3.1.2-1. The system status and warning components are shown as expert systems or portions of expert systems. 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 finally, in the far left column some comments. The system status and warning monitor will communicate with lower level components and, at this level, be responsible for aggregating total space station status. There will be a preferred subsystem status monitor which looks at the status of the computers upon which the top level advisor is resident.

The communications component can use standard keyword, command, and pattern recognition software techniques to process commands to extract their semantic aspects. Processing speed will be an appropriate method of improving performance for this element.

The data management component of the top level advisor needs a semantic linker portion. This would be a large "blackboard" in planning parlance. The common working memory of the top level advisor would be managed by this element. One approach to its construction would be to analyze in detail the space station and build a model sufficient to well define inferencing about it. This could be done if we presume a stable configuration. As this is not possible, we must adopt a more flexible approach and provide for additional, as yet undefined components of such a model expressed using knowledge representation techniques as yet unspecified.

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	– computer processor	L	———	High speed existing technology
flyers	– signal processor			
ground				
–Data Management	Data Computer	M	Semantic Linkers	Note: a large blackboard with utilities
– Mission Planner Short term	– Symbolic processor	H	Planning	
Long term	– computer processor	H	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 parocessor	M	– Planner Optimization Techniques	
–Control Execution Monitor	– computer processor	L	———	

Figure 5.3.1.2-1 Attainable Automation Levels

The mission planner uses high levels of automation and must interface with all other top level advisor components. It requires both planning and deep reasoning technologies. Planning is obvious but the deep reasoner would allow checking out a candidate plan. The mission schedules would consist of a planner and a set of classical optimization techniques. The scheduling planner would sequence output from the mission planner and consult standard data bases to derive a time context for the mission elements.

The resources monitor and resource schedules basically will use low to medium complexity automation approaches. Resource monitoring on a resource-by-resource basis is a straightforward comparison of a parameter value with an acceptable range. If we consider resource optimization across the space station as well as the corresponding tradeoffs of resource allocation to competing subsystem users, there is a much larger problem. AI techniques will in all probability be called for.

The control execution monitor simply checks that the action ordered by the ground, the crew, or the top level advisor has taken place. Conventional techniques will be sufficient to accomplish this element.

5.3.1.3 Cooperating KBS Components - The previous section implicitly called for making use of various artificial intelligence and conventional software techniques in a cooperative manner. Figure 5.3.1.3-1 points out both where advances in techniques 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. We have noted where complexity and size factors impact the components. The technology needs, where known, appear in the right-hand column.

The search speed and organization of rule bases which encode heuristics will be important for expert systems. Knowledge base management and heterogeneous representation within a single expert system will be important. For planners, the computational speed of the inference engine will be key as well as techniques to improve speed of access to higher order language (HOL) based software--especially databases. Of course semantic relationships between HOL databases and the planner will be important.

Technology	Components	Complexity	Size	Needs
Expert System	Heurstics (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 5.3.1.3-1 Structural Attributes of AI Technology Base

Deep reasoners will require significant knowledge engineering support tools to successfully baseline and manage the rule base. We anticipate that the conventional data bases supporting the deep reasoners will have to be carefully interfaced.

Learning and prediction systems need much development work. We currently lack the cognitive processing paradigms upon which to found an adequate approach to knowledge engineering for these systems. There is a requirement for domain paradigms and appropriate models in the application areas of these systems. There are likely to be many intelligent subcomponents of learning systems which would use cooperating, orchestrated inference engines acting on separate components of the knowledge base.

In natural language work, the need for knowledge engineering tools is evident. Natural language for command and control will drive up the required speed of processing in such systems . This will in turn drive up the speed at which the inference engine must work.

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.

5.3.1.4 Comments on Rule Structure - Accepting the premise of distribution of KBS components throughout the functional hierarchy of the space station, we should note that there will be a noticeable difference in their rule structures. Figure 5.3.1.4-1 is an attempt to illustrate this. At the lower levels of the functional hierarchy, one anticipates simple rule structure very close to algorithmic structure. At higher levels the relations used in the rules will move closer to common language usage and less formal definition. The objects discussed in the rules will be more highly aggregate. For example, at lower levels, rules would contain variable names extensively, whereas at higher levels we would manipulate mission plans or complete sets of resource allocations. Further, we anticipate an evolution in each of these rule sets towards the more highly aggregate objects and less well-defined relations ("good" is an example) throughout the space station life.

Moving in Towards Center of the Radial Architecture		Early	Later
	Subsystem and payload sensors	if variable (i) > 100° and variable (j) < 2 then set warning flag	if variable (i) > 100° and variable (j) < 2 then check condition 4 and if condition 4 is on and variable (k) = 4 then switch to backup else shut down
	subsystem and payload management	if warning flag on system 12 and condition 4 is on then evaluate trending predictor 2 (tp2) if tp2 within bounds set flag else shut down	if warning flag on system 12 and switch to backup at time (later) then status repairs/warnings file and evaluate tp2. if tp2 out of bounds then initiate plan
	system of subsystems management	if status normal then check repairs/ warning file. If change then evaluate change and initiate plan.	if failure predictor says component 12 unstable then plan backup and inform core functions of predicted performance profiles for next time interval
	core functions	if mission event scheduled at time t and power sysstem status is normal and system (i-j) status is acceptable then initiate event planning. If event plan element is type 2 then run resource model. If resource model results acceptable then generate instructions to subsystems	if station performance model is acceptable and mission plan element 12 is next then predict success of mission plan element 12 and plan actions to assure success > good and update long range station support plan if resources will be expended.

Figure 5.3.1.4-1 Varying Heuristics Will Change the Rule Structure

5.3.2 Other Systems

5.3.2.1 Power – The role of KBS in the power subsystems will be in the area of load management, fault detection/diagnosis, or energy storage management. One additional computer over and above those required to provide power subsystem functionality would be flown in the mid-1990s. This system would contain templates, diagnosis procedures, stored variable patterns and KBS components. Its function would be monitoring the power subsystem. It would be hosted with the power system SDP. The computer's basic function would be data manipulation although we envision some limited mathematical models being run to support evaluation of alternatives. Its software functions would include a conventional data base oriented templating system, an expert system for fault diagnosis, and one or more deep reasoning components. One of these deep reasoners would attempt to understand the state of energy resources and storage systems with respect to what is happening elsewhere in the space station. Also, a reasoning system would attempt to understand power loads from a similarly "large" view. They would communicate with the top level advisor, first through the communication system when it is on the ground and, later, directly. The actions recommended by these systems would be communicated to the crew, when present, for approval; or to the ground when the view is absent. Should the station be in fully autonomous mode due to exceptional circumstances on the ground the recommendations would be executed automatically. This is seen as crucial but a rare occurrence. The more these systems are used and the more their rules evolve, the higher our confidence in automatic operation will be.

The hard automation aspects of EPS autonomy will depend upon embedded microprocessors. There will be an EPS controller whose job will be to coordinate mode commands and setpoints to other systems and to its subordinate embedded controllers. This is well within current state-of-the-art for microprocessors. A good discussion of how these microprocessors could control the EPS is given in a recent Honeywell Study "Automated Subsystem Control Final Report" Vol 1 1/84.

5.3.2.2 GN&C

```
*****************************************************************
*                         ** NOTE **                            *
*                                                               *
* The original objective for subsystem assessments included     *
* Power, ECLSS and Data Management, as shown in Section 1.0     *
* and 4.0 herein. However, due to a greater amount of source    *
* material available for Guidance, Navigation and Control       *
* (GN&C) than Data Management, the decision was made to re-     *
* place data management with GN&C for this portion of the       *
* automation study.                                             *
*****************************************************************
```

This system has the responsibility for managing the sensing and acquisition of information, computation, and actuation required to provide position and attitude control for the Space Station and to point its solar arrays, radiators, and payload mounting surfaces. The GN&C system will interface with the Information and Data Management system, Communication and Tracking system, and Propulsion system to perform these functions. The GN&C system will also manage the traffic control function and proximity operations. GN&C support will be provided to the payloads attached to the station and to the station traffic.

The key approach to automation in the GN&C system is through hard automation techniques using error detection, redundancy, fault tolerance, and extensive built-in test. Reliability is paramount. Existing techniques will apply, although significant work in refinement of the control laws for flexible structures of the size of the station will be needed. Also, careful attention will be needed to control a formation of spacecraft during rendezvous and docking maneuvers.

Current thinking foresees two SDP components for the GN&C system split in accordance with the functions of 1) navigation and traffic and 2) guidance and control. There will be need for multiple computers for each function and the capability to run the functions of one subsystem on the other. If we can validate an adequately detailed control law model during ground or flight test, it will be advantageous to fly that model even if control is managed through simplified forms of the laws.

The role of KBS elements for GN&C may well be restricted to status monitoring or perhaps traffic analysis and control. Traffic control is so important that it is more likely it will be run off-line and contingency plans loaded as templates.

5.3.2.3 ECLSS - The ECLSS will primarily function as a closed system but will require resupply. As such, it will be a regenerative, partially closed system. We foresee a completely closed system as a goal of the advanced space station. The ECLSS will control atmospheric pressure and composition, module temperature, humidity, atmospheric revitalization, water management, and metabolic waste management.

Significant hard automation based approaches will be used in the ECLSS. Fundamentally, current industrial process control techniques will be necessary. The controllers must manage the processes and the backup control. The automation should also increase system availability and reliability by constraining its operation to the proper performance envelope/domain.

Dependence on reuseable resources may be reduced by integrating control of the ECLSS with mission planning from the top level advisor and running resource utilization models. This moves us closer to the use of intelligent automation.

There is little clear need for KBS elements in the ECLSS. Status monitoring up to the top level advisor certainly will occur together with some coupling to mission planning and scheduling. In general, however, its inclusion is not crucial.

5.3.3 Summary

5.3.3.1 Scarring - Table 5.3.3.1-1 shows some of the scarring or design aspects needed to accommodate the automation techniques we have discussed. Detailed analysis to solve these issues was not within the scope of this effort. 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 we should be sure to oversize the subsystem computers 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. We should emphasize discrete event type simulations instead of queuing theory-based methods. System transient state performance/ response is the key area to investigate while queuing theory methods focus on examination of the steady state.

Table 5.3.3.1-1 Scarring and Prioritization

SCARRING	PRIORITIZATION
- SUBSYSTEMS USING FAULT TOLERANT COMPUTERS	- PERIPHERAL MEMORY ACCESS
- ADEQUATE SIZING OF PERIPHERAL MEMORY ACCESSIBLE ON THE ODDNET	- TOP-LEVEL ADVISOR
- EFFECTIVE USE OF TIMESLICING FOR MEMORY ACCESS	- DEVELOPMENT SUPPORT TOOLS
- 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	

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 we can bias the data management system towards synchronous or asynchronous operation. This is turn could cause significant data use of the bus. We should accommodate 32-bit processors in the SDPs. This allows use of virtual memory operation and can also serve to mitigate some of the performance degradation caused by fault-tolerant approaches. The CPUs of these machines run fast and they are packaged compactly enough for flight.

We need to provide a significant overdesign of the bus interface units (BIU) or interface devices (ID). Again, significant performance modeling is required to support this analysis. Inadequate sizing of these units (speed) could severely affect thoughput 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, we should enforce functional encapsulation or bounding to the maximal extent. This will minimize data flow in the system and allow easier maintenance and upgrade of the software. We should use ADA if it and its support environment are available; however, planning for an alternative such as the programming language C should take place now.

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. We should note that 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. We may need local disc or bubble memory peripheral storage.

The issue of integrating KBS with standard software and data bases is important. We cannot afford nor need standalone "expert systems." We must exploit KBS techniques in conjunction with conventional techniques, viewing each of these as merely ways of encoding intensional knowledge.

The priority of functional areas requiring work is shown in the right-hand column of Table 5.3.3.1-1. Foremost is peripheral memory access and intrasystem communication. This requires extensive modeling. Next is the top-level advisor. This system requires investment in AI planners, expert systems, and semantic linking.

We cannot ignore the issues involved in adequate development support. The next section, 5.4, discusses many highly functional tools to support construction of KBS and conventional software. The investment in tooling is crucial, as it allows management of complex software. We should 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.

5.3.3.2 Time Phasing of Needs - If we arrange both product; e.g., systems onboard space station, and development process support needs by time, we can get an idea of the extent to which some of the automation approaches may be implemented. Figure 5.3.3.2-1 shows this arrangement, focusing on key examples. Initially, we will have proof of concept expert systems, planner experiments, and deep reasoner experiments all running on the ground. In the mid-1990s we anticipate at least one onboard symbolic processor and some onboard expert systems for fault detection/diagnosis. At about 2000 we expect large stable expert systems, fast planners and some learning systems all onboard. There will be several symbolic processors and extensive cooperation between the KBS components. By IOC we will need test aids for distributed systems, and KBS, plus space station specific VLSI design aids, and a KBS development support environment.

		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 5.3.3.2-1 Overall Placement of Automation Needs by Time

Well before IOC we will need a stable comprehensive software support environment for the selected space station language. 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 we would need to have semantic linkers and intelligent V&V tools. This is all quite feasible.

Figure 5.3.3.2-2 shows that we can anticipate with confidence large numbers of mission support personnel required on the ground through the mid-1990s. The date by which reductions could become sizeable could move earlier if the automation program does not see many risks realized. It is possible, but not predictable, that significant reductions could be attained in 1993-1994.

	Now	IOC	FOC
Role of Man in Space	3-6 people mission operations	6-8 mission operations mission operations monitoring analysis Some planning payload operations assembly some control	6-8 mission operations monitor Planning analysis mission operations mission concurrent development mission control
Role of man on ground	500-1000 people – mission operations monitor planning analysis – program support payload operation – assembly and mission concurrent development – mission control	500-1000 (increase) – mission operations monitor planning analysis – reduced program support – mission concurrent development – reduced control standing army	200-300 – mission operations monitor – reduced analysis

Figure 5.3.3.2-2 Role of Man

5.4 DEVELOPMENT SUPPORT NEEDS

5.4.1 Introduction

It is well known that modern software development today must be supported through the proper toolset. While that used to mean simply the proper debuggers and compilers it now refers to more and more involved major software aids. The Figure 5.4.1-1 shows an idealized system development life cycle. Tool needs vary depending on where in the life cycle one is and what sort of application is being developed. It is not surprising that the tooling needs supporting an advanced space station data processing system are important.

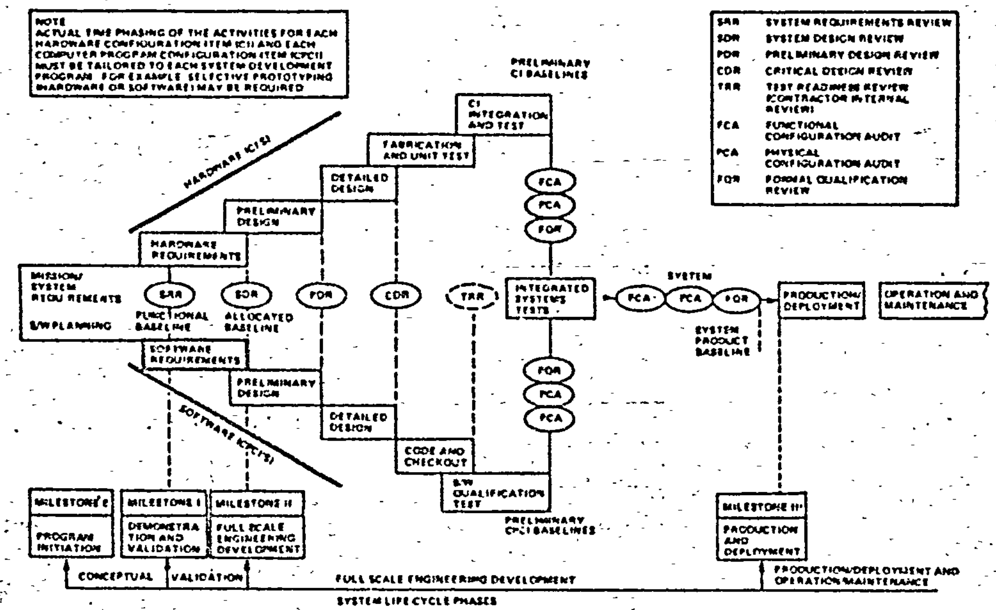


Figure 5.4.1-1 Idealized System Life Cycle

5.4.2 Test for KBS

KBS will play a large role in the space station software. Current KBS test techniques are based on normal software test techniques. These techniques include state and path enumeration. The functionality assigned to "data" or rules and knowledge in KBS make such approaches to test inapplicable. There is a need to develop criteria for success in testing KBS such that adequate meaningful test plans can be written. Implicit in this need is a further need for well defining a design approach for KBS which is visible and which is tied to the definition of testability. As in conventional software, one must accept the challenge to design testable systems rather than a posteriori apply test criteria. The technologies which apply to the goal of test for KBS include world modeling, expert systems, and learning systems.

5.4.3 Intelligent Validation and Verification (V&V)

Software V&V is a laborious and crucial task at present. Automating portions of the V&V process will allow larger software systems to be flown at constant or reduced risk. The larger and more complicated a software system the more difficult the V&V task. This is especially true in software with tightly coupled components. A KBS software V&V aid could signficantly reduce risk in large onboard systems. The aid would possess knowledge of requirements design, and configuration information and make comparisons with the aid of a human. It would function as a reference manager for the human and, eventually, be able to recognize larger and larger software components. Work by the Knowledge Based Software Assistant Group (Cheatham, Rick, Balzer, Fowler) at MIT has made progress in this area. The required technologies include a deep reasoner, learning systems, and interface to conventional databases generally not kept current.

As testability is closely tied to the notion of satisfaction of requirements, we must model the application domains and structure. The expert systems will manage test execution and basically evaluate how the system performs under test, against the criteria for success. Learning systems can aid in collecting and structuring new information about the performance of KBS and how requirements are satisfied. At base simply developing criteria for test of KBS would aid in their development. The application of these other techniques is quite likely within the next ten years.

5.4.4 Knowledge Based Systems Development Environment

Development of KBS for the space station cannot fluently occur nor can it occur in a structured, controlled manner without a proper development support environment. Such an environment would contain tools including production systems, knowledge and rule base semantic linkers, improved debug aids, and a wide collection of system support utilities on machines which run LISP and PROLOG in firmware. Support of the knowledge engineering aspects of the problem is important. Application specific knowledge elicitation templates linked to design tools are appropriate. Improved production systems which provide means for managing large scale rule and knowledge bases apply. Once again the need to allow KBS to contain heterogeneiously represented knowledge exists. Tools to coordinate among variously represented knowledge (semantic linkers) should be built.

The first problem to be solved is in coordinating information contained in conventional databases of text and code. The system must eventually consider intensional aspects of this data.

5.4.5 Test for Distributed Systems

Distributed systems rapidly become too complex for exhaustive, deterministic test. The presumption that subsystems can be tested as such and then assembled into a system which is not exercized as a whole system until flight test is a notion which introduces risk. Highly distributed systems may have hundreds of thousands of accessible states. State and path enumeration techniques tend to be myopic ignoring the low probability—but allowable system states. Without appropriate intelligent test support, test conductors have little choice but to follow this approach.

A two order of magnitude performance increase may be achieved by migrating a function from mechanization in a HOL running on a multiprocessing system to a VLSI chip. Through provision of a laboratory facility hosting VLSI design aids, software development tools, firmware development tools and a custom board building shop, systematic movement of software into VLSI may be achieved. This trend should be put in place early on in the space station life and continued throughout it. Properly implemented, it is possible that more general computing power would be available later in the space station life than initially due to this migration of functionality to VLSI.

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 we can bias the data management system towards synchronous or asynchronous operation. This in turn could cause significant data use of the bus. We should accommodate 32 bit processors in the SDPs. This allows use of virtual memory operation and can also serve to mitigate some of the performance degradation caused by fault tolerant approaches. The CPUs of these machines run fast and they are packaged compactly enough for flight.

We need to provide a significant overdesign of the bus interface units (BIU) or interface devices (ID). Again, significant performance modeling is required to support this analysis. Inadequate sizing of these units (speed) could severly affect throughput in the system.

An intelligent, knowledge-based test planner and test conductor can significantly aid in this area. The goal is that the KBS test-aid act autonomously--either in accordance with apre-analyzed plan or opportunistically. If operating opportunistically, it would "drive" the system around in state space while recording observations. When systems were much less complex, test was able to do this while causing the system to visit all accessible states. This is no longer possible in any reasonable amount of time.

The KBS test-aid would make use of planners, expert systems, and deep reasoners. The planners would construct test plans in accordance with the results of the other components. The expert system would focus on test conducting and data organization perhaps codifying existing heuristics. These could be coupled to a deep reasoning system for data analysis which in turn would stimulate the planner to devise another test component.

5.4.6 VLSI Design Aids

VLSI promises economies of speed, size and weight for complex algorithms. Reduction of weight and size of existing hardware components may also be achieved.

What is needed is a tool to translate algorithms to circuits and circuits to an optimal circuit complete with layout. Additionally we require test tools for VLSI chips including simulators. These could be accomplished through computer aided design systems (CAD) and special specification tools. Much of the work currently underway for the chip manufacturers can apply.

Tailoring these systems to space station specifics should be a manageable task yet should allow improved performance of GN&C algorithms or more complex algorithms to be flown for constant performance.

6.0 ASSEMBLY AND CONSTRUCTION

6.1 MISSION MODEL SELECTION

6.1.1 Overview

This section presents a brief overview of the four major mission categories included in the assembly and construction area of this study:

1) Space Station IOC buildup
2) Space Station Expansion
3) Large Spacecraft and Platform Assembly
4) Geostationary Platform Assembly

The majority of effort spent on these four missions was focused on the IOC Space Station buildup with considerable lesser amounts 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, will have 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 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 towards technology transparency.

6.1.2 Selection Criteria

The purpose of the mission model selection was to identify 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 sufficient to typify major technology drivers involved in evolutionary changes required over a 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 were identified as shown in Table 6.1.2-1.

Table 6.1.2-1 Selected 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)	
- Manned Geostationary Platform (LM-13)	

Features of the missions 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 for a long time span, with a starting point where considerable resources have already been expended and using operational orbits where both manned and unmanned activities have been identified. Basic structural configurations that are compatible with a number of generic type large space structures and missions that have been evaluated from both a deployable and erectable standpoint were included.

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 geosynchronous platform. This time flow has a direct utility for 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 and available resources. However, general results from many of the prior studies that have looked at specific missions in considerable detail (see references 37 and 41) indicates that the mission uniqueness and state of the art implementation have the greatest impact on design conceptualization.

The assessment of this mission set must be a continuing process. When the results turn out to be the same or very similar, the true merit of value is in the increase in confidence level. Sources for information and candidate concepts for continuing studies are numerous: the NASA Space Systems Technology Model; the Military Space Systems Technology Model; various government and commercial traffic models; the wealth of magazine and journal articles that propose scenarios for the future of space; and knowledgeable members of the space community. Candidates compiled from these sources can be compared and evaluated with respect to technology coverage and evolving space trends. In general, early study trends indicate construction and erection, while more recent study trends used deployment and assembly.

6.1.3 Reference Mission Models

A brief background description on each of the four selected reference missions is presented in the following paragraphs.

6.1.3.1 Space Station IOC Buildup - At the study kickoff, three concepts were presented for IOC consideration: the "CDG planar," the "delta-truss," and the "power tower." A quick look at these three indicated a number of common construction functions. However, at the second technical interchange meeting (TIM), the "power tower" was identified as the reference configuration for the SSAS. The selection was in line with the Space Station program office "Skunk Works" that had selected the "power tower" as the reference configuration because it was seen as maximizing the accommodation of current user and growth requirements while demonstrating acceptable design and operations characteristics. It was also recognized that the "planar" and "power tower" configurations are members of the same family, which differ basically in their placement of the manned modules and experiment bases with respect to the articulated solar collection devices. (24)

The reference IOC Space Station configuration is shown in Figure 6.1.3.1-1. The Space Station operates in a local vertical-local horizontal (LVLH) orientation, with its keel along the local vertical direction and the solar array boom perpendicular to the orbit plane (POP). The earth-pointed end of the Space Station contains earth-looking payloads. The zenith-pointed end contains solar, stellar, and anti-earth viewing payloads and communication antennas. Non-viewing payloads are located at various places on the Space Station, and the pressurized modules are located near the bottom of the keel. Servicing equipment is located along the keel on either side, with the front and back surfaces of the keel kept free for traverse of the Mobile Remote Manipulator System (MRMS). The servicing and refueling facilities, OMV and OTV technology demonstration equipment, and satellite storage and equipment areas are located at various places along the structure.

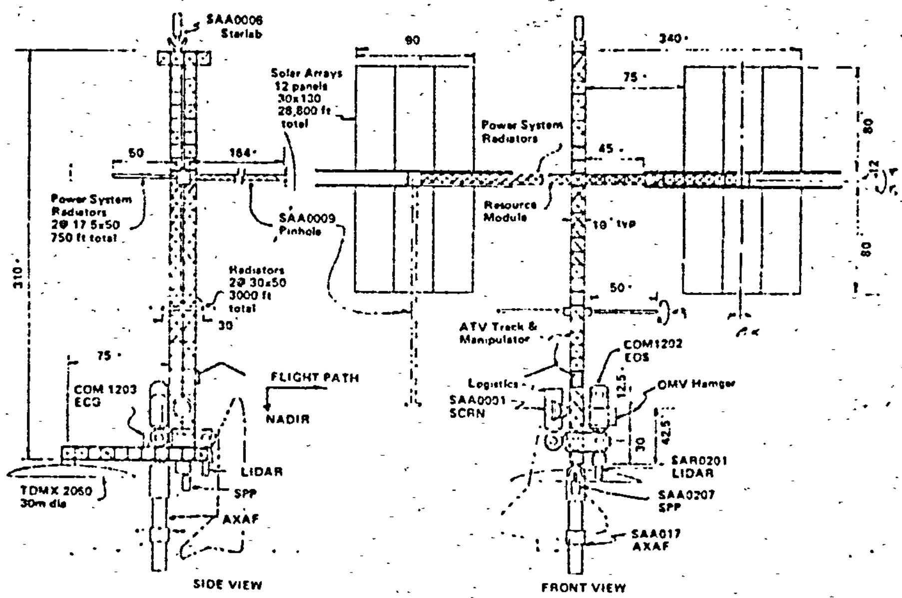


Figure 6.1.3.1-1 Power Tower IOC Configuration

Some options for the truss structure on the station are shown in Section 6.2. Some of these options are deployable, some are erectable, some are pre-integrated with subsystems, and some have subsystems installed on orbit after deployment of the structure.

The information presented here is extracted from the "Space Station Reference Configuration Description" document, dated August 1984. For more detail on the above data and on berthing and docking, refer to the referenced document.

6.1.3.2 Space Station Expansion - After initial assembly and construction of the Space Station has been completed, a second phase will commence. Present plans call for development of an onboard Space Station based servicing facility. The functional characteristics of this facility will have the capabilities to service and refuel free-flying serviceable satellites (that have been brought to the station), co-orbiting platforms (interpreted to be multi-payload spacecraft that can be berthed to the station), payloads attached to the station, the OMV, and the OMV kits. The Servicing Facility will also provide for the storage of satellites, the OMV, two OMV kits, ORUs, instruments, and tools.

Once the Servicing Facility is completed, it is envisioned that existing and new users will require expansion of capabilities present on IOC. It is not clear at this time just which capabilities will grow and to what degree--or how that growth will drive the station evolution.

An attribute of the reference Space Station configuration is that it can support growth in any or all of its initial capability areas: servicing and refueling, construction of large space structures, materials processing, life science research, astrophysics and solar physics, earth remote sensing, or sensor development. Growth of some of these capabilities would require increased crew size (e.g., servicing, construction, life science research). Growth of other capabilities would require significantly increased power (e.g., materials processing). Whichever capabilities eventually come forward as growth requirements, the reference configuration should gracefully evolve to meet them.

A projection of potential expansion drivers and solutions related to the assembly and construction area are discussed in the following paragraphs. The majority of the expansion is centered about the lower keel area. The capabilities of the onboard laboratories will increase with the addition of six laboratory modules. Keeping in line with growth, there will be an addition of habitational modules for more astronauts.

Structure has to be added to support the new modules. Again, the cube structure will be deployable as well as erectable. Some of the lower laboratories and experiments require a view of earth, limb to limb. As a result, each addition must be well planned prior to any build up.

One of the major considerations for growth is the power system. The IOC utilizes solar panels to produce 75 kw. In its expanded configuration, the dynamic power system should produce 300 kw. The same is true for the radiators, with corresponding size increases.

The reaction control system has to be updated to handle the additional masses. Satellite servicing adds a whole new dimension to the Space Station. A satellite servicing bay, a satellite stowage bay, and a refueling bay is just the start. Fuel cells as well as berths for OTVs are needed.

Eventually, the stowage areas must increase to handle increased servicing and repair. Also some of the laboratories (i.e., manufacturing and refueling) may be separated from the station and operate independently in co-orbit as free fliers.

6.1.3.3 <u>Large Spacecraft and Platform Assembly</u> - The assembly of large spacecraft for purposes of this study is represented by one category candidate, the Large Deployable Reflector (LDR). A brief description of the current concept of this system and general information needed when assessing on-orbit assembly is presented in the following paragraphs.

Figure 6.1.3.3-1 represents the current baseline concept for LDR. It reflects the telescope requirements given in Table 6.1.3.3-1 and represents a consensus of the Asilomar workshop. (18)

The telescope is an f/0.5 Cassegrain with a segmented, actively controlled primary reflector. The primary reflector segments are made from either lightweight, low expansion glass or a composite honeycomb sandwich. The individual segments are supported from the backup structure at three attachment points. Each attachment point incorporates a position actuator so that the segment is adjustable in two axes of tilt and one of piston. In this example, 37 hexagonal segments, each 2.8 m across, make up the 20 m primary reflector. The sunshade keeps direct sunlight from the reflector and reflected sunlight from the detectors. In the latter case, a more complicated baffling system may be required, which is not shown in Figure 6.1.3.3-1.

Figure 6.1.3.3-1 LDR Baseline

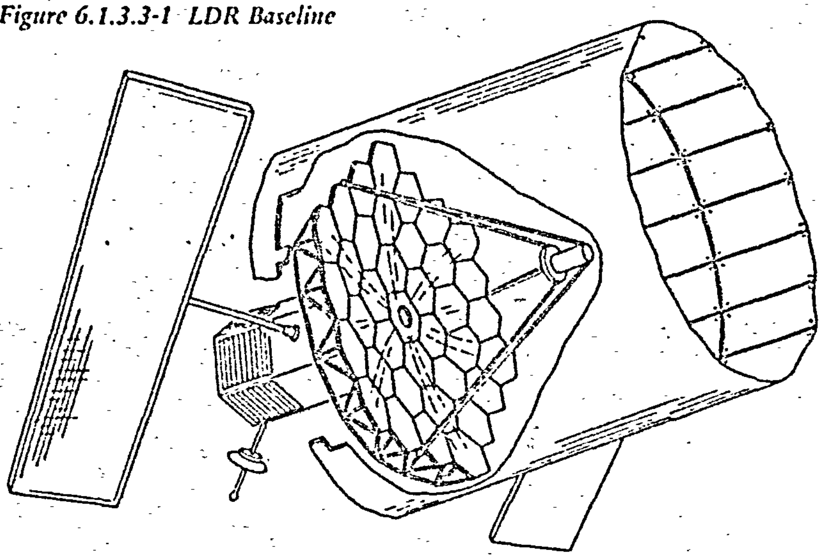


Table 6.1.3.3-1 LDR Requirements

LARGE DEPLOYABLE REFLECTOR (LDR)
• DEDICATED ASTRONOMICAL OBSERVATORY FOR 1990's
• 20 M F/0.5 PRIMARY REFLECTOR, DIFFRACTION LIMITED AT 50 MICRONS.
• F/10 CASSEGRAIN OPTICS
• SEGMENTED PRIMARY REFLECTOR, ACTIVELY CONTROLLED
• LIGHTWEIGHT REFLECTOR SEGMENTS, 2-3 M, <20 KG/M^2, SUPPORTED BY TRUSS BACKUP STRUCTURE.
• OVERALL SURFACE ERROR <2 MICRONS RMS
• ACTIVE CONTROL SYSTEMS FOR FIGURE, POINTING, VIBRATION
• SURFACE MEASUREMENT SYSTEM
• SUNSHADE FOR THERMAL CONTROL
• FOCAL PLANE INSTRUMENTS COVERING SPECTRAL RANGE 30-1000 MICRONS, CRYOGENIC, COHERENT AND NON-COHERENT.

The active optical system includes, as well as the position actuators on the primary reflector segments and secondary mirror, a system for measuring the optical errors. There are at least three methods under consideration. The first would use edge sensors at the segment boundaries, as is planned for the University of California 10 m telescope. This only determines the shape of the primary reflector; the relative positions of the secondary and focal plane would still need an additional measurement system. The second method samples a portion of the incoming wavefront from a point source. Figure and misalignment errors of the optical elements show up as departures from a plane wave at the focal plane. There are methods to deconvolve the wavefront and determine uniquely which optical element is in error.

The third measurement method uses direct laser range finding. A steering mirror at the Cassegrain focus steers a laser beam to at least three points on each reflector panel sequentially, via a reflection off the secondary mirror. Retroreflectors on the primary send the beam back to the secondary and, in turn, back to the focal plane where an interferometer measures the phase path length through the complete optical system. The use of two frequencies can remove the fringe ambiguity.

Closely associated with the figure measurement and control is pointing and structural vibration control. Since LDR will be a relatively light structure for its size, it will have low natural frequencies. Any onboard disturbance such as slewing, secondary mirror chopping, pumping of cryogenic fluids, gyro noise, etc., will excite the natural frequencies of the structure. Active damping of the structure, where an incipient vibration is damped by feeding in a disturbance of equal amplitude but opposite phase, may be necessary. Pointing and slewing forces can be tailored such that the spectrum of the forcing function contains minimum power at the lowest resonant frequencies of the structure.

The instrument package will be housed just behind the vertex of the primary reflector at the Cassegrain focus. A complement of 13 instruments were listed at Asilomar and were termed "the astronomers dream, but the technologists nightmare." The number of instruments will undoubtedly decrease, but the general classes of instruments will probably remain the same. The four instrument classes baselined are the same as those suggested at Asilomar.*

*Paul N. Saranson, Samuel Guilkis, and T. B. H. Kuiper, "Large Deployable Reflector (LDR): A Concept for On Orbiting Submillimeter-Infrared Telescope for the 1990s," Optical Engineering, Vol. 22, No. 6, December 1983.

6.1.3.4 Geostationary Platform Assembly - The last group looked at was assembly and construction of geostationary (GEO) platforms. Two candidates were identified as shown in Table 6.1.2-1. The first one, "Advanced Large Commercial Communications System," is one of the landmark missions (LM-7) described in section seven of the NASA Space Systems Technology Model, Vol. III, January 1984.

The objective of this satellite is to provide capability to interconnect approximately 25 million users anywhere in the U.S., direct from user-to-user through wrist-size radiotelephones. The system uses a single large communications satellite in geostationary orbit. Due to the very small antenna size possible in such a radiotelephone, the satellite antenna must be large (70-100 m diameter).

Present estimates on the weight of this satellite is 30,000 kg. The system will also have a 300 kw solar cell power system and transfer itself to GEO following assembly and checkout. Three Shuttle flights are required to place the required materials and support equipment at the low earth orbit construction site. A key feature of this satellite is the electronics modularization to allow unmanned maintenance at the operating site. The large electrical power source on board required for communications would also be used to power ion engines to make the transfer. Ion engines would be rotated to provide on-orbit attitude and stationkeeping translational control. The satellite will be serviced manually by an Advanced Teleoperator Maneuvering System.*

*Ivan Bekey, "Big Comsats for Big Jobs at Low User Cost," Astronautics and Aeronautics, February 1979, pp. 42-56.

6.2 SPACE STATION IOC BUILDUP

6.2.1 Description

The mission models all utilize common elements: pressurized modules, power generation devices, and assembly hardware. The pressurized modules are identical vessels with different functions to be interchanged with one another. This modular approach increases the flexibility of the system to be expandable for future requirements. Power generation devices can be passive solar arrays or dynamic solar power systems. Assembly hardware is the structure that ties the modules, experiments and power devices together. This structure consists of box trusses formed into cubes that run the length of the power tower. (44) The truss structure will be deployable, erectable, or a combination of both.

All the construction scenarios have common assembly techniques with variations for different situations. The assembly of the Space Station utilizes a combination of four support equipment types.

1) Mobile Remote Manipulator System (MRMS). The MRMS is described elsewhere in this Section.
2) Extravehicular Activity (EVA)
3) Shuttle Remote Manipulator System (SRMS)
4) Automatic Mechanisms

The SRMS is used for transferring cargo from the Shuttle bay to the Space Station. Its principle function is to lift the cargo and implace it. It is capable of lifting any load to a maximum of 65,000 pounds.

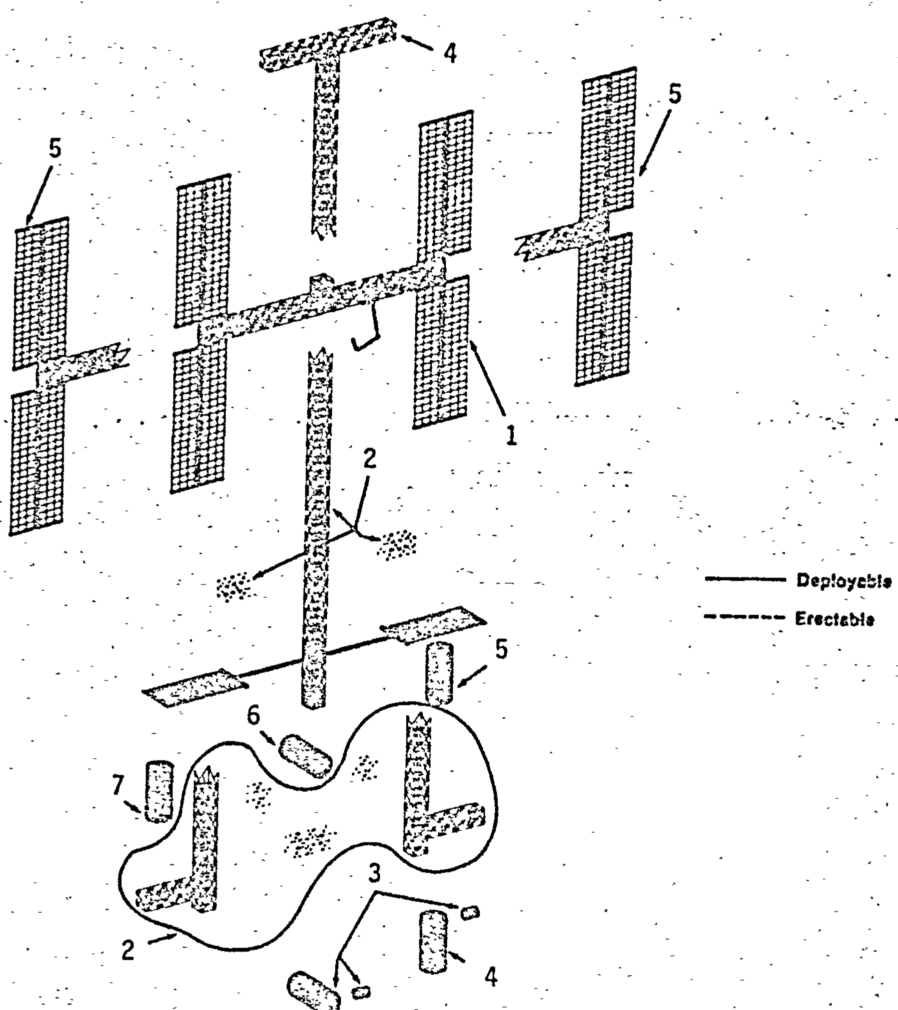
The EVA astronaut works both by himself and in conjunction with the SRMS or the MRMS. The astronaut will guide the manipulators as well as provide individual human manipulation.

6.2.2 Assembly/Construction Scenario

The assembly of the IOC forms the basis for future growth and development. Certain guidelines need to be understood and assumptions made in order to develop a feasible construction scenario.

Seven Shuttle flights have been identified to have the basic Space Station operational. The structure utilizes a combination of deployable and erectable structures with the majority of the booms and keels deployed automatically. The structure is shown in Figure 6.2.2-1.

Figure 6.2.2-1 Erectable/Deployable Structure on Space Station



The scenario for the first flight is shown in Figure 6.2.2-2. A major activity of this flight is the transport and installation of the Mobile Remote Manipulator System (MRMS) to assist in the subsequent construction effort. (The MRMS is referred to as the "Autonomous Transport Vehicle," or ATV, until installation of an RMS manipulator arm.) The high utility of the MRMS is indicated in Figures 6.2.2-3 and 6.2.2-4, which summarizes the tasks or operations to be performed by the MRMS and projects the percentages of operations methods to be employed for each flight. See Sections 6.2.3 and 6.6.1 for a description of the MRMS system.

Figure 6.2.2-2 Flight 1 Scenario

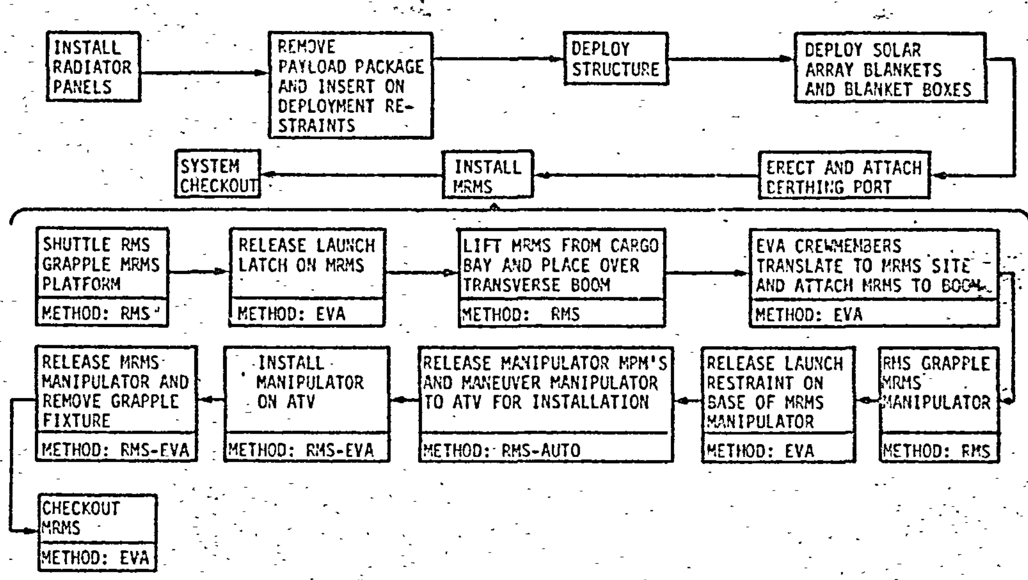
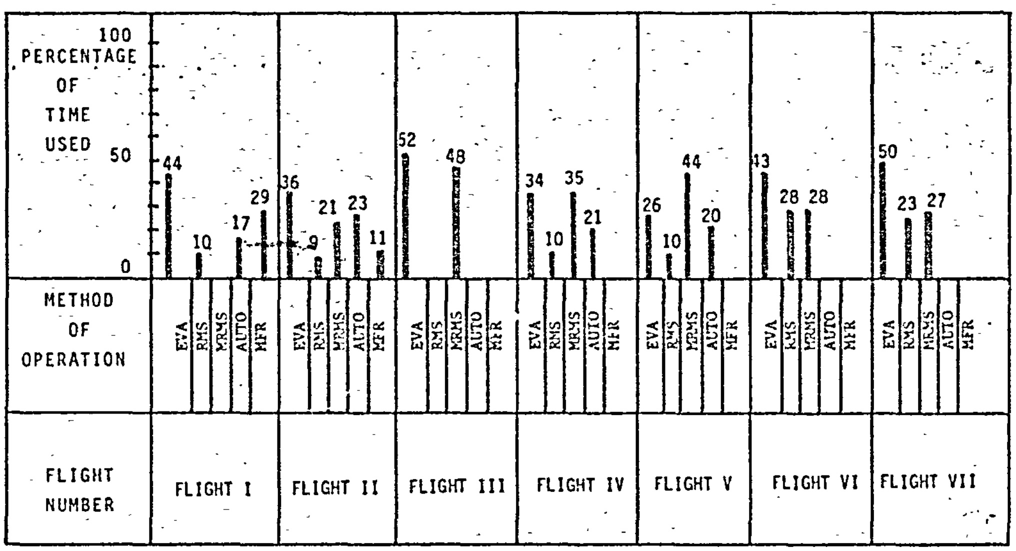


Figure 6.2.2-3 MRMS Tasks and Operations

MRMS TASK/OPERATION	FLIGHT I	FLIGHT II	FLIGHT III	FLIGHT IV	FLIGHT V	FLIGHT VI	FLIGHT VII
-REMOVE PACKAGE* FROM PAYLOAD BAY		▲	▲	▲	▲	▲	▲
-TRANSPORT PACKAGE	●	▲	▲	▲	▲	▲	▲
-ATTACH PACKAGE TO STRUCTURE	●	▲	▲	▲	▲	▲	▲
-ERECT STRUCTURE		▲					
-UNFOLD RAILS		▲		▲			
-UNFOLD BOOMS & ARMS		▲					
-RELEASE LAUNCH RESTRAINTS			▲				

*PACKAGES CONSIST OF MODULES, EXTERNAL EXPERIMENTS, ANTENNAS, AIRLOCKS, ARRAYS AND DEPLOYABLE STRUCTURES.

Figure 6.2.2-4 Projected Operation Method Percentages



The start of the IOC will begin in the Shuttle bay. The power conditioning radiators are attached to the stowed transverse boom. Using an automatic deploy mechanism, the boom is extended outward. Having the transverse boom deployed, the Mobile Remote Manipulator System (MRMS) is affixed to the truss structure. The solar arrays at the end of the transverse boom are deployed. The final assembly of this flight is a single bay perpendicular to the boom. It houses a berthing ring for docking on the next Shuttle mission. The entire structure is then released from the Shuttle. The configuration is shown in Figure 6.2.2-1, subelement 1, which shows the configuration after the first shuttle flight.

Flight II continues the construction of the structure. The lower keel package is attached to the transverse boom and deployed. The radiator support booms are next unfolded from the lower keel. Two keel extension bays are erected on the port and starboard sides of the lower keel boom. Erection of extension bays constitute the placement of structural rods into nodal joints.

Next, radiator panels are installed in the port and starboard heat exchanger booms. The port keel extension boom package is removed from the cargo bay and attached to the port side of the recently-erected keel extension bay. The port keel extension structure is deployed by its mechanism. The procedure is then repeated for the starboard keel extension structure. Both extension structures are tied together by internal support bays that are to be erected by EVA with the use of the MRMS. The configuration after the second flight is shown in Figure 6.2.2-1, subelement 2.

With the majority of the assembly hardware constructed, Flight III begins the addition of modules. First, the module mounting structure is installed on the keel extension structure. Habitat Module 1 (HM1) is removed from the payload bay and attached to its mount. The EVA astronaut connects all utilities associated with the module. The final packages in the cargo bay are the two airlocks. Airlock 1 (AL1) is attached to HM1 while AL2 is temporarily attached to HM1. It will be transferred to its permanent location when the remaining modules are in their final configuration.

The Flight IV cargo bay contains the HM2 and the upper keel structure package. The Shuttle docks at HM1, and HM2 is attached to HM1. The connection of the utilities are then mated to HM2 by the EVA with the MRMS. AL2 is removed off HM1 and attached to HM2. The final installation of this flight is the upper keel. It is transported from the module area to the transverse beam structure. Once attached, the upper keel is deployed to its full configuration. See Figure 6.2.2-1, subelements numbered 4.

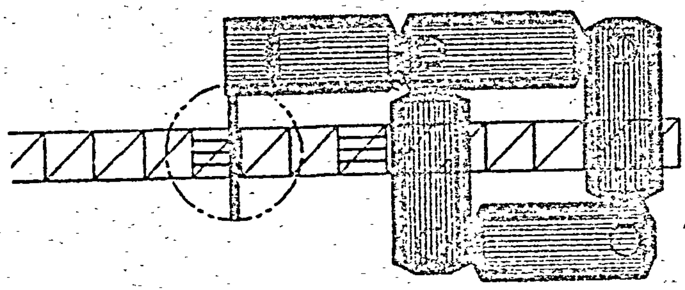
Flight V carries the third module. The Shuttle will again dock at HM1. The next module is the Logistics Module (LOG1) and is attached to HM2. With the EVA and the support of the SRMS, the port solar array addition package is loaded on the MRMS. It is transported to its attachment site on the transverse beam. Once attached, it is deployed. This procedure is repeated for the starboard solar array addition package. See Figure 6.2.2-1, subelement numbered 5.

At this point in the assembly sequence, the modules are activated for inhabitance. With the station permanently manned, prolonged assembly tasks can be conducted, such as installation of permanent hard lines and verification of any attachments.

On Flight VI, Laboratory Module 2 (LAB2) is attached between the HM2 and the keel extension structure. The remainder of the payload will be for spares or external payloads. No defined package has been designated at this time. Assembly will probably require transportation and attachment to the system.

Flight VII is a repeat of Flight VI, except the module is LAB1. Again, miscellaneous items and payloads will occupy the launch package. The module arrangement is shown in Figure 6.2.2-5.

Figure 6.2.2-5 Module Arrangement



6.2.3 Conceptual Design

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 and EVA positioning arms. It plays an important dimension in the buildup of the Space Station Initial Operating Configuration (IOC) and is the only 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. Its work load begins with the second flight. The combination of crane/astronaut on the positioning arm is utilized in locating, latching, and deploying the lower keel. 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 necessary for both the growth of the Space Station and assembling spacecraft.

The assembly task becomes more involved when a bay is erected between the lower keel and keel extension. The work depends on the mobility of the positioning arms and the dexterity of the astronaut to place and lock the various tubular segments together.

The remaining five flights all contain a module. The Shuttle docks and the module is removed from its bay via the SRMS or the MRMS. An astronaut latches the module to the MRMS logistic platform. The EVA man is anchored to the platform by the positioning arm which also reacts all forces caused by his movements. The MRMS pulls its way to the next location where the module is to be attached. It could be in the next bay, at the end of the keel, or perpendicular to that bay. The MRMS crane positions the module, and the astronaut makes all the necessary connections. Besides the modules, there is a variety of packages that include antennas, experiments, and miscellaneous electronic boxes.

The basic size of the MRMS is approximately 9 feet square, the size of a single bay. Its design consists of three basic layers as shown in Figure 6.2.3-1, and further discussed in Section 6.2.4. The figure shows the initial configuration, with an RMS attached, located on the Space Station structure.

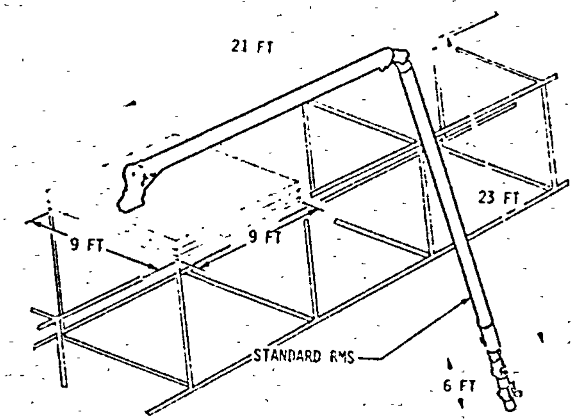
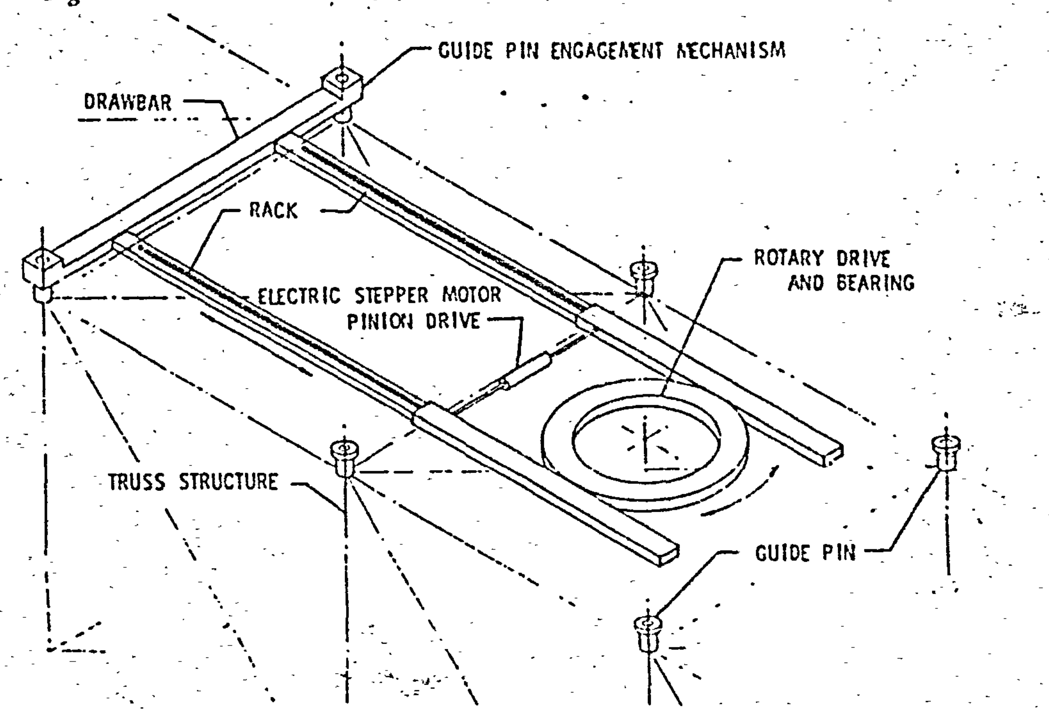


Figure 6.2.3-1 Mobile Remote Manipulator System Elements

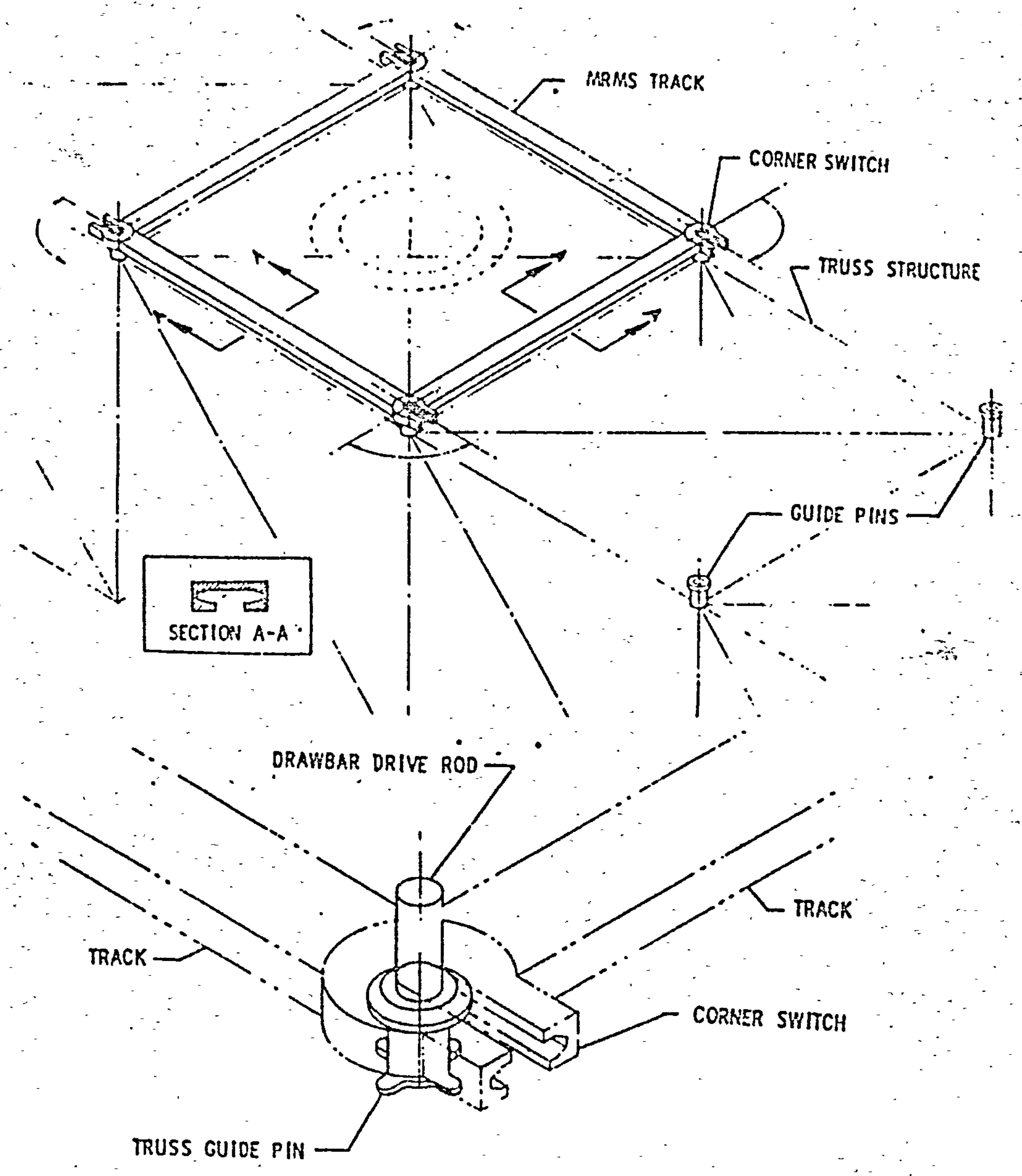
The bottom layer consists of a square track arrangement which rides on guide pins attached to the truss nodes. The flat tracks are connected on the corners by "switches" that rotate 90°. See Figure 6.2.3-2. The switches are aligned to permit motion over the guide pins in two orthogonal directions. The 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 stepper 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.

Figure 6.2.3-2 MRMS Drive System



This central element is capable of rotating 360°. The transverse translation involves pivoting 90° as well as the push/pull feature. The corner switch uses an open top mechanism feature that permits the drawbar to lock onto a guide pin which is also occupied by a track switch as shown in Figure 6.2.3-3.

Figure 6.2.3-3 MRMS Switch Arrangement

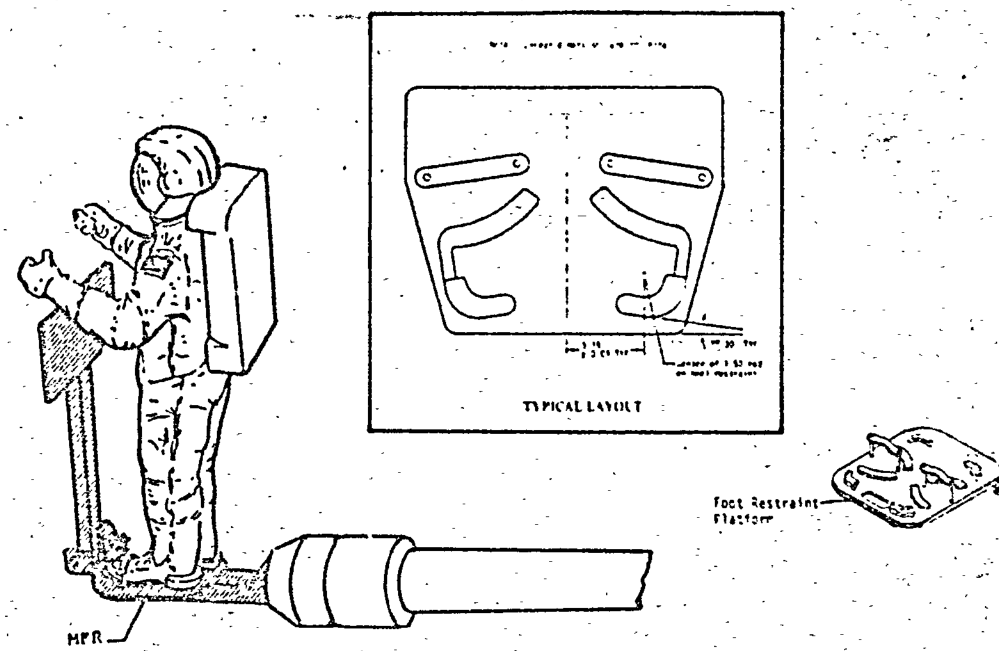


The logistics platform is the top layer. It serves to transport payloads along the Space Station surface. It has the ability to rotate relative to the track layer and remain fixed when the central element pivots. Instead of using a separate roll drive, the switches would have to be lockable in a rigid position and the top two layers would move in unison. The logistics platform has another option in locking itself to the lower layer and have the middle section pivot relative to the top and bottom.

Besides having the temporary storage capability of the flat top, the top layer features the space crane. The crane is envisioned to be a Shuttle RMS transposed onto the platform. The Shuttle is capable of carrying two arms on a single launch. One SRMS would remove the second arm with the help of EVA astronauts and affix it to the top layer of the MRMS.

Also required are Mobile Foot Restraint (MFR) positioning arms. An astronaut in EVA suit is positioned within the work envelope by the MFR on the end of the RMS. Control of the MRMS optionally resides with the EVA astronaut(s) (see Figure 6.2.3-4).

Figure 6.2.3-4 Mobile Foot Restraint for EVA



The MRMS will have a self-contained, rechargable 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.

Two of the many possible functions of the MRMS are shown in Figures 6.2.3-5 and 6.2.3-6. In the first, the track layer only of the MRMS is attached to the Reaction Control System (RCS) and the system is transported to its specified location on the structure. In the second figure, the MRMS is used after the first shuttle flight to continue the Space Station construction. In the upper two figures, the truss segment is removed from the payload bay and positioned on the structure. The truss segments are then unfolded and attached to the structure prior to rigidizing and deployment of the new section. Note that in this figure the MRMS is being viewed from one underside.

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Figure 6.2.3-5 RCS Attachment to Structure

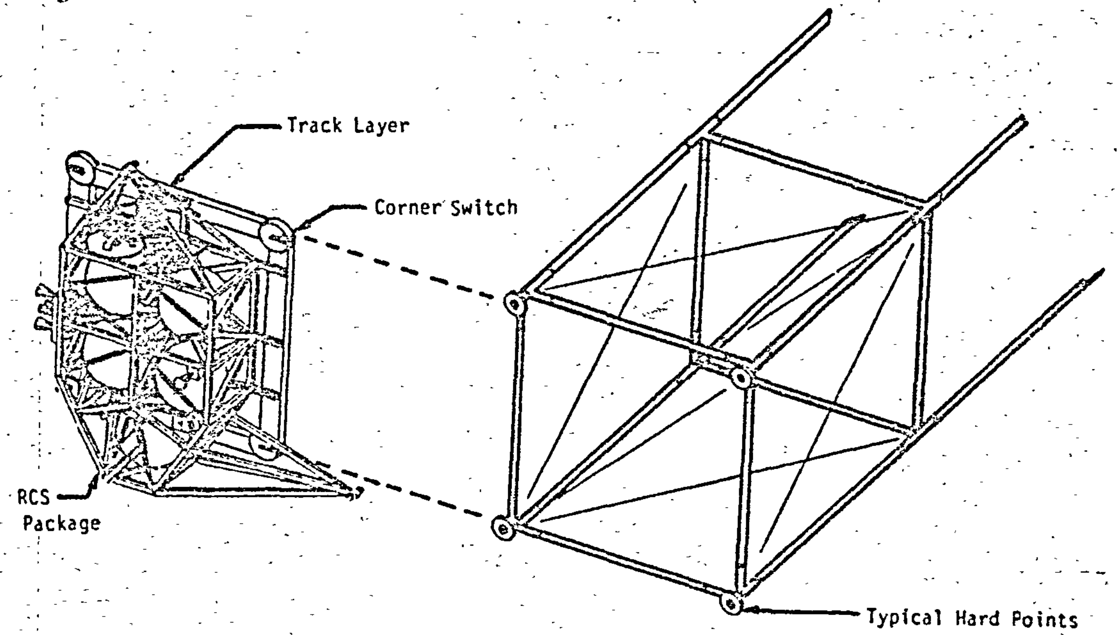
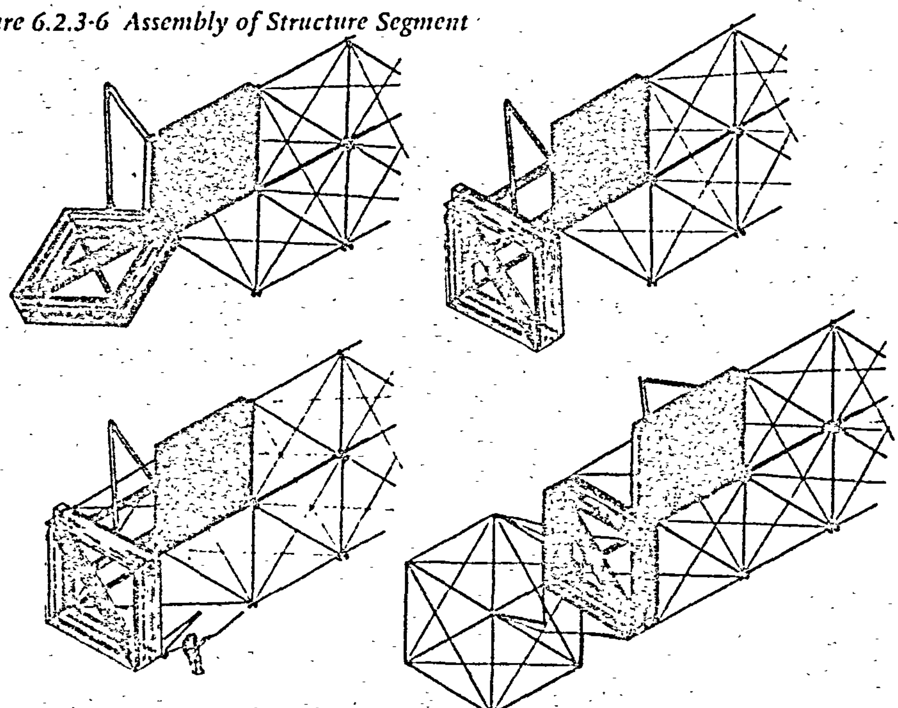


Figure 6.2.3-6 Assembly of Structure Segment



6.2.4 MRMS Evolution

A summary of the anticipated MRMS System evolution is shown in Figure 6.2.4-1 and the top-level requirements in Table 6.2.4-1. 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 positioning arms have the freedom to translate along opposite sides of the top layer. This capability greatly expands the work volume of the positioning arm as well as the astronaut. It also has the option to have the astronauts work as a pair in a dual-arm mode. The Telepresence Work Station (TWS) will be incorporated, to at-least partially replace the EVA need, in the 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. Note that the overall evolution is covered in this section rather than splitting between subsequent sections.

Figure 6.2.4-1 MRMS System Evolution

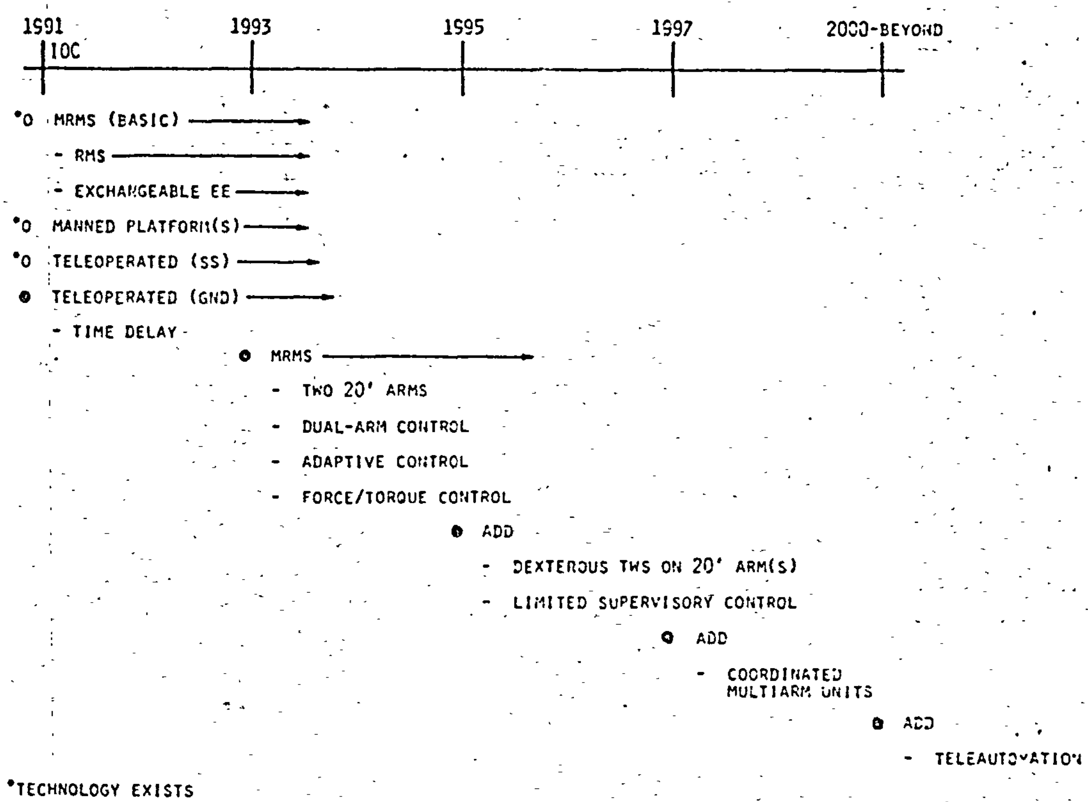


Table 6.2.4-1 MRMS Requirements

<u>SYSTEM REQUIREMENTS:</u>

- STATION ASSEMBLY
- MODULE REMOVAL
- OMV/OTV BERTHING IN THE HANGAR AREA
- DEPLOYMENT OF THE OMV/OTV FROM THE HANGAR AREA
- AID TO OMV, OTV, AND SATELLITE SERVICING
- MAINTENANCE & REPAIR

<u>HARDWARE REQUIREMENTS:</u>

- POSITION ASTRONAUTS (TWS) FOR EVA FUNCTIONS
- TRANSPORT MODULES AND/OR PAYLOADS FROM THE SHUTTLE CARGO BAY
- MOVE IN TWO ORTHOGONAL DIRECTIONS

Two astronauts are shown duringconstruction activities with the MRMS in Figure 6.2.4.2, which shows the utilization of the two 20-foot positioning arms in conjunction with the Mobile Foot Restraint system (Figure 6.2.3-4) and the RMS crane. Major components of this advanced MRMS are shown in Figure 6.2.4-3, which depicts the three-layer construction of the system. The strongback cube assembly steps, utilizing the MRMS are shown in Figure 6.2.4-4.

Although the EVA astronaut 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 the TWS at the end of the positioning arms, as shown in Figure 6.2.4-5. The TWS has the same or greater capabilities than man, yet reduces the amount of support equipment and preparatory work. The TWS is shown in greater detail in Figure 6.2.4-6.

Typical system and subsystem design requirements are listed in Tables 6.2.4-2 and 6.2.4-3. An isometric of a potentially suitable joint drive for a positioning arm is shown in Figure 6.2.4-7. This particular drive is part of the Protoflight Manipulator Arm, which is resident and in use at Marshall Space Flight Center. This drive was zero backlash and imbedded sensors (resolver and tachometer). Greater accuracy could be achieved by incorporating optical encoders. Figure 6.2.4-8 is a schematic of the same drive, showing the cable routing across the joint.

For additional source information refer to Appendix A, 26, 29 & 34.

Table 6.2.4-2 MRMS System Requirements

	PROPOSED VALUE
- MODE OF TRANSLATION	PORTABLE/TRANSPORTATION
- PHYSICAL FEATURES	ANTHROPOMORPHIC
- DESIGN ASSEMBLY	MODULAR SEGMENTS
- WEIGHT	GOAL OF 600 LB
- SIZE (FIT WITHIN)	4 FT DIA, STOWED
- OPERATIONAL LIFE	10 YEARS, WITH MAINTENANCE
- LOAD CARRYING, SAFETY FACTOR	YIELD 1.5, ULTIMATE 2.0
- ELECTRIC POWER, VOLTAGE	28 $\pm$ 4 VDC
- SPARE WIRES PROVIDED	20%
- CONNECT/DISCONNECT CAPABILITY	REMOTE WITH MANIPULATORS
- PROVISION AGAINST MISMATING	KEY AND KEY WAY POLARIZATION
- SYSTEM SAFETY DESIGN	FAIL-SAFE OPERATION
- MAINTENANCE APPROACH	MODULE REPLACE
- NAMEPLATES AND IDENTIFICATION	PERMANENT IDENT.
- VIEWING ACCESS (IDENTIFIERS)	DIRECT VISUAL, CCTV OR MIRRORS
- SPACE STATION INTERFACES	RMS, MRMS, 7 FACILITY SERVICES

Table 6.2.4-3 MRMS Subsystem Requirements

- ARMS, CONFIGURATION (SLAVE)	MODULAR, ANTHROPOMORPHIC (2)
- HORIZONTAL MAXIMUM REACH	50 IN
- DEGREES OF FREEDOM	7
- JOINT ORDER: SHOULDER	PITCH AND YAW
UPPER ARM	ROLL
ELBOW	YAW
WRIST	ROLL, ROLL, ROLL (COMMON INTERACTION)
- TIP FORCE ARM FULLY EXTENDED	50 LB
- TIP SPEED ARM FULLY EXTENDED (NO LOAD)	18 IN/SEC
- BACK DRIVEABILITY, FULL EXTENSION	3 LB TIP FORCE
- BRAKING ACTION	PROVIDE ON ALL BACKDRIVABLE JOINTS
- FORCE LOOP RESPONSE	VARIABLE BETWEEN 0.2 AND 4.0 Hz
- ARM DEFLECTION	NOT TO EXCEED 1.0% OF TOTAL TRAVEL
- ARM BACKLASH	NOT TO EXCEED 0.2% OF TOTAL TRAVEL
- END EFFECTOR	STANDARD PARALLEL VICE GRIP MOTION
- INTERCHANGEABLE MOUNTING	DECOUPLED AT WRIST FOR TOOL INTER.
- CCTV/LIGHTS	TOTAL COVERAGE OF ARMS ACTIVITIES
- PAN/TILT DEVICE	$\pm$ 90° TILT, $\pm$ 180° pan
- ILLUMINATION AT WORKSITE	60 FT CANDLES

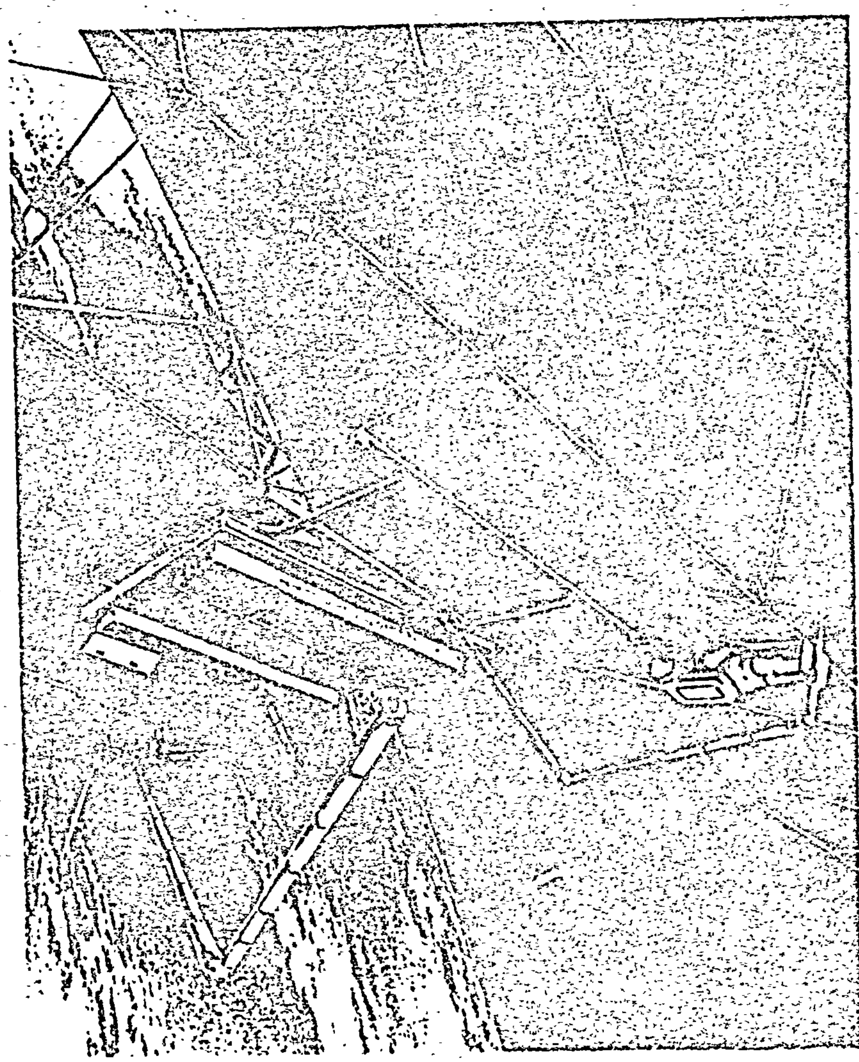


Figure 6.2.4-2 Construction with MRMS

Figure 6.2.4-3 MRMS Elements

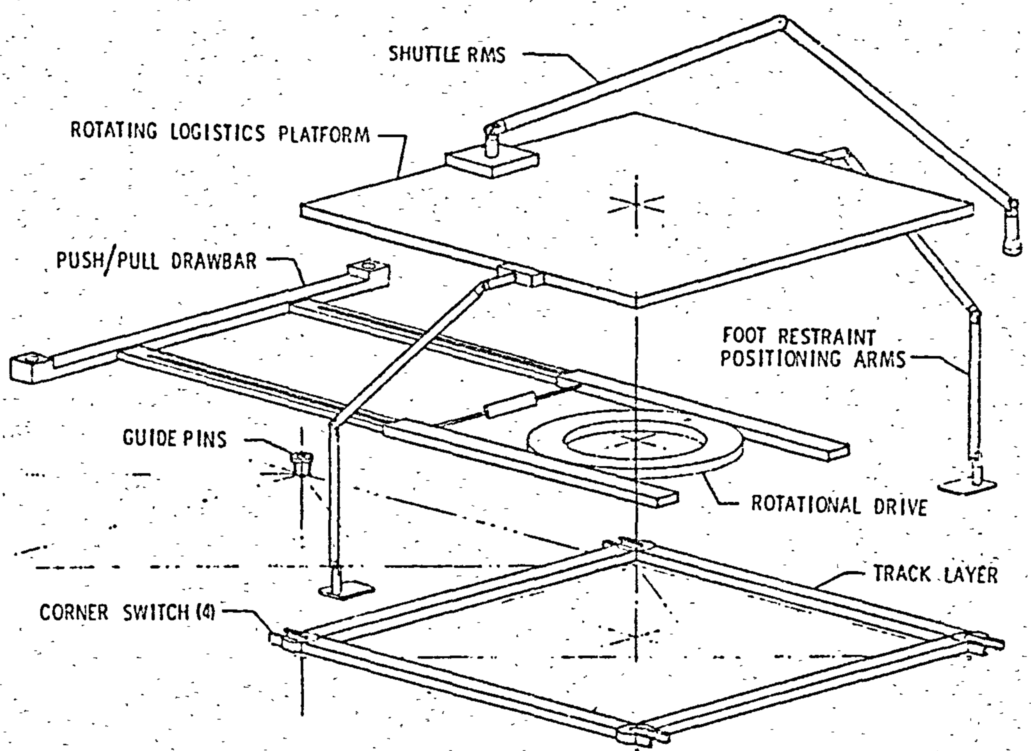
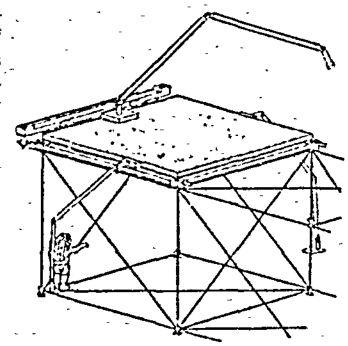
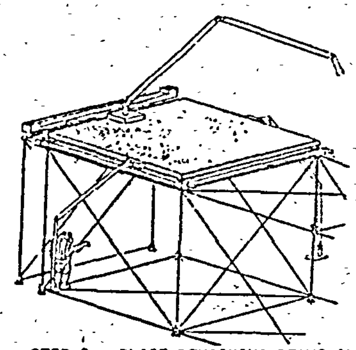


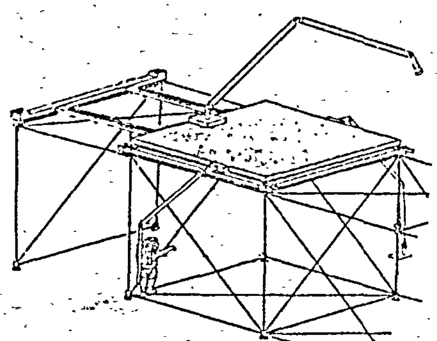
Figure 6.2.4-4 Strongback Cube Assembly Steps



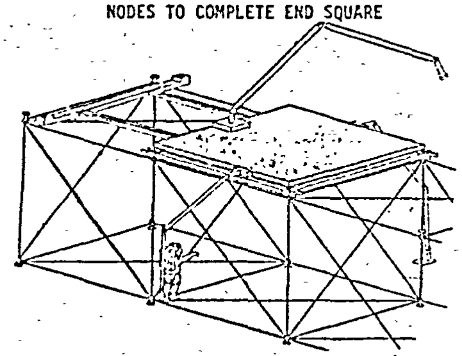
STEP 1. PLACE CORNER NODES IN CRAWLER PLATE WITH CROSS BEAM



STEP 2. PLACE REMAINING BEAMS AND CORNER NODES TO COMPLETE END SQUARE



STEP 3. EXTEND CRAWLER PLATE 9 FEET AND EMPLACE TOP BEAMS AND CROSS BRACE



STEP 4. EMPLACE BOTTOM BEAMS AND CROSS BRACES TO FINISH CUBE

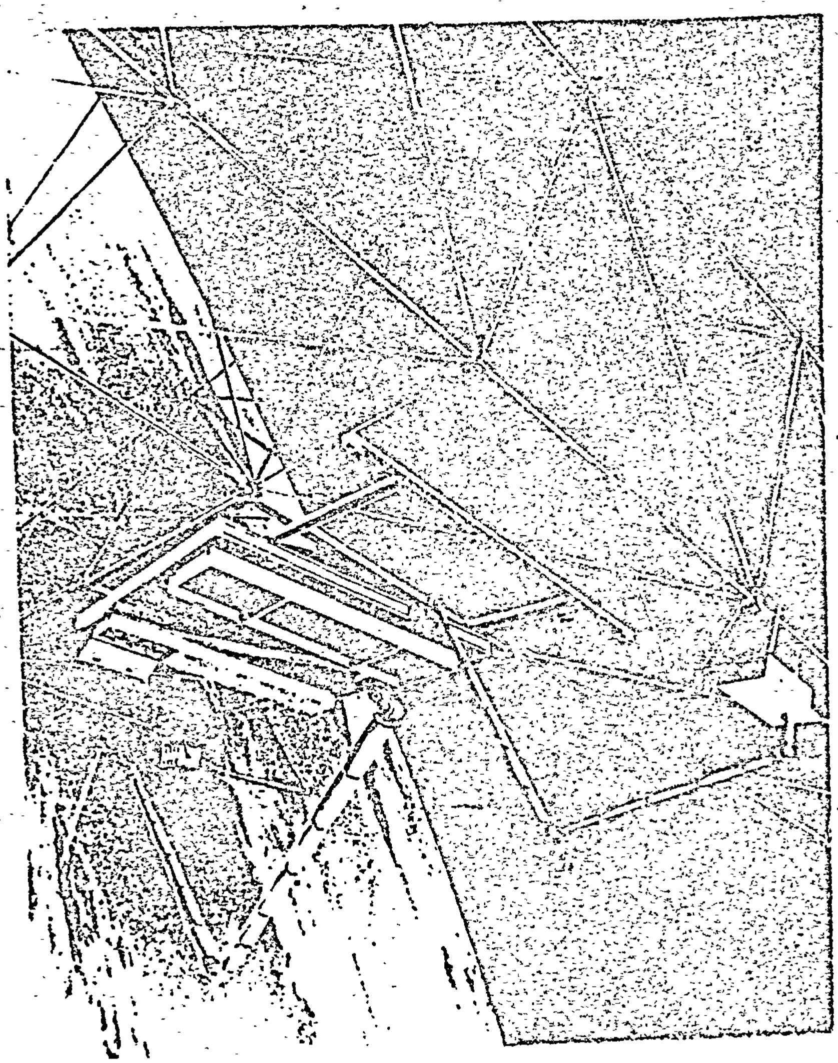


Figure 6.2.4-5 MRMS with TWS System

Figure 6.2.4-6 TWS Configuration

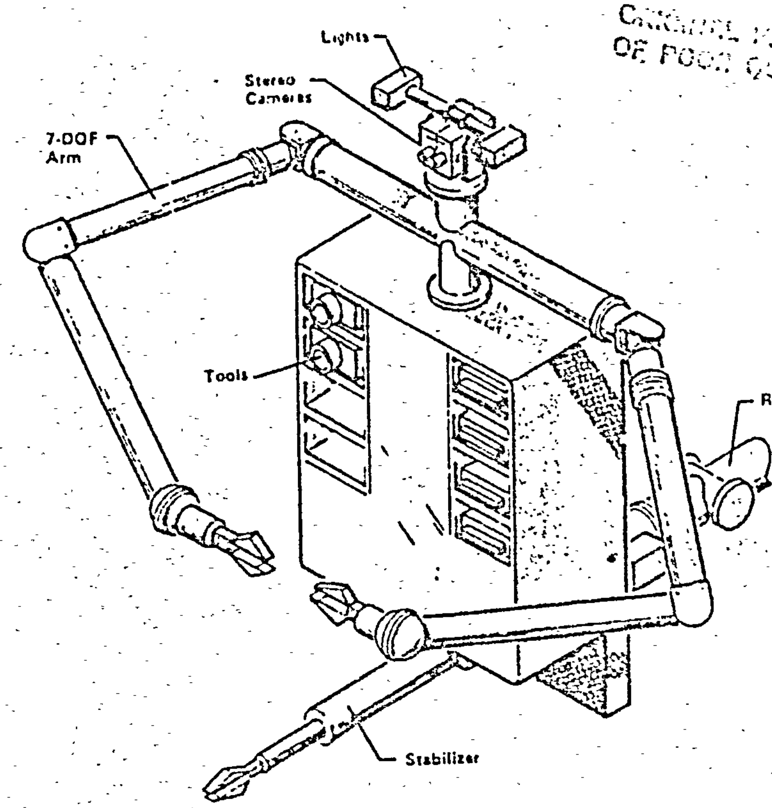


Figure 6.2.4-7 Elbow Yaw Drive Module

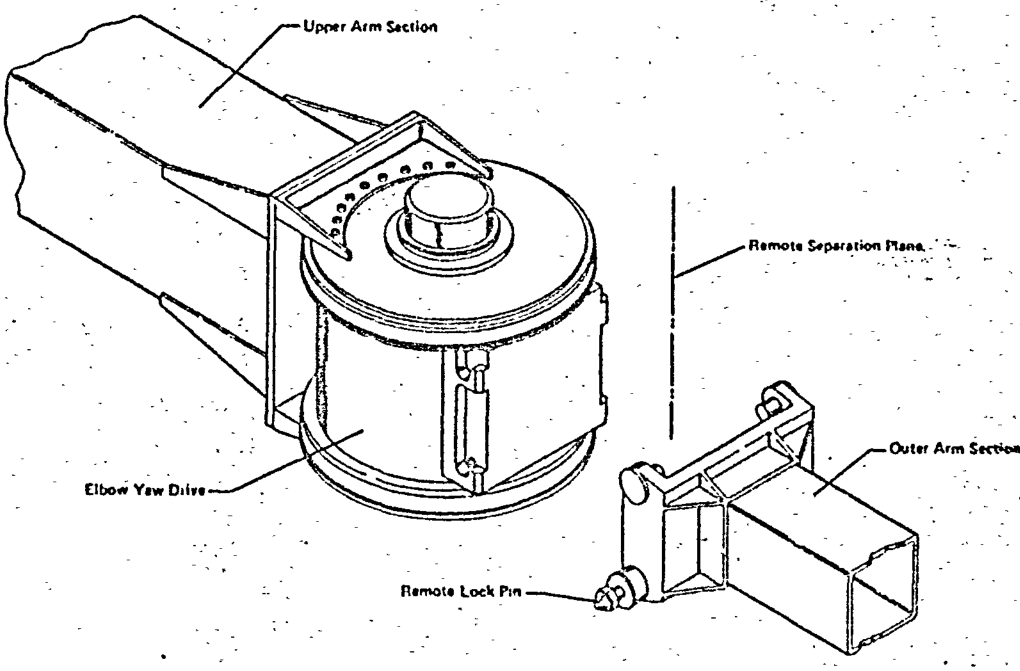
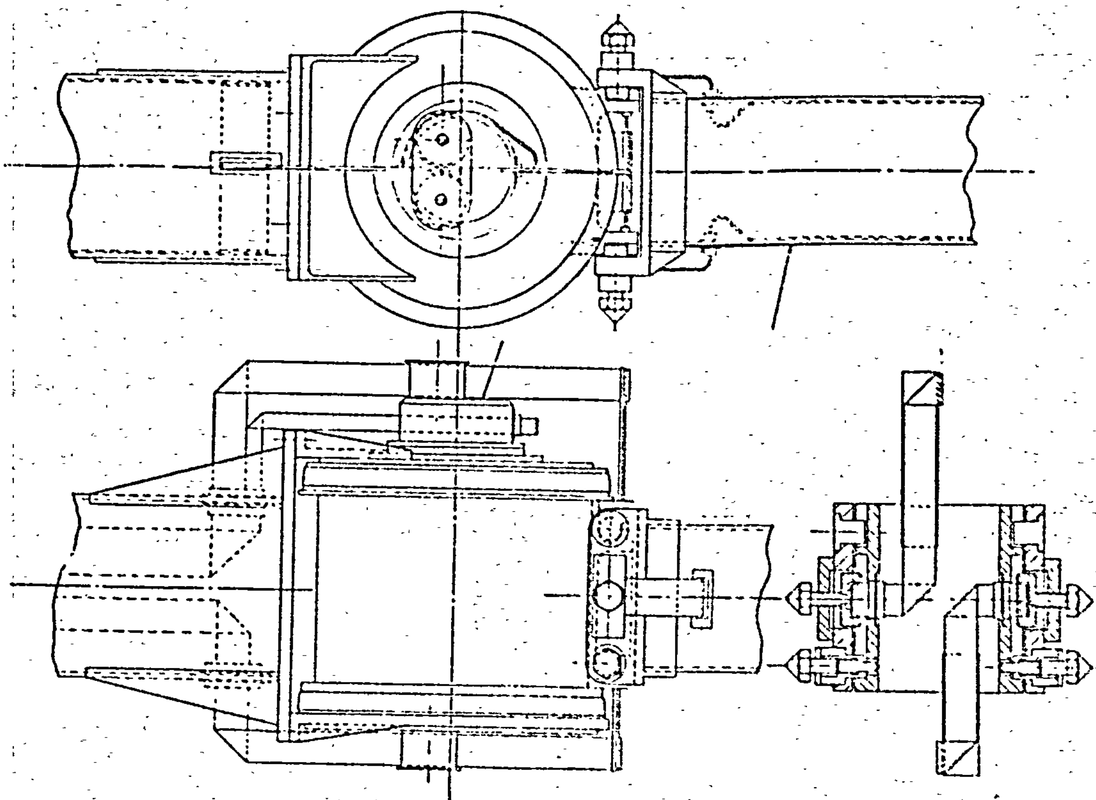


Figure 6.2.4-8 Elbow Yaw Drive Schematic



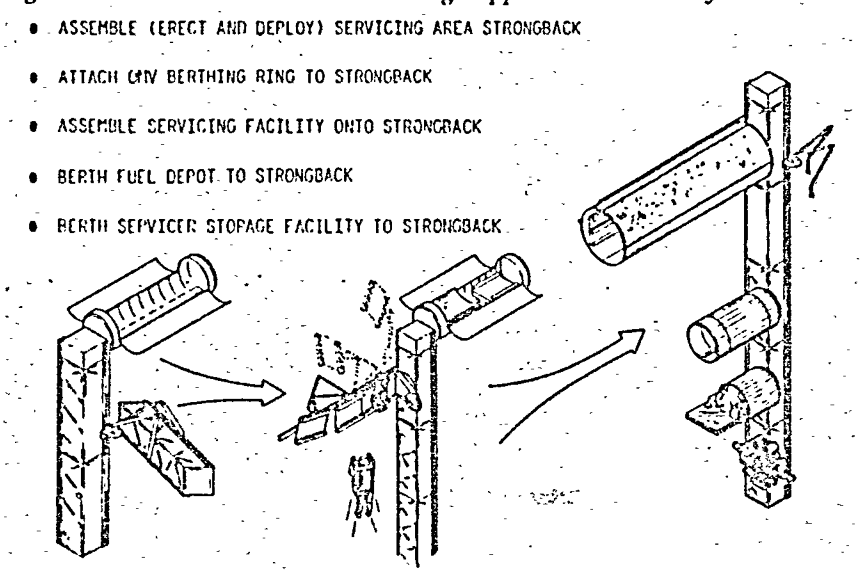
6.3 SPACE STATION EXPANSION

6.3.1 Description

The concept mission selected to represent the expansion or modification of an IOC Space Station was the Technology Development Mission (TDM) No. 3 concept, developed and presented in Contract NAS8-35042, "Definition of Technology Development Missions for Early Space Station - Satellite Servicing." The objective of TDM 3 is to demonstrate assembly or modification operations at the Space Station. This TDM emphasizes assembly of servicing related elements of the Space Station and is designed to be completed with two Shuttle missions.

The major activities which must be planned and executed for the successful completion of the mission are shown in Figure 6.3.1-1.

Figure 6.3.1-1 TDM3—Satellite Servicing Support Area Assembly



These activities have been grouped into three phases for further decomposition into more detailed work elements:

1) Strongback Assembly and OMV Berthing Ring Attachments
2) Servicing Facility Assembly onto Strongback
3) Fuel Depot and Services Storage Facility Docking.

6.3.2 Assembly/Construction Scenario

6.3.2.1 Phase 1 - Strongback Assembly Description - The major TDM events and top-level derived requirements for Phase 1 are shown in Table 6.3.2-1.

Table 6.3.2-1 Phase 1—Strongback Assembly

EVENTS	REQUIREMENTS
• FIRST STS DOCKS TO SS • TRANSFPORT AND ATTACH STS CARGO CANISTERS TO STAGING AREA. • REMOVE STRONGBACK SECTION FROM CANISTER AND DEPLOY, USING RMS. • POSITION DEPLOYED STRONGBACK SECTION INTO LATCHES OF STAGING AREA. • ASTRONAUT IN EVA CONNECTS/CHECKS LATCHES • REPEAT PROCEDURE FOR REMAINING STRONGBACK SECTIONS. • ATTACH CABLING TO STRONGBACK USING EVA CREW. • ATTACH OMV BERTHING RING TO STRONGBACK.	SS • RMS ACCESS FROM STS DOCKING AREA TO SERVICE AREA • STRUCTURAL INTEPFACE AND UTILITIES PASS-THROUGH FOR SERVICING STRONGBACK. • RMS TRACK CLEARANCE FOR PAYLOADS SS RMS • RMS CONTROL CONSOLE • TWO ARM CAPABILITY SERVICING SUPPORT AREA EMU/MMU • RMS/RMS TRACK • COMMUNICATIONS - CC TV - AUDIO • TOOLS/EQUIPMENT - LIGHTS - TETHERS - TOOL CADDY - LATCHING TOOL

The staging area is the Space Station structural interface for the servicing strongback. Shuttle cargo canisters will be attached to the side of the staging area. These canisters will carry all parts to be assembled during the mission. The use of these cargo canisters will free the orbiter for return to earth and reduces travel of the station manipulator. The interim storage canisters could be designed and configured to be lightweight storage enclosures to provide thermal and micrometeoroid shielding for storage of OMV, servicers, and replacement modules.

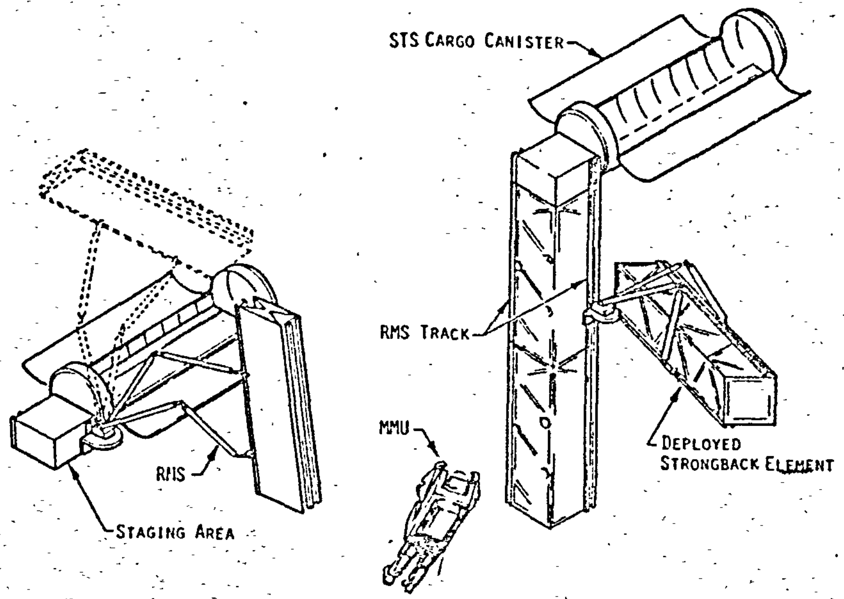
This phase includes removal of folded deployable service strongback support elements, deployment of the elements to full extension (by a dual-armed manipulator or by astronauts in EVA), and the attachment of the five elements. The strongback elements will be automatically latched using the RMS manipulator or latched and verified by astronauts in EVA.

Figure 6.3.2-1 shows a visual representation of the deployment and attachment of the servicing strongback elements.

The RMS construction crane lifts the canisters containing the stowed strongback structure from the payload bay and transfers the canister to the RMS. The canister is transported by RMS to the staging area and attached. The RMS is used to remove each strongback section from the canister and assist in deployment. Each strongback section will be latched onto the preceding section and will be visibly verified by EVA crew members.

The strongback is composed of five 29-foot sections. Using the RMS and EVA crew, cabling is removed from inside the staging area and is moved down along the strongback, being attached at appropriate locations by the EVA crew.

Figure 6.3.2-1 Phase 1–Service Support Area Assembly



6.3.2.2 Phase 2 - Servicing Facility Assembly - The procedure used and discussed in Phase 1 is also used in the assembly of the servicing facility. The elements of the servicing facility will be included in the first Shuttle mission.

The RMS will be used to attach individual track sections of the servicing facility, with an EVA crew verifying latch-up. Both a support cradle and carousel mechanism, to rotate satellites, will be installed for use in servicing vehicles.

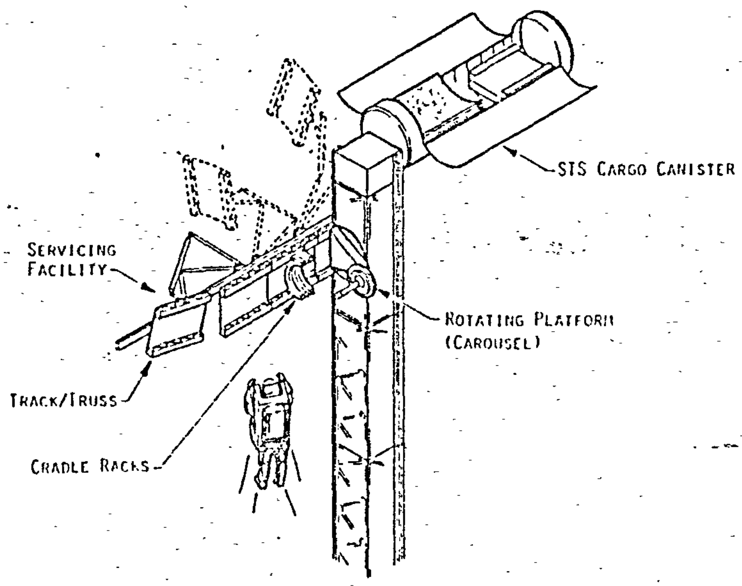
The requirements for inside the servicing facility are listed below in Table 6.3.2-2.

Table 6.3.2-2 Phase 2–Servicing Facility Assembly

EVENTS	REQUIREMENTS
• REMOVE SERVICING MODULE BASE TRUSS FROM CANISTER. • POSITION AND DOCK BASE TRUSS AT INTERFACE POINT ON STRONGBACK • REMOVE SECTION OF SERVICING FACILITY TRACK FROM CANISTER. AND ATTACH TO BASE TRUSS. EVA CREW VERIFIES LATCH-UP. • REPEAT PROCEDURE FOR REMAINING SERVICING FACILITY TRACK SECTIONS. • ATTACH CRADLE INTO SERVICING FACILITY TRACK. • ATTACH HARD COVER SECTIONS. • ATTACH SERVICING MODULE CABLING TO STRONGBACK CABLING USING EVA CREW. • CHECKOUT FACILITY SUBSYSTEMS.	<u>SERVICING FACILITY</u> • LIGHTING AIDS • WORK STATION - FOOT RESTRAINTS • STORAGE BINS • PAYLOAD CRADLE/CAROUSEL MECHANISM • THERMAL CONTROL • ASSEMBLY/MAINTENANCE TOOLS/EQUIPMENT - TOOL CADDY - POWER RATCHET TOOL/BATTERY POWER TOOL - MODULE SERVICE TOOL - DISCONNECT AND JAM REMOVAL TOOLS • BERTHING CAPABILITY • COMMUNICATIONS - CC TV - AUDIO

The assembly of the servicing facility is illustrated in Figure 6.3.2-2.

Figure 6.3.2-2 Phase 2–Servicing Support Area Assembly



The RMS will position and dock the servicing hangar base truss to the strongback. EVA crew will visually verify latch-up. The RMS will return to the staging area and remove a section of the servicing hangar track/truss. The RMS will attach the track/truss to the base truss, with an EVA crew to visually verify latch-up. This procedure is repeated for the remaining sections. The RMS will then install the carousel mechanism on the base truss and cradle support elements on the servicing track. A hard cover will be assembled around the servicing facility using the RMS with astronaut EVA support. Cabling attachments by the EVA crew will be the final step in the assembly of the servicing facility.

6.3.2.3 Phase 3 - Fuel Depot and Services Storage Facility Docking - The third phase of this TDM involves the docking and checkout of the fuel depot and installation of the servicer storage facility on the servicing strongback.

Each of these servicing elements is transferred directly from the Shuttle cargo bay to appropriate interface points on the strongback using the station manipulator. An EVA crew member will verify latch-up and connect all utility cabling. System/subsystem checkouts will then be conducted.

The major events and top-level functional requirements are listed in Table 6.3.2-3.

Illustrated below (Figure 6.3.2-3) is the transport of the servicer storage module by the station manipulator to the interface point on the strongback. The dual-armed tracked manipulator is one application of the requirement to transfer these elements from the STS to distant assembly installation points on the servicing arm.

Table 6.3.2-3 Phase 3—Fuel Depot and Servicer Storage Facility Docking

EVENTS	REQUIREMENTS
• SECOND STS DOCKS TO SS • TRANSFER FUEL STORAGE DEPOT FROM STS RMS TO SS RMS. • POSITION AND DOCK FUEL STORAGE DEPOT TO INTERFACE POINT ON STRONGBACK. EVA CREW VISUALLY VERIFIES LATCH-UP. • ATTACH FUEL STORAGE DEPOT CABLING TO STRONGBACK CABLING USING EVA CREW. • CHECKOUT FUEL STORAGE DEPOT SUBSYSTEMS. • REPEAT PROCEDURE FOR SERVICER STORAGE FACILITY.	SS • FUEL TRANSFER CONTROL CONSOLE FUEL DEPOT FACILITY • STORAGE TANK(S) MANAGEMENT DEVICES • TRANSFER EQUIPMENT FROM LOGISTICS SUPPLY TANK(S) • PROPELLANT LOADING EQUIPMENT FOR OMV • PROPELLANT TRANSFER GAUGING EQUIPMENT - CONTAMINATION MONITOR • COMMUNICATIONS - CCTV SERVICER STORAGE FACILITY • COMMUNICATIONS - CCTV • BERTHING PORTS

Figure 6.3.2-3 Phase 3—Servicer Support Area Assembly

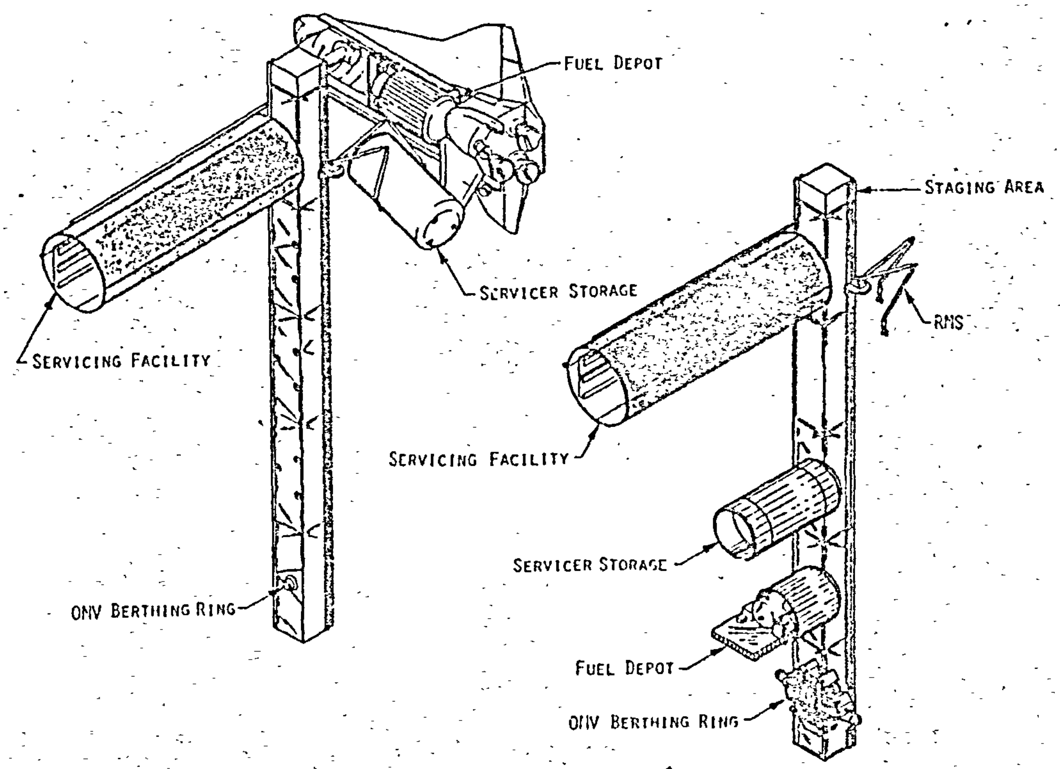


Figure 6.3.2-3 presents a conceptual Space Station satellite servicing support area containing many of the support elements considered requisite to enable servicing operations at a fully-developed early Space Station.

The support area is connected to the Space Station by a strongback support element, which provides distancing from the nucleus of the station. As shown, the servicing support area contains a central servicing facility, a fuel depot, a Space Station manipulator capable of translation throughout the area, an Orbital Maneuvering Vehicle (OMV) berthing port, and a servicer/module storage facility.

6.3.3 Conceptual Design

The conceptual design for this TDM configuration is separated into two parts: the servicing facility module designs and the assembly and construction support equipment designs. Each part has its own unique design features and interface requirements. Based on information presented in the "Space Station Reference Configuration Description" document, the conceptual design of the above items should address the following concerns identified therein:

1) Two dedicated work sites or "bays" are required: one bay is needed to perform servicing operations and the other to perform refueling operations. Several of the spacecraft serviced or repaired contain optical instruments that are highly sensitive to molecular and/or particulate contamination. Separate facilities for servicing and refueling operations are necessary to prevent possible contamination of optics.

2) This concern with the sensitivity of payload instruments to various contaminants dictates that the servicing bay be separated and/or "upstream" from the refueling and fluid storage areas, from the orbiter berthing area, and from any pressurized modules that may vent contaminants (e.g., laboratory or commercial modules).

3) The refueling bay and fluid storage area should be located so as to reduce any hazard potential to satellites being serviced, instruments/payloads externally attached to the station, or station systems such as the solar arrays or radiators.

4) An access corridor with sufficient clearance must be available for the OMV with attached payload to move close enough to the station so that the MRMS can grapple and berth the OMV and the payload.

5) MRMS access to servicing facility elements is required so that payloads may be moved between the servicing, refueling, and storage areas. Also, Orbital Replacement Units (ORUs) must be moved between the orbiter and the ORU storage area.

6) A clear translation path is needed for the movement of EVA crews between the core modules and the servicing facility elements.

7) The elements of the servicing facility will need to be provided with utilities including power, lighting, CCTV, liquid lines, and data/communications.

8) The elements which make up a servicing facility that accommodates IOC mission servicing are the following:

   a) Servicing Bay: A cylindrical volume (not necessarily enclosed) which is 30 feet in diameter and 70 feet in length. This volume allows for the berthing of a 15-foot diameter by 60-foot long satellite with clearances all around for movement of EVA crew and the placement of work stations. The servicing area will have provisions for berthing payloads either by a Flight Support Structure (FSS), which has tilt and rotation capabilities, or by trunnion latches. Moveable or reattachable berthing assemblies would permit the berthing of more than one payload in this area.

The servicing bay is attached to, and parallel with, the upper keel above the transverse boom.

b) Refueling Bay: A cylindrical volume with the same approximate dimensions as the servicing area and similar berthing mechanisms. The refueling bay is situated on the lower keel just above the radiators.

c) Satellite Storage Area: A cylindrical volume with the same dimensions as the servicing area (i.e., 30-foot diameter by 70-foot length) and with the same berthing mechanisms. (This volume is in excess of the approximate 15-foot diameter by 60-foot long volume which is actually required for storage purposes. However, allocation of the additional volume would permit this area to evolve into another servicing area for the growth station.) The satellite storage area is located across the upper keel from the servicing bay.

d) Fluid Storage Area: An area which will provide facilities for storage of propellants, pressurants, and coolants for the payloads. It is located just beneath the refueling bay at the top of the keel extensions.

e) OMV Storage Area: A cylindrical volume approximately 15 feet in diameter and 4 feet in length. The OMV storage area is situated on the keel extension just beneath the radiators.

f) OMV Kits Storage Area: Two cylindrical volumes approximately 15 feet in diameter and 4 feet in length. They are located on the keel extensions opposite to the OMV storage area.

g) ORU Storage Lockers: Each enclosed rectangular locker is 3 x 5 x 5 feet. Ten lockers will be available for ORU storage. They are placed on the power boom in board of the alpha joints for convenient access from the servicing bay.

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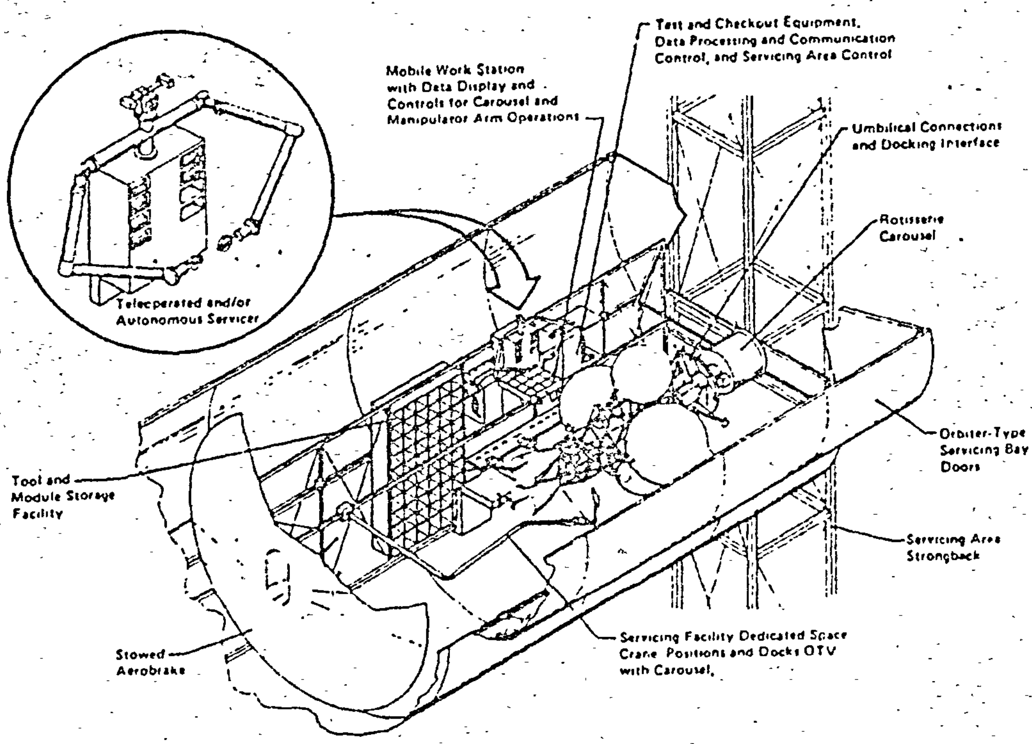
h) Payload Instrument Storage: An enclosed rectangular compartment which is 10 x 20 x 30 feet. It is situated on the lower keel opposite the refueling bay.

i) Tool Storage Lockers: Each enclosed rectangular compartment is 3 x 5 x 5 feet. Four lockers will be available for tool storage. They are located with the ORU storage lockers.

6.3.3.1 Servicing Facility Design - The far-term servicing facility design will incorporate technologies which have been developed in other applications. Figure 6.3.3-1 shows the facility with an advanced end-effector developed for use on the RMS, the Telepresence Work Station (TWS), in the 1995-1997 time frame. The TWS is discussed in Section 6.6.1.

Figure 6.3.3-1 Conceptual Space Station Servicing Facility Bay



6.3.3.2 Assembly and Construction Support Equipment - The purpose of this effort was to identify support equipment concepts with present or future application to expansion considerations for Space Station. The approach used depended on the top-level events and requirements previously shown in Tables 6.3.2-1, 6.3.2-2 and 6.3.2-3. Items on these tables were inspected to indicate those that are common to all tables and also common to equipment currently available with the Shuttle. Table 6.3.3.2-1 summarizes the types of major support equipment required in building onto the IOC Space Station. It should be noted that the overall support equipment complement needed in an operational Space Station, i.e., servicing, manufacturing, etc., could well be a subset of the total identified in Table 6.3.3.2-1. Depending on the actual Space Station and Support Module configuration, and on trade studies of concept alternatives, overlapping assembly and construction support equipment will be combined into a composite, efficient set.

Table 6.3.3.2-1 Assembly and Construction Support Equipment List

Function	Possible Equipment
- Manipulators, Fixed Base	- Shuttle Remote Manipulator
- Transporter, Mobile Base	- Rail Mounted Platform (New)
- Dual Manipulator, Attached to Rail Mounted Mobile Base	- (2) Shuttle-Like Remote Manipulators
- Portable Docking Device	- Universal Docking Unit (New)
- Aligner	- EVA, TV, Laser
- Fastener	- EVA, Manipulator, Portable Latching Tool, etc.
- Cherry Picker	- Shuttle-Manned Foot Restraints
- Tool Caddy	- Universal Tool Storage (New)
- Lighting	- Portable Lighting Unit with Cameras (Shuttle Unit)
- Rotating Base	- Carousel Mechanism (New)

6.4 LARGE SPACECRAFT AND PLATFORM ASSEMBLY

6.4.1 Description - The capability of having on-orbit assembly and construction is a valuable resource for missions involving large structures. It allows the mission to be flexible by not having the Shuttle bay limit the size and the mass of the various components. With the Space Station operational, it can store pieces and assemble major components/structures that cannot be carried on a single flight.

To obtain increased resolving power, sensitivity, and broader wavelengths, the size of the projected astrophysic payloads would have to be increased. Unfortunately, this means major components like the optical system would have to be folded (a standard practice). The autonomous deployment mechanism will be very expensive, complicated, and possibly unreliable. Modular assembly in space offers another option that is technically feasible and economically attractive. Having man assist, the structure can be simplified with the payload having reduced mass.

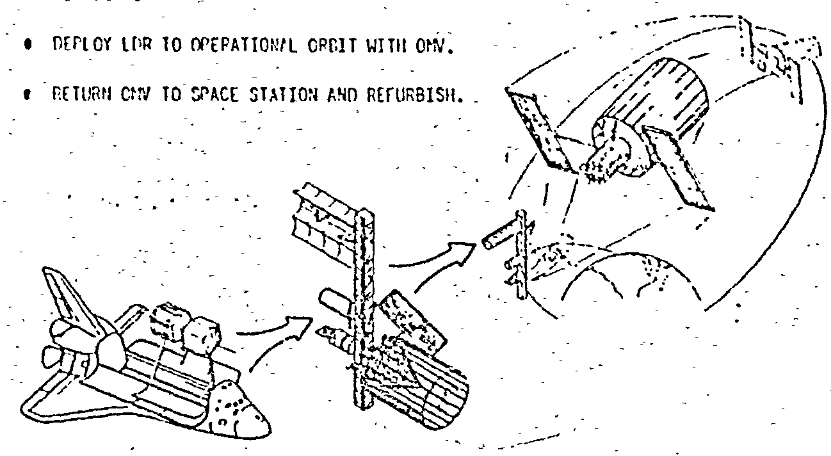
The reference mission identified in Section 6.1.3 is the Large Deployable Reflector (LDR). It will operate between the 30 and 1000 micrometer range and will be suited for observations of massive interstellar clouds associated with active star formation. This submillimeter and far infrared observatory will be in a low-earth orbit.

The assembly and construction scenario for this reference mission (LDR) is based on earlier work performed on contract NAS8-35042, "Definition of Technology Development Missions (TDM) for Early Space Station - Satellite Servicing." The specific mission identifier was TDM 4.

The major activities that must be executed for successful completion of assembling the LDR from the space station are illustrated below in Figure 6.4.1-1. These activities are separated into three phases: (1) Spacecraft Package and Primary Mirror Assembly, (2) Secondary Mirror and Sunshade Assembly, and (3) Orbital Transfer Operations. The mission selection LDR and the assembly approach depends on the assumption that a shuttle or shuttle derivative can deliver to space Station the LDR's structural elements, reflector segments and subsystem modules. There are five primary components to LDR that have to be integrated: the primary reflector and its backup truss, science instrument, spacecraft, secondary reflector, and sunshade. The modular design approach calls for the major subsystems to be physically separate during launch and assembled on orbit.

Figure 6.4.1-1 Assembly of Large Spacecraft

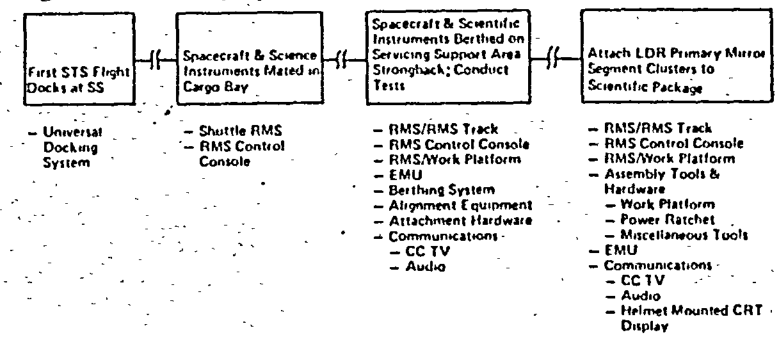
- DELIVER LARGE DEPLOYABLE REFLECTOR (LDR) STRUCTURAL ELEMENTS AND REFLECTOR SEGMENTS TO SPACE STATION IN TWO ORBITER MISSIONS.
- ASSEMBLE LDR ON SERVICE STRUCTURE STRONGBACK USING MMU AND STATION RMS/WORK PLATFORM.
- DEPLOY LDR TO OPERATIONAL ORBIT WITH OMV.
- RETURN OMV TO SPACE STATION AND REFURBISH.



6.4.2 Assembly/Construction Scenario

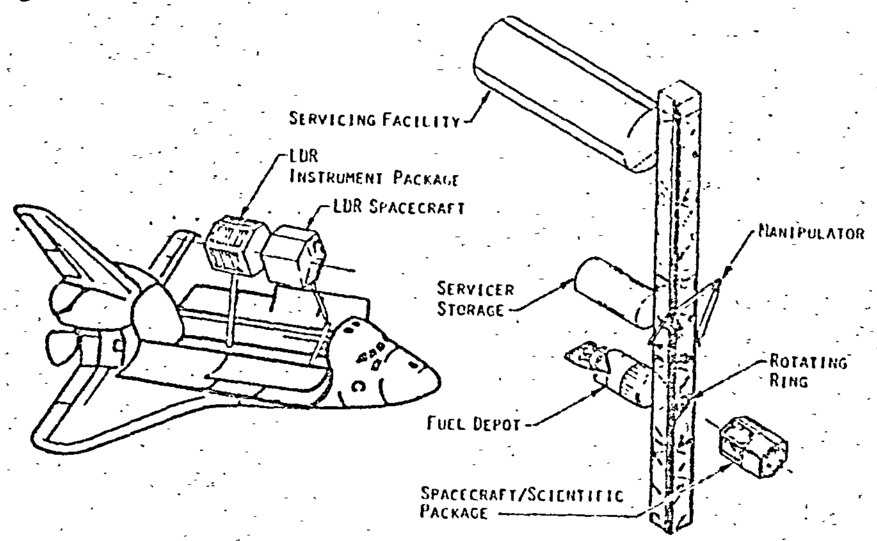
6.4.2.1 Phase 1 - Spacecraft Package and Primary Mirror Assembly - Figure 6.4.2.1-1 shows Phase 1 — the functional block flow for handling the modules from the launch stowage location in the orbit bay, through the primary mirror assembly.

Figure 6.4.2.1-1 Spacecraft Package and Primary Mirror Assembly



Initially, the spacecraft is mated to the science instrument. This could be done in the cargo bay or on the servicing support area of the Space Station. Figure 6.4.2.1-2 shows the cargo bay option in which the LDR science instruments are mated to the LDR spacecraft using the shuttle cargo bay RMS. This package is transferred to the Space Station RMS which will then transport and attach the spacecraft/scientific instrument package to the rotating ring located on the servicing strongback to aid in the assembly process.

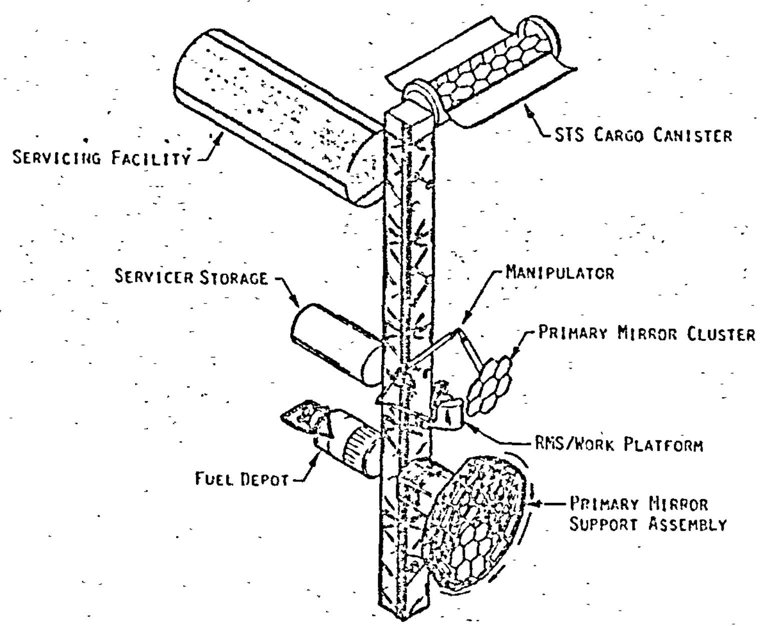
Figure 6.4.2.1-2 LDR Assembly--Phase 1 (Cargo Bay)



The most important feature in the modular design is the interfaces. They should be simple and straightforward with assembly accomplished in a controlled manner. Tests will be conducted to verify the integrity of the spacecraft mated with the science instrument. The next component attached is the primary reflector. The mirror is attached in segment clusters to a backup truss.

An assembly approach of the LDR primary mirror segment clusters is illustrated in Figure 6.4.2.1-3. The Space Station's dual arm RMS, traveling on its track network, delivers to the assembly area one of the LDR's primary reflector segments. Assembly is accomplished by astronaut EVA, with the astronaut located on a portable work platform that is mounted on the end of the RMS arm. The work platform will contain specially designed attachment tools, RMS control console and video presentations of assembly procedures. The rotating ring will be used for the assembly of follow-on segment clusters.

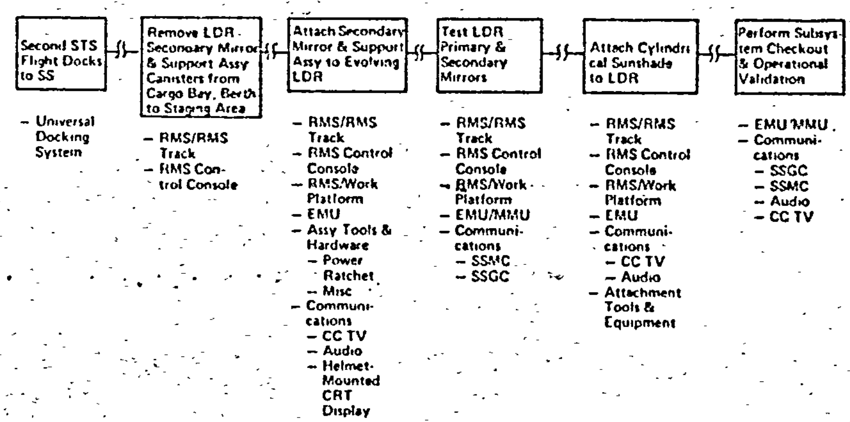
Figure 6.4.2.1-3 LDR Assembly–Phase 1 (Mirror Clusters)



6.4.2.2 Phase 2 - Secondary Mirror and Sunshade Assembly - The next Shuttle flight carries the secondary mirror. This starts Phase 2, which involves the attachment of the secondary mirror support, secondary mirror and the LDR sunshade as shown in Figure 6.4.2.2-1. The secondary mirror is attached to the primary mirror by a tripod structure. This is accomplished using Shuttle RMS/work platform controlled by astronaut in EVA operation. Assembly equipment and assembly tools are situated on the work platform. Following attachment of the secondary mirror, LDR primary and secondary mirrors are operated, evaluated and tested.

The last major component, the sunshade elements, can be attached to the primary mirror support assembly at this point.

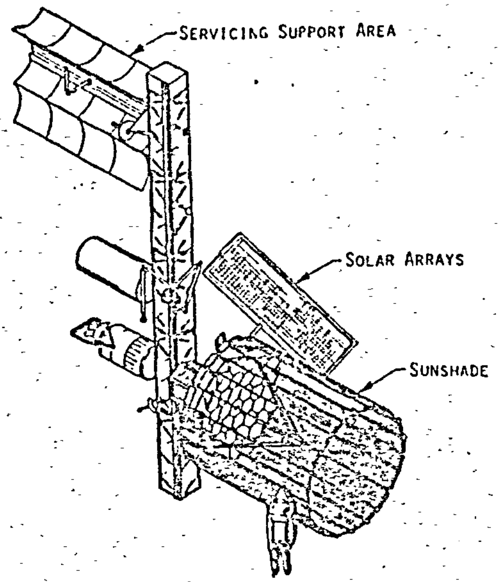
Figure 6.4.2.2-1 Secondary Mirror and Sunshade Assembly Functional Flow



The deployment of the individual sunshade elements is demonstrated in Figure 6.4.2.2-2. The initial sunshade element is deployed, by astronaut in EVA operation, and remaining elements are attached to the adjoining sunshade segment. Following completion of sunshade attachment, the LDR assembly is complete.

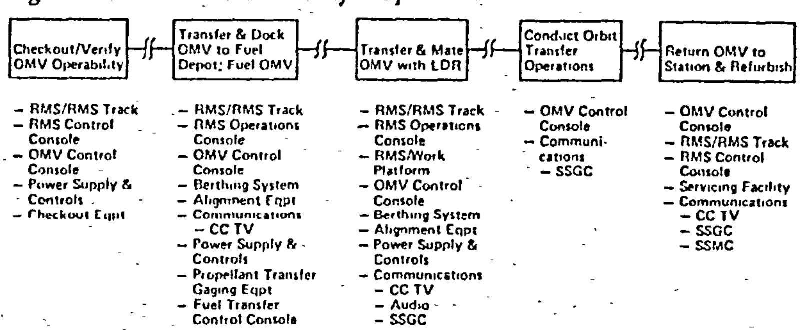
The system is checked out by performing an operational validation test.

Figure 6.4.2.2-2 Phase 2—LDR Assembly of Sunshade and Solar Arrays



6.4.2.3 <u>Phase 3 - Orbital Transfer Operations</u> - The Large Deployable Reflector is now ready to be transferred to its final operational orbit. The orbital maneuvering vehicle (OMV) is checked, refueled, and transferred to the integration facility. There the LDR and the OMV are mated as indicated by the functional flow shown in Figure 6.4.2.3-1.

Figure 6.4.2.3-1 Orbital Transfer Operation Functional Flow

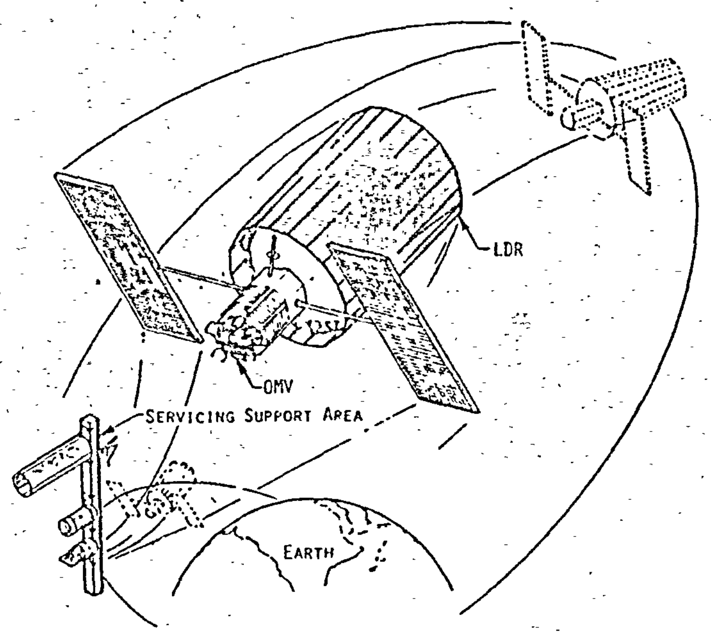


A Space Station mission control crewmember will use an RMS console to move the RMS over to the OMV berthing port and grapple the OMV. The RMS controller will then move the mated and checked-out RMS/OMV to the fuel depot for a remote refueling operation. The OMV is attached to the fuel depot and loaded with fuel/or mission load. The OMV is transported and mated to the LDR structure.

The OMV/LDR will cold-gas away from the space station to a distance of 2000 - 3000 feet to minimize contamination from the plume of the OMV main engines, and complete orbit transfer operations.

Finally, the OMV will take the LDR to operational orbit, release it, and return home to be refurbished as illustrated in Figure 6.4.2.3-2.

Figure 6.4.2.3-2 Phase 3—LDR Assembly/Deliver



6.4.3 Conceptual Design

Construction scenarios being developed reference deployable modules or tetrahedral substructures on which hexagonal mirror facets are located using a special remote manipulator. This manipulator could be the MRMS. Besides having this crane, it serves as the logistic vehicle between the cargo bay and the assembly facility. The scenario starts with the MRMS removing the scientific package, the mirror facets, and structure and delivering them to the assembly facility. The observatory instruments are attached to a "temporary" support structure that initiates the assembly. This structure permits the package to rotate about its centerline. The centerline is canted 7° to ease assembly work. The crane is important in locating the support structure on the instrument module. The frame consists of tetrahedral trusses assembled in rings with the interior rings attached to the instrument module. As sections of the support structure are completed, hexagonal mirror facets are moved from the MRMS and secured to the structure by EVA astronauts on the foot restraint manipulators. Attachment is via three points that are motor controlled for fine positioning. The instrument module pivots about the mirror axis, thus permitting the astronauts to assemble the mirror with moderate motion of the work station to which they are attached. The MRMS need only translate front and back. The 7° canted axis permits the entire mirror to be assembled with elevations of the astronaut not totaling more than three feet. One or two rings could be assembled during each revolution of the module.

Two EVA astronauts could work together in assembling the primary reflector. If the mirror panels are too bulky for two men, the MRMS crane will be able to hold them in place.

The next component to be assembled is the sunshade. The sunshade may consist of a number of tubular structural elements that are joined together by simple latch connectors. A blanket of optically opaque material connects the structural tubes. The shade is built for one side of the hexagon. As a shield is finished, it is pivoted at the mirror-shield intersection and raised by the MRMS crane manipulator. One or both EVA astronauts may be used to construct the sunshade.

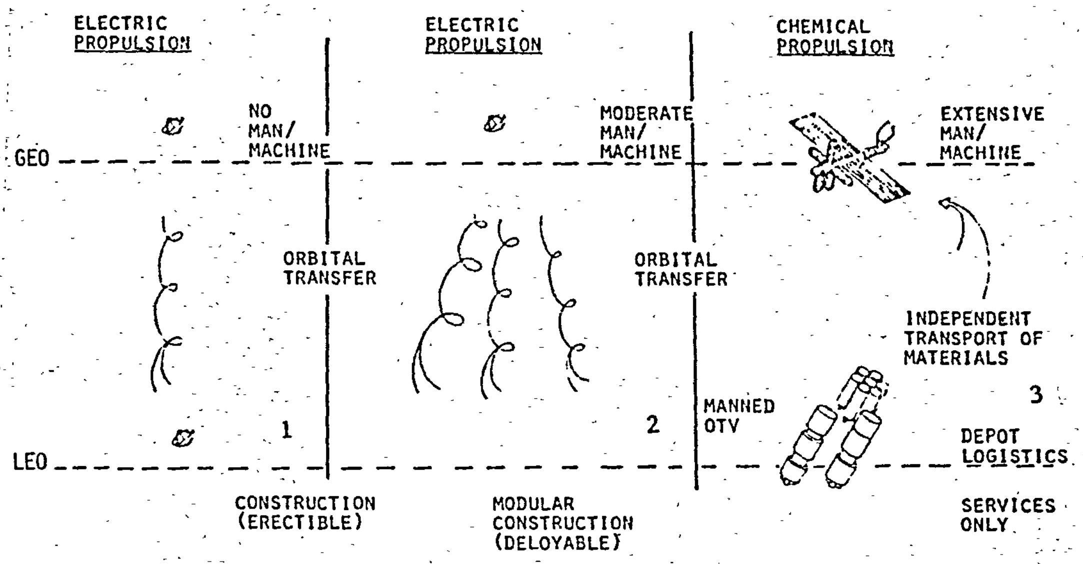
Once two sides of the sunshade are erected, the support structure for the secondary reflector can be assembled. It will consist of circular tubes, raised and locked together to form a tripod. With two legs fixed, the tripod can be rotated to its final position. With the secondary mirror in place, the remaining four sides of the sunshade can be completed. A number of studies both completed and ongoing are discussed in references 15, 18, & 31.

The MRMS crane and EVA astronauts are utilized in joining the spacecraft with the scientific instruments. After all final checks are made, the LDR is placed into orbit with the aid of the OMV.

6.5 GEOSTATIONARY PLATFORM ASSEMBLY

The assembly and construction (A&C) of a Geostationary (GEO) platform represents assembly and construction techniques that are most futuristic due to a number of new constraints. These constraints also open up a number of new alternatives for the assembly and construction spacecraft system designer to consider. Figure 6.5-1 illustrates the primary range of alternatives open to the constructable and maintainable GEO platform designer that have the greatest impact on availability of construction materials, support equipment and personnel. These are: 1) assemble or construct the GEO platform completely in low early orbit (LEO) and transport to GEO as a single unit, 2) assemble or construct the GEO platform as modules and transport to GEO where final assembly would take place, and 3) assemble and construct the GEO platform completely at GEO.

Figure 6.5-1 Construction Location Options



The A&C operational mode selected has a significant impact on construction scenarios, system designs, and program costs. A review and assessment of the above options resulted in selecting item 1 from above for further definition. Rationale for selecting 1 over 2 and 3 depended on the observation and intuition that 2 is more costly than the other reference missions; and that 3 would most likely involve humans at GEO.

A major problem in utilizing humans in GEO is the long-term effect of radiation which is minimal in low earth orbit. To reduce the radiation doses to man, a composite shield is required, comprised of a low density material to absorb electrons, followed by a high density material to deflect the Bremsstrahlung (penetrating secondary x-rays). The high energy protons resulting from solar flares present a more difficult shielding problem than electrons. Therefore, a strategy based upon solar prediction, coupled with a well-shielded area of retreat, may be applicable. The effects of radiation are cumulative with time. The longer a crew is on orbit and the more time spent in suited EVA, and the less protection received from the EVA suit, the more protection the habitat must provide. The added impact of the shielded habitat being transferred to GEO is an extremely high cost item and should be compared against a teleoperation control mode from ground.

6.5.1 Description

The reference mission selected to represent this cases is an advanced commercial communications system configured as a single large communications satellite in geostationary orbit. (3) Its purpose is to interconnect approximately 25 million users anywhere in the U.S., direct from user-to-user through wrist-sized radio telephones, according to the "NASA Space Systems Technology Model," Volume III, fifth issue, dated January 1984. This specific mission is covered under the section called Landmark Missions and identified as LM-7. This is a fairly large satellite in that it measures over 500 feet from tip to tip, with an antenna that must measure between 230 to 330 feet in diameter.

The satellite is expected to weight 30,000 kg, have a 300 kw solar cell power system, and transfer itself to GEO following assembly and checkout at a LEO Space Station.

Large platforms of this type will require two or more Shuttle launches to place their components in LEO. It is proposed that by the time this system is launched it will be assembled by human-like machines (intelligent manipulators) with astronauts as contingency backups. Once completed it will be propelled to GEO using relatively low thrust chemical rocket engine or electrical propulsion (EP) systems. The advantage of an EP system is the large electrical power source on board needed for communications would power ion engine to perform the transfer. Once the operational orbit is reached, these ion engines could be rotated to serve for on-orbit attitude and stationkeeping translational control. Also, the modular configuration required of the electronics to allow unmanned repair in the operating orbit lends itself well to initial assembly by similar unmanned systems.

6.5.2 Assembly and Construction Scenario

Since this satellite represented a future capability the assembly site selected is based on a LEO Space Station configuration that may either be manned or unmanned.

The scenario proposed is separated into three phases: a) initial GEO platform assembly of satellite at a LEO Space Station base, b) checkout and deploy modules to GEO, and c) activate in GEO at satellite operational site.

The major activities and functional steps required to execute the assembly portion of this mission are listed in Table 6.5.2-1.

Table 6.5.2-1 Overview of Satellite Assembly

Activity Events Sample	Assembly Support Equipment
- Position Rotating Base on Assembly Fixture	- Work Station and Adjustable Rotating Platform
- Remove Package* from Payload Bay	- RMS Access and Working Envelope
- Transport Packages	- MRMS
- Assemble Base Support Structure	- Advanced MRMS
- Deploy Package Sections and Attach or Attach Deployable Sections to Structure and Deploy	- Advanced MRMS/MMU
- Remove and Setup Antenna Surface Alignment and C/O System	- MRMS-TWS
- Rotate Structure as Required	- Remote Control Console
- Attach Space System Support Modules and C/O Electronics	- MRMS-TWS
- Release from Assembly Support Structure	- MRMS
- Deploy from Space Station and Perform Final c/o Prior to GEO Transfer	- OMVs and MMUs

*Packages consist of deployable structures, and modules, i.e., subsystems and major components.

The assembly overview includes removal of folded deployable antenna sections and support elements from the cargo bay. Transfer to the assembly site where these elements are deployed to full extension (by a dual-armed manipulator or by dual MRMSs moving in opposite directions along the keel length) and positioned and attached at the proper location. The same or similar steps are repreated until assembly is completed.

6.5.3 Conceptual Design

Figure 6.5.3-1 shows a visual representation of the satellite on its rotating support fixture that in turn is mounted on the large space structures assembly support beam. This beam runs perpendicular to the main keel structure. This configuration provides greater flexibility in adjusting to various satellite diameters and also provides a worksite with greater compatibility to a standardized manipulator reach. Also, due to the overall length of this satellite (+500 feet), it may be necessary to have a separate co-orbiting space platform for assembly of the structure. Some large space structures have unique satellite characteristics that make it difficult to assemble satellites with high accuracy optics and large antennas in the current Space Station environment. For example, a co-orbiting platform separated from the Space Station could provide an assembly environment with lower contaminants, lower vibration disturbances, greater worksite flexibility, and be able to accommodate large satellites. For additional information see reference 30.

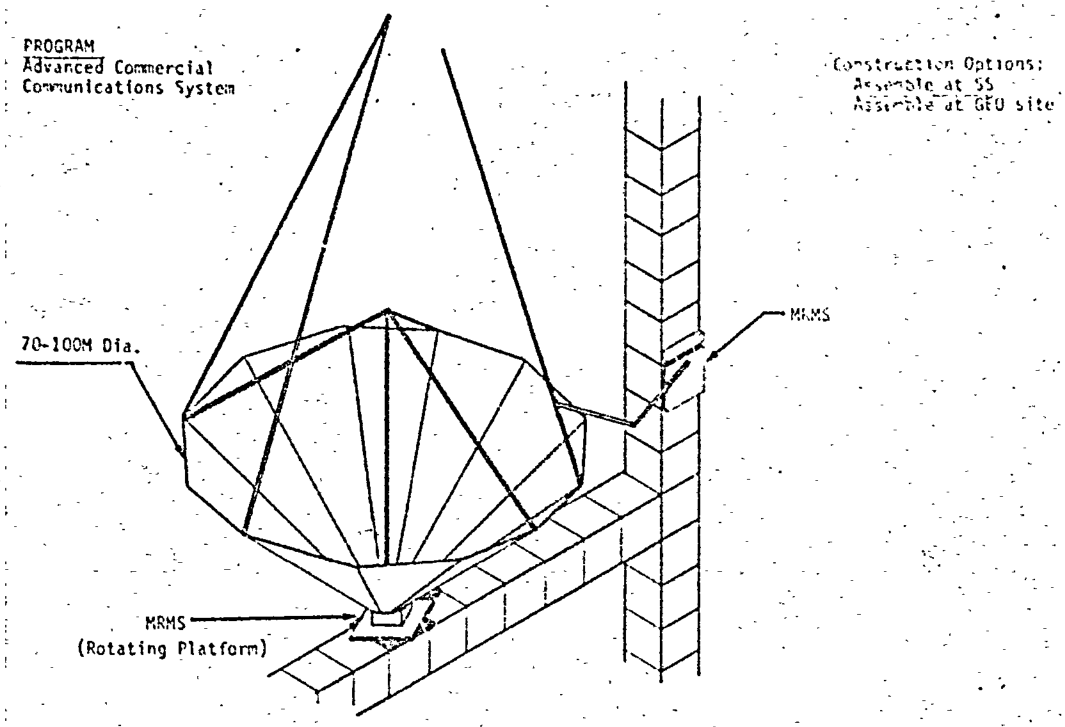


Figure 6.5.3-1 Geostationary Platform Assembly

6.6 ANALYSES

This section provides a collection from prior sections on analyses trade studies relevant to the Mobile Remote Manipulator System (MRMS) design characteristics and utilization concepts. Also, a analysis of the commonality of general assembly and construction hardware with respect to the four reference mission models is described. The commonality provides the basis for the automation assessments presented in subsequent sections. The initial cut at a common list of ACSE is presented in Table 6.6-1.

Table 6.6-1 Summary of Assembly Construction Support Equipment Candidates

Primary Support Equipment Candidates

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. Mobile Foot Restraint (MFR - Shuttle)
7. Closed — Cherry Picker
8. Universal Docking (Berthing) Unit
9. Fasteners (Inherent in Design)
10. Fastener Tools, (clamp, weld, rivet, etc)
11. Universal Tool Storage Unit
12. Portable and Mobile Lighting/Camera Unit
13. Portable Control Box/Pendant
14. Special Function Manipulators (5-DOF or Less)
15. Carousel Mechanism (Satellite Assem Fix)
16. Structure Deployment Aid
17. Alignment and Surface Accuracy Tools (Gross)

Table 6.6-1 (concl)

18. Alignment and Surface Accuracy Tools/Sys (Fine)
19. Checkout Tools, (Mechanical, Electrical and Data)
20. Portable Deployable Sun Shade
21. Special Purpose End Effectors (Manipulator Exchange)

6.6.1 MRMS and Other Trade Studies

The MRMS, as described and illustrated earlier in this section, consists of three basic elements or layers; level 1 is the track layer, 2 the central element and the top layer is the logistics platform. The following study data are functionally organized by the MRMS elements.

6.6.1.1 Track Layer -

a) Track Concepts - The present concept envisions a set of two parallel tracks the size of the IOC space station cube structure elements (see Fig. 6.6.1.1-1). The tracks are designed to slide on pins located at the nodes of the structure.

The MRMS must be attached to the structure on which it is working because it has no free flying capability. The IOC structure is proposed to be composed of tubing and there are several attachment options as shown in Figure 6.6.1.1-2.

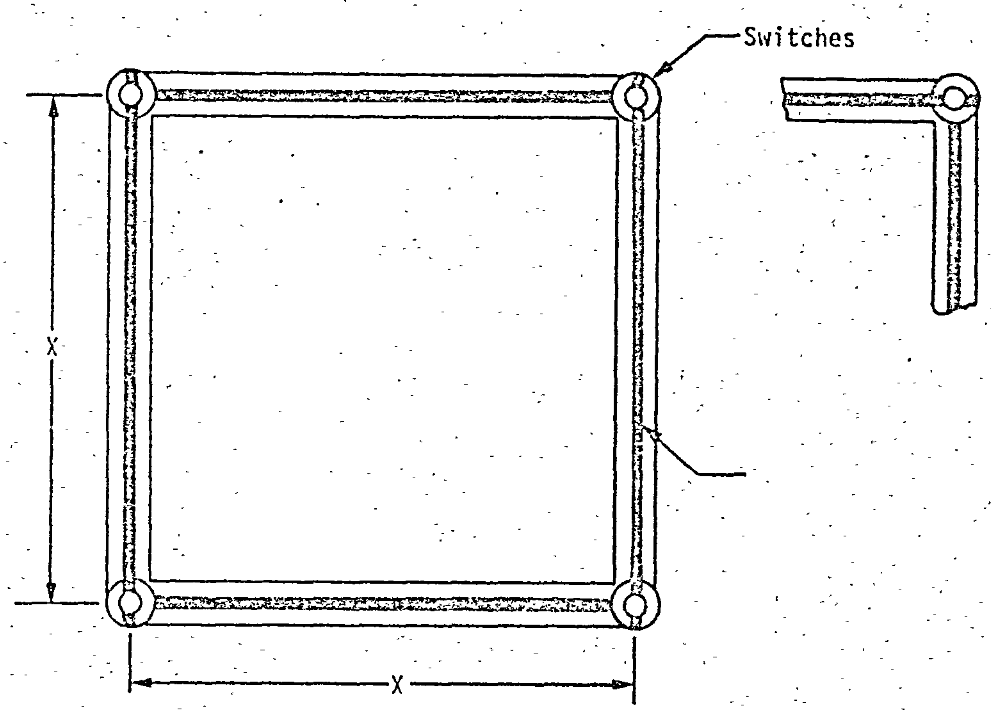


Figure 6.6.1.1-1 MRMS Track Layer

The first (top) concept shown in the Figure is the leading choice for attaching the MRMS to the structure. Most of the other concepts have problems with moving in the required two orthogonal directions. The addition of the pins at each node minimizes the weight and modification needed to the existing structure concept. Adding tracks to the structure would result in significant weight problems.

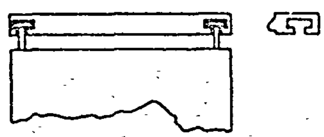
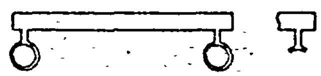
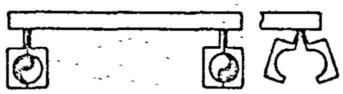
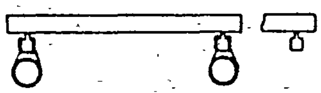
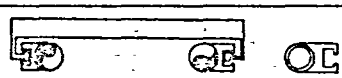
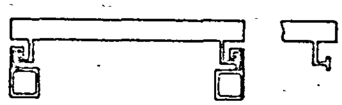
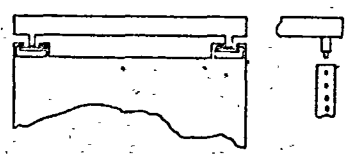
ATTACHMENT	COMMENTS
	ADVANTAGE-Lightweight Vehicle Minimum Modification To Structure
	ADVANTAGE-Lightweight DISADVANTAGE-Special Track Tubing Problems In Changing Directions
	ADVANTAGF-No Nodes Or Modifications To The Structure DISADVANTAGE-Grasp & Release Several Times To Change Directions
	DISADVANTAGE-Extra Mass To The Structure
	DISADVANTAGE-Inability To Change Planes
	DISADVANTAGE-Same As Above
	DISADVANTAGE-Added Mass And Complexity To Structure

Figure 6.6.1.1-2 Attachment Technique

The ability to move normal to its facing direction is accomplished through the use of switches at the corners of the track structure. By turning all joints 90°, the tracks are realigned to move in that direction.

b) Node Shapes - The shape of the nodes varies with the mating track as shown in Figure 6.6.1.1-3.

The node should be flat with a stem diameter equal or greater than the radius of the top disk. With the surfaces of the head and track parallel, the vehicle will be totally captive with good overlap of mating parts. The corners should be slightly rounded to reduce binding problems due to misalignment.

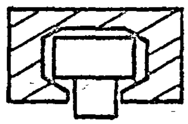
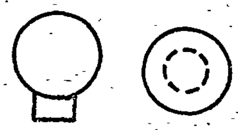
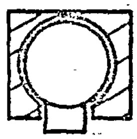
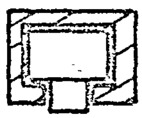
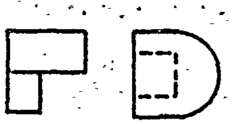
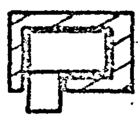
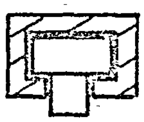
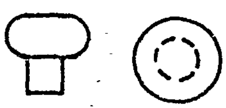
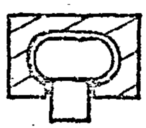
NODES	TRACK	COMMENTS
		Due to bevels, the edge of the nodes wear due to point contact instead of surface contact
		Not enough surface area to retain good attachment
		High stress concentration at the intersection of the stem and the head
		Non-symmetrical shape makes attachment difficult when moving in a orthogonal direction
		Contact surfaces are flat, increased area contact and friction
		Rounded corners, easier for track to slide on without binding from misalignments

Figure 6.6.1.1-3 Node Shape Options

The passing of tracks over nodes is the most feasible concept for the attachment of the vehicle to the structure, but it is also a function of the drive mode (level 2). Currently, the addition of nodes is the reference configuration.

The IOC structure is made up of 9-foot length cubes. As a result, the track lengths including switches are 9-feet long. The length of the tracks will determine the tolerances between the node and track. Thermal gradients will tend to twist the tracks. There is never a case when there is more than one node on a single track section.

c) Rolling Motion Concept - The above node and track concepts involve a sliding motion between the track and the node. A possible alternative would be incorporation of a technique using rolling motion, as shown in Figure 6.6.1.1-4.

The rolling contact will reduce friction and wear on the system, but also adds a greater degree of complexity.

Lubrication at the sliding interfaces will help reduce friction build-ups and temperature hot spots. The lubrication will be either a sealed fluid or a dry type that is a space qualified technique.

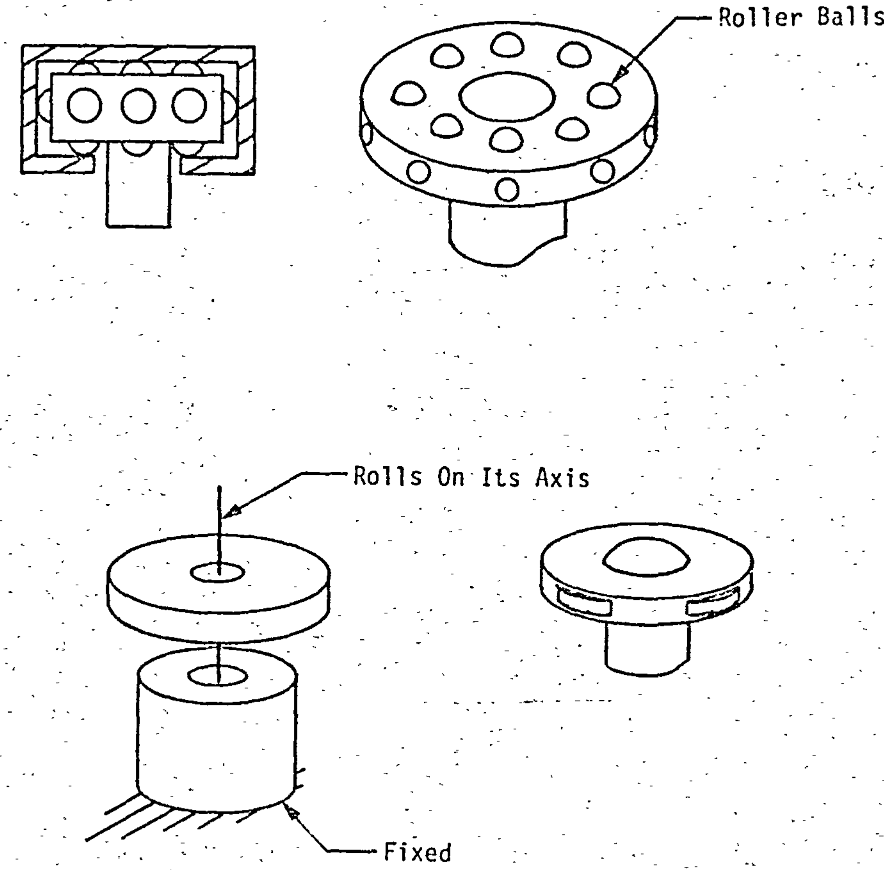


Figure 6.6.1.1-4 Rolling Motion Concepts

d) Corner Switches - The switches at each corner of the tracks will rotate a minimum of 90°. By rotating each of the four corner switches in the same direction, it allows the nodes to switch from one set of tracks to the other.

When work is being done by the upper level crane or positioning arm, the stability of the tracks or its ability to stay rigid in relationship to the structure is important. The switches need to be locked to the node. This can be done by a cam arrangement such that as the switch turned, it would tighten at some point beyond the 90° rotation. Table 6.6.1.1-1 compares the motor control technique for each corner switch.

Table 6.6.1.1-1 Corner Switches Motor Control Comparisons

Mode of Control	Comment
One motor controls all four switches	- One motor controls all switches simulateously through linkages - All four switches turned in same direction - If one switch binds, everything binds
One motor controls a pair of switches	- No advantage over one motor per four switches - Both pairs must be controlled in unison if the vehicle is to move in the orthogonal direction
Individual motors on each switch	- Fine adjustment of each switch to change orthogonal direction - The capability to adaptively tighten its grip on the individual node; e.g., the movement produced by the crane may require the front two switches to be fixed rigidly whereas not the back switches.

There is no advantage in having only two motors. One motor for each switch has the capability to adjust the grip on each node, but if the control for one of the motors fails, the vehicle would not be able to change direction. The same is true for the one motor mode when a switch fails to turn. In either case, the MRMS would have to be repaired. A redundancy can be built into the one motor system by adding a backup motor. There is a tradeoff between redundancy and added mass.

Sensors will be needed both internally and externally to the switches. The internal sensor input will be the pointing direction of the switches. The external sensor will determine the relationship between the switch and the nearest node.

6.6.1.2 Central Element - Level 2 is the drive layer. There are a number of possible drive techniques as shown in Table 6.6.1.2-1.

Table 6.6.1.2-1 Drive Technique Alternatives

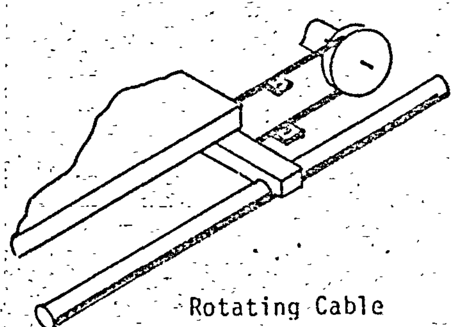
Type of Drive	Amount of Scar	Advantages/Disadvantages
Push/Pull – Draw bar pulls out and attaches to next set of nodes. Once attached, draw bar will pull entire vehicle.	Nodes on structure joint	+ Very light & compact + Minimum scar – Size determined by structure – Not very fast
Wheeled-vehicle rolls about structure surface	Method of attachment must be revised to conform to rolling vehicle. Need tight tether or rail for attachment.	+ Very fast movement – Complex mechanism for stability – Problem changing Direction
Rotating cable or chain that latches	None for movement but possibly for attachment	+ Fast movement – Length of rotating device dependent on truss dimensions – Complicated mechanism
Robotic crawler reaches and position itself to move	None	+ No scar – Not very fast – Complicated – Heavy

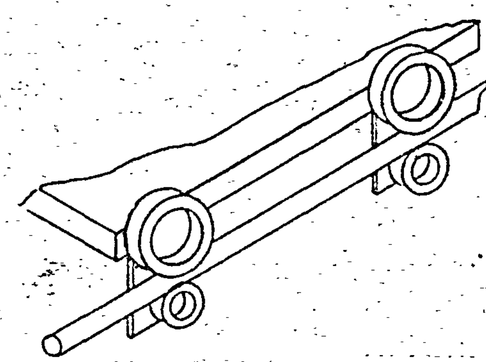
The drive level is the means by which the vehicle moves about a structure. One basic requirement for the space station IOC is that the vehicle has the capability for movement in two orthogonal direction.

Figure 6.6.1.2-1 Other Drive Techniques

1) Reference Drive Configuration - The push/pull system is the reference drive configuration from the Langley paper on a Mobile Remote Manipulator System. The drive system consists of a drawbar attached to the vehicle by a set of gear racks driven by a DC motor. The drawbar is extended to the next set of nodes where the base is locked. By pulling the bar in via the DC motors, the entire vehicle is pulled forward.

2) Alternate Drive Concepts (see Figure 6.6.1.2-1) - A wheeled vehicle would be motor driven with propulsion accomplished by friction between wheel and structure. A device would have to be developed to hold the wheels in contact with the structure.





The rotating belt is a pulley system that would be deployed to a minimum length of two bays. It is very similar in concept to the push/pull scheme. As the latches on the belt catch the next cross struts, the vehicle is pulled forward to that point. It would repeat the scenario on the next cross strut.

The fourth mode is a crawler. With a minimum of three arms, the crawler would systematically move one arm at a time to a new reference configuration forward. By attaching and releasing, it would work its way forward.

The push/pull reference configuration is the least complicated drive. It is well suited to a space station truss type structure and has many advantages as noted in Figure 6.6.1.2-2.

MRMS DRIVE MODES	IMPACT ON WEIGHT OF STATION STRUCTURES	COMPLEXITY IN ERECTION OF STATION STRUCTURE	IMPACT ON WEIGHT OF MRMS	IMPACT ON STORAGE VOLUME IN ORBITER	FREEDOM OF MOVEMENT OF DRIVE SYSTEM	RATE OF MOVEMENT OF DRIVE SYSTEM	MAINTENANCE	RELIABILITY	PLANE CHANGE CAPABILITY	VERSATILITY
•PUSH-PULL MOTION	Positive	Positive	Negative	Neutral	Neutral	Neutral	Neutral	Positive	Neutral	Neutral
•WHEELS THAT DRIVE ON A RAIL SYSTEM	Neutral	Negative	Negative	Neutral	Neutral	Positive	Neutral	Positive	Negative	Neutral
•MOVING CHAIN, CABLE, OR BELT THAT CARRIES THE VEHICLE.	Negative	Negative	Positive	Positive	Negative	Positive	Neutral	Neutral	Negative	Negative
•CRAWLING MOTION WITH LEGS THAT GRASP AND WALK ABOUT A STRUCTURE	Positive	Positive	Negative	Negative	Positive	Negative	Neutral	Negative	Positive	Positive

POSITIVE EFFECT NEUTRAL NEGATIVE EFFECT

Figure 6.6.1.2-2 Drive Mode Effects

The drive system is built above a roll drive in which the MRMS can move orthogonally to its present direction by rotating the drawbar 90°. The track system is designed to rotate the corner switches when the vehicle is required to move in that direction.

c) Spanning Rates - The one area that is not optimal is the spanning rate of the push/pull drive. A scenario and predicted spanning rate of the reference drive is shown in Figure 6.6.1.2-3 as compared to two other methods--a rotating beam design or a inch-worm design.

VEHICLE	PATTERN OF MOVEMENT	SCENARIO	PREDICTED RATE IN SPANNING 400 FT.
PUSH-PULL	1 2 3 4 5 ONE CUBE AT A TIME	o LOCK DRAWBAR o PUSH PLATFORM FORWARD o LOCK PLATFORM o RETRACT DRAWBAR	PUSHING TIME - 80 MIN. LATCHING TIME - 45 MIN. (45 BAYS) TOTAL - 125 MIN.
ROTATING BEAM	2 3 6 1 4 5 ONE WIDTH AT A TIME	o LOCK END o PIVOT ASSEMBLY o LOCK OPPOSITE END o PIVOT ASSEMBLY	SWING TIME - 33 MIN. LATCHING TIME - 90 MIN. (45 BAYS) TOTAL - 123 MIN.
1ST PLATFORM 2ND PLATFORM INCH-WORM	ALTERNATIVE FIVE BAYS AT A TIME	o LOCK FIRST PLATFORM o REMOVE SECOND PLATFORM o EXTEND ARM o REPLACE SECOND PLATFORM AND LOCK o REMOVE & RETRACT FIRST PLATFORM	ARM TIME - 67 MIN. ALIGN & LOCK TIME - 32 MIN. TOTAL - 99 MIN.

Figure 6.6.1.2-3 Spanning Rates of Different Modes of Movement

From the predicted spanning rates, the push/pull vehicle would require the most time. The rotating beam is a little faster, but sacrifices storage space and stability. The inch-worm drive is 20% faster and takes advantage of the 50-foot reach of the RMS. Unfortunately, the second platform takes up considerable space and weight in the Shuttle cargo bay.

The rate at which the push/pull drive travels is a function of the mass of the vehicle, the torque advantages of the rack and pinion, and the size of the DC motors.

d) Alignments - The gear rack supports the drawbar. It must be sufficiently rigid such that the box section does not twist to throw off the alignment of the drawbar and nodes. Its mass and alignment when sliding is supported by bearing surfaces.

Alignment of the drawbar with the node is critical. The relationship of one node to the next is known. When the drawbar is fully extended, it should activate a limit switch and be situated on top of the node. Sensors in the motor will verify the location of the drawbar. Both the drive pin and node opening should be beveled to facilitate mating. A sensor will indicate when the pin is locked and the platform is about to move. The entire push/pull procedure should be automatic. The only possible human interaction will be to determine the direction of movement or as an override in case of a malfunction in the drive. The direction of movement can be automated by having knowledge of the desired path. The same is true for any malfunction where a self-diagnosis and reset/repair will allow the vehicle to automatically continue.

6.6.1.3 Logistics Platform - The third level is the logistics plane. It will contain a storage platform with an RMS crane and possibly positioning arms. The platform will initially be a flat deck, 9-feet by 9-feet. Centered on one edge will be the crane. Having the crane on an edge opens up the entire center for storage.

a) Cargo - Some of the packages transported on the MRMS during the space station IOC buildup are listed in Table 6.6.1.3-1.

Table 6.6.1.3-1 Space Station Elements

FLIGHT	MAJOR SPACE STATION ELEMENTS
I	*REMOVAL OF MRMS BY SHUTTLE RMS
II	-LOWER KEEL, PORT KEEL EXTENSION, LOWER BOOM, CLOSEOUT, AND BERTHING STRUCTURES
	-MAIN RADIATOR BOOMS
	-MAIN RADIATOR PANELS
	-RCS
III	-HM1 (HABITATION MODULE 1)
	-AL1 (AIRLOCK 1)
	-AL2 (AIRLOCK 2)
IV	-HM2 (HABITATION MODULE 2)
	-UPPER KEEL AND UPPER BOOM STRUCTURE
	-ANTENNAS
V	-LOG1 (LOGISTIC MODULE 1)
	-PORT AND STARBOARD SOLAR ARRAY WING PAIR
	-PORT AND STARBOARD OUTBOARD TRANSVERSE BOOM STRUCTURE
VI	-LAB2 (LABORATORY MODULE 2)
	-EQUIPMENT SPARES
	-EXTERNAL EXPERIMENTS
VII	-LAB1 (LABORATORY MODULE 1)
	-EQUIPMENT SPARES
	-EXTERNAL EXPERIMENTS

The radiators, booms, and arrays are long instruments that are deployable. Of all the packages, the modules and the experiments are the largest and the most awkward. The logistics module is approximately 14 feet in diameter and 42 feet long. Examples of external experiments are shown in Table 6.6.1.3-2.

The OTU servicing technology mission is the largest package, having dimensions 65 feet by 30 feet by 30 feet and weighing up to 1760 pounds. It would have to be deployed and assembled in space due to the limitations of the cargo bay dimensions. Depending on the size of the various subassemblies, the subassemblies might be larger than the logistics surface. An option is to pull an extra MRMS without its crane or positioning arms. This would effectively double the storage area.

C-2

Table 6.6.1.3-2 Example of External Experiments

EXAMPLE OF EXTERNAL EXPEPIMENTS		
MISSION NAME	EXTERNAL DIMENSIONS	WT.
EARTH OBSER-VATION INSTRU-MENT TECHNOLOGY	10Mx10Mx2M	300KG
SIRTF	8.5Mx4Mx4M	400KG
OTV SERVICING TECH	20Mx10Mx10M	800KG

b) Structure - The MRMS must carry heavy loads, yet be light and flat as possible for storage in the Shuttle bay. The structure must be stiff enougth to react the moments produced by the crane.

A variety of materials are candidates for the storage platform and surface. A stiff material is characterized by a high modulus of elasticity and a high area moment of inertia. The density should be reasonably low to avoid excessive weight.

c) Storage Rack - The storage rack must be as adaptable and generic as possible. Thus, a flat top perforated with attachment holes and a honeycomb type structure are ideal candidates. There are a number of ways to attach the cargo to one surface. Some examples are shown in Figure 6.6.1.3-1, assuming box-type cargo elements.

However, long, thin beams and airlocks require a different type of attachment. The platform should be basic, with unique items requiring specialty interfaces.

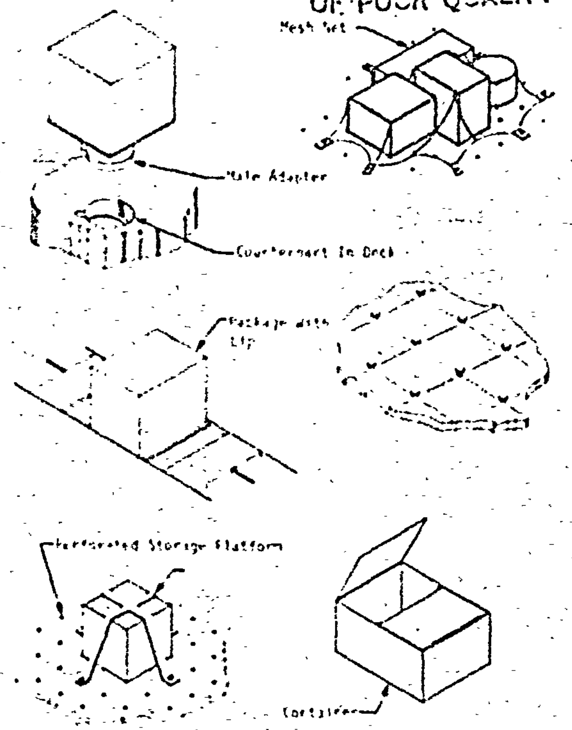


Figure 6.6.1.3-1 Cargo Attachment Techniques

The layout of the various modules is important with the loads evenly balanced on the platform. Excessive overloads could bind a track or make alignment of the drive pin impossible. The removal of an item should not shift the CG excessively. The layout is also dependent on the reach envelope of the crane and the positioning arms. Interlocks or tethers would insure that the packages remain firmly secured.

d) <u>Drive System</u> - Built into the logistics plane is a roll drive. The platform can be rotated to some position that will give the crane or positioning arm its maximum reach. The added degree of freedom is like adding an extra joint to the arms.

Both the logistics platform and the drive system rotate relative to the track layer. By attaching the push/pull mechanism to the platform the number of roll drives can be consolidated. There is no problem having the crane/arms rotate when the drive mechanism moves to change direction and vice versa. There should be a manual release in which the drive layer can be decoupled from the platform.

The roll drive fixes the platform to the track layer. With the drawbar extended and free to rotate, the crane can turn the drive layer to any position. An internal sensor like an absolute resolver should be used to monitor the position of the drawbar and return it to a predefined home position.

6.6.1.4 MRMS Manipulators -

a) RMS - The shuttle is equipped to carry two RMS arms. One arm will be detached, transferred to the MRMS storage platform, and reattached. The length of the arm from shoulder to wrist is a little over 50 feet long. The RMS is shown in Figure 6.6.1.4-1.

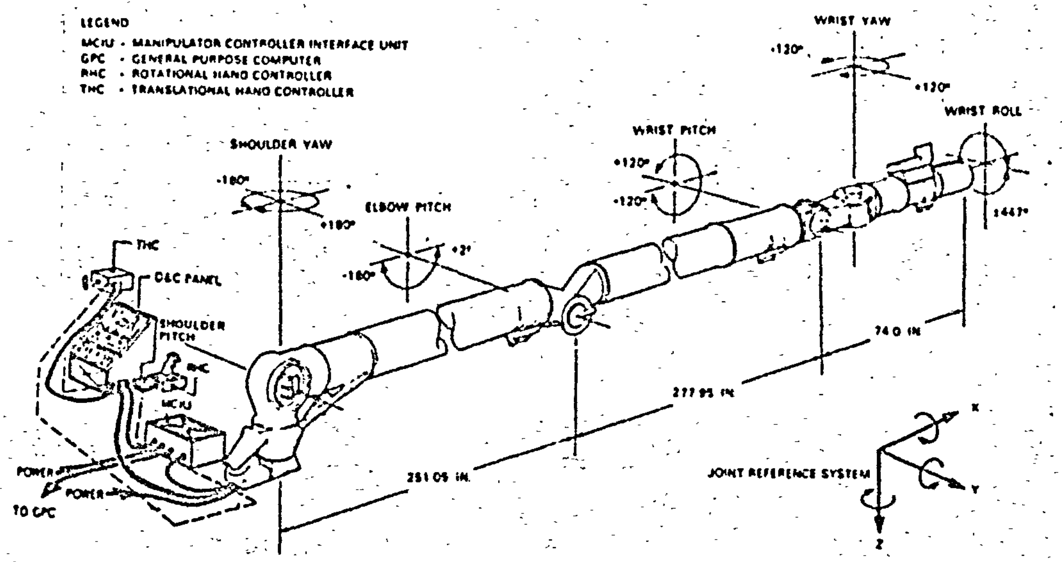


Figure 6.6.1.4-1 Space Shuttle RMS

The 6-DOF RMS is capable of handling any cargo transported in the shuttle bay. The maximum dynamic envelope of cargo is 15 feet in diameter and 60 feet in length. The RMS is designed to routinely handle 32,000 pounds and 65,000 pounds in contingency.

All the RMS drives are geared-electrical DC motors. Two hand controllers are used; a rotational hand controller (RHC) and a translational hand controller (THC). Each joint is backdriveable with brakes activated to hold a position. The RMS is a tested, proven and available hardware for immediate use, but this does not restrict the MRMS into only using an RMS. It could also use an existing arm, with or without modifications, to fit a particular need.

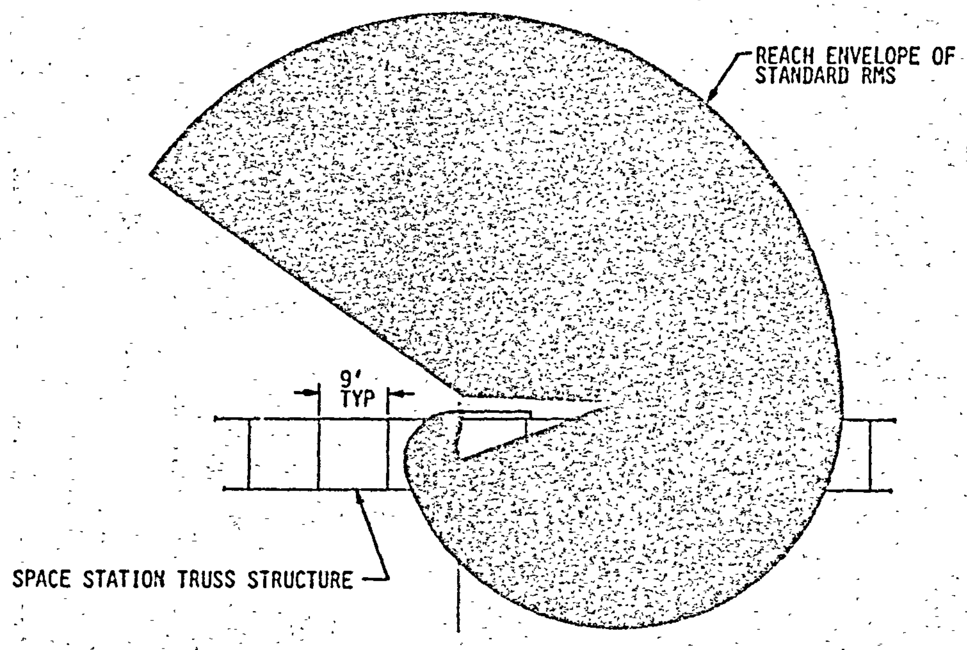


Figure 6.6.1.4-2 RMS Reach Envelope

Figure 6.6.1.4-2 shows the reach envelope of a standard RMS. The RMS is capable of servicing six cubes of the truss structure without moving. There is a cone shaped void close to the vehicle that cannot be reached. The positioning arms (paragraph c below) can fill this gap or the work can be planned to be done two bays away from the vehicle.

A modification of the shoulder joint can improve its overall reach envelope, especially close to the structure. This modification would require off-setting of the shoulder pitch drive beyond the edge of the logistics platform. As a result, the arm would be allowed to hang straight down and make access to the bottom of the truss feasible. This offset is illustrated in Figure 6.6.1.4-3

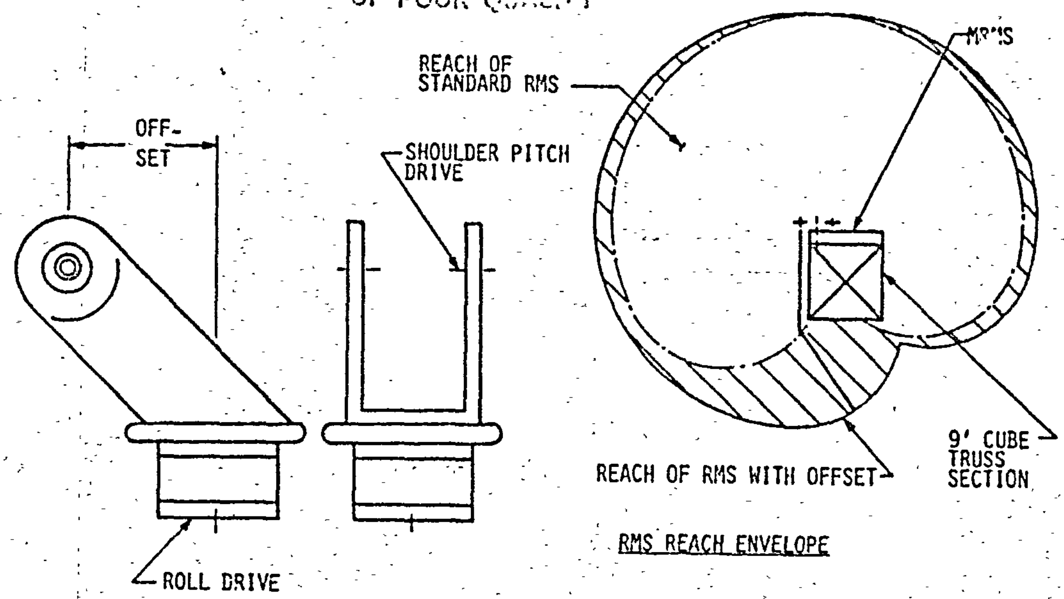


Figure 6.6.1.4-3 RMS Offset Reach Envelope

b) End Effectors - The present configuration of the RMS uses a snare type device for the end-effector. There are a variety of different end-effectors that can be interchanged with the snare device. Figure 6.6.1.4-4 depicts two other end effectors that mate with particular grapple targets.

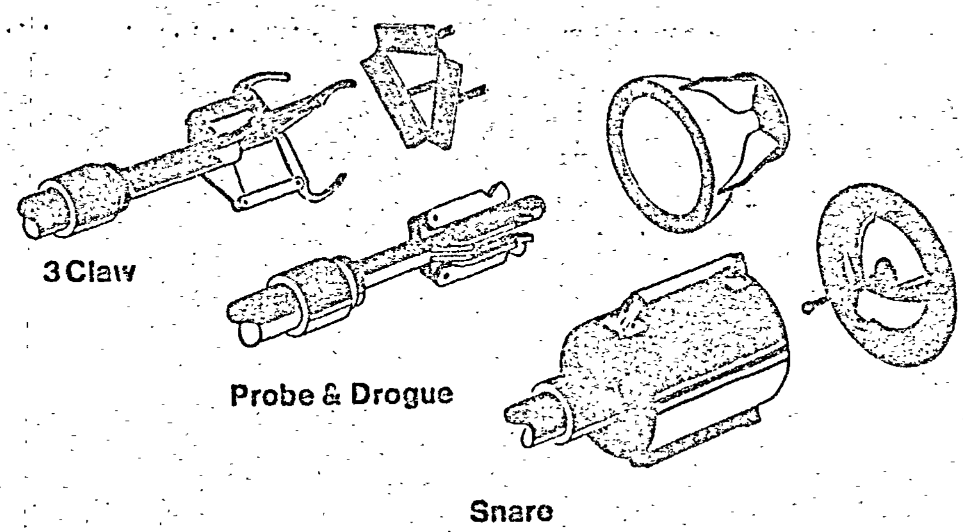


Figure 6.6.1.4-4 RMS Grapple End Effectors

The end effector for the crane will be a general purpose open/close device. Its main objective will be to pick up, hold, and position the various cargo packages.

Sensors are needed at both the end-effectors and at the systems level. Cameras are needed for looking at the gripper. Proximity sensors along the length of the crane will help in obstacle avoidance. Each joint of the crane needs velocity and position data.

c) <u>Positioning Arms</u> - The robotic positioning arms are attached to two adjacent sides of the crane on the logistics platform. The arms are located parallel to each other such that they will straddle the IOC cube structure. The positioning arms place work stations in strategic locations to obtain maximum accessabilty to job sites.

The two positioning arms are assumed identical. If one arm was considerably longer than the other, their ranges would overlap and create a versatile system.

Depending on arm length and joint limits, voids are created where the arm cannot reach. As a result identical tasks on both sides of the vehicle might intersect one void and miss another. Having two identical arms also reduces the amount of spare parts needed. Past studies have also shown the need for both the upper and lower arm segments to be identical in length. Joint-to-joint dimensions for an arm segment should be a minimum of 10 feet long to be able to reach the underside of the space station box trusses. The joint orders of the positioning arm and crane are shown in Figure 6.6.1.4-5.

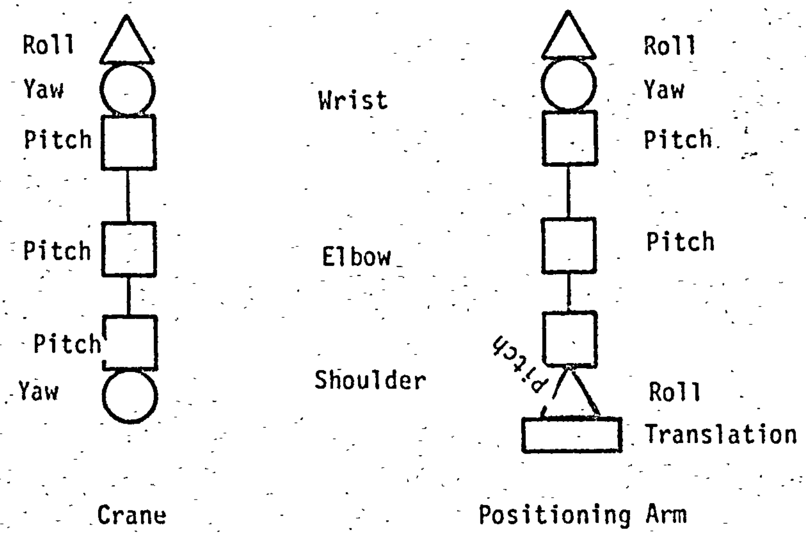


Figure 6.6.1.4-5 Joint Orders

The joint configuration of the positioning arm is similar to the crane except for the shoulder. The positioning arm has an additional translation feature that allows the arm to move across the edge of the logistics platform. Between the translation drive and the pitch drive is a shoulder roll. The advantage in having a roll drive is that it can turn the shoulder pitch into a shoulder yaw by rolling the arm 90°. A reach envelope of the arms is shown in Figure 6.6.1.4-6.

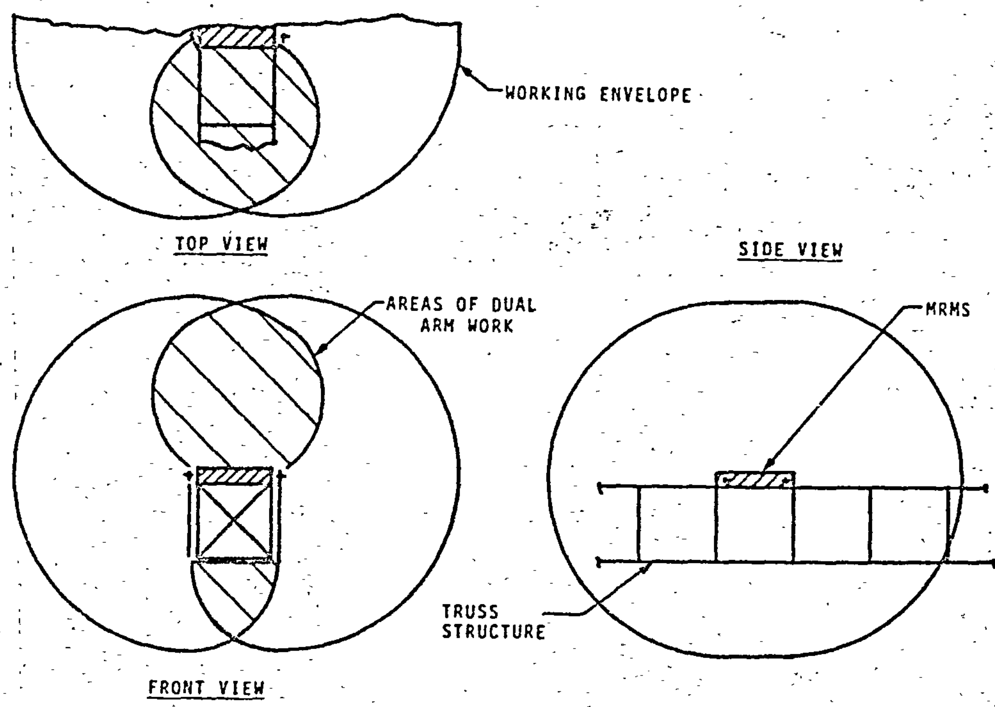
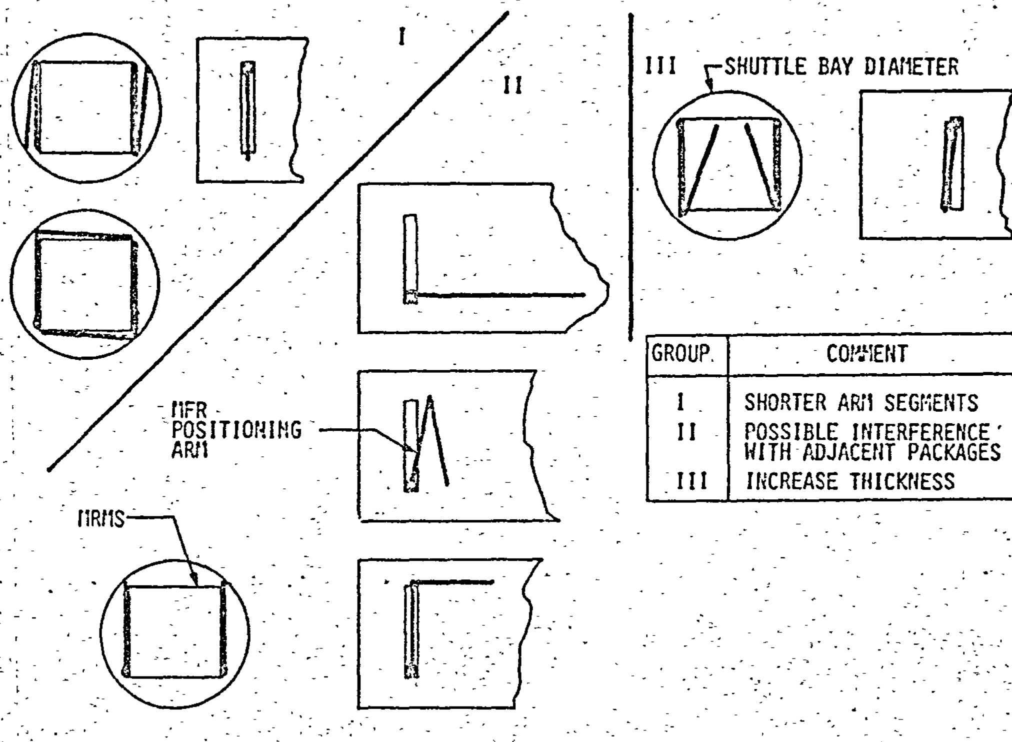


Figure 6.6.1.4-6 Positioning Arms Reach Envelope

One advantage of having the two arms is the ability to perform coordinated dual arm work. The robotic joints will be similar to the RMS but scaled down to match the load requirements. The electric DC motors will be backdriveable and monitored for velocity and position. When power to the drives is removed, the brakes will hold its position.

One criteria for the positioning arm length is its ability to be stowed in the shuttle cargo bay. There is a variety of storage options as shown in Figure 6.6.1.4-7.

Group I is the most compact packaging for the arms. The arms do not add to the width of the package as compared to the third group. Unfortunately, the arm lengths in Group I will be shorter than the other groups. The shorter lengths could suit particular needs. Group II could have arms double the length of Group I but uses space required for adjacent packages. See Figure 6.6.1.4-8 for the location of the MRMS in the first launch package.



GROUP	COMMENT
I	SHORTER ARM SEGMENTS
II	POSSIBLE INTERFERENCE WITH ADJACENT PACKAGES
III	INCREASE THICKNESS

Figure 6.6.1.4-7 Positioning Arms Shuttle Bay Stowage

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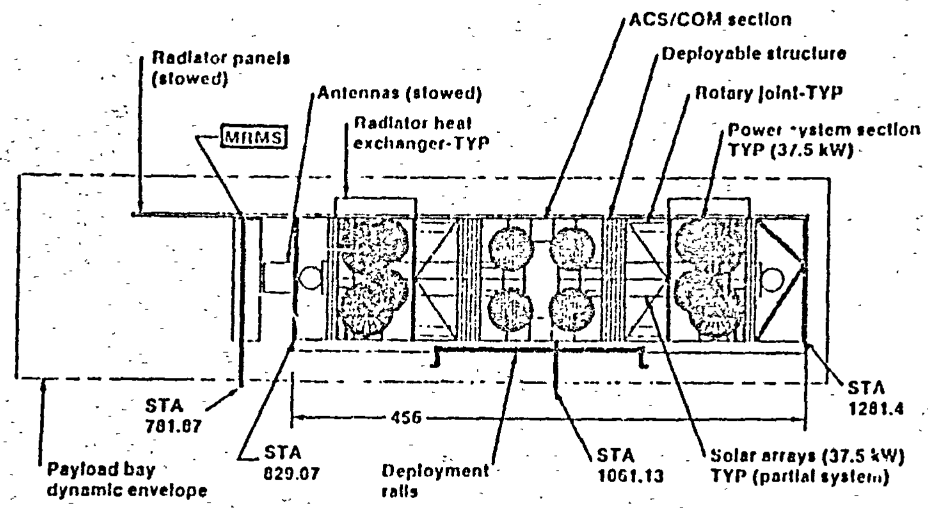


Figure 6.6.1.4-8 MRMS Launch Stowage Location

The precision of the positioning arm does not have to reflect the specifications of the RMS. Its main objective is to get into the working range of the end effector work station. The work station will be designed for an EVA astronaut.

d) EVA - The astronaut accomplishes intricate, dexterous work that cannot be performed by the crane. The astronaut is nearly tall enough to erect a IOC cube section by hand. His positioning arm will maneuver the astronaut to the work area. Complete control of the arm is at his finger tips. The control panel is situated directly in front of him, but far enough away to minimize interference.

The astronaut's feet are restrained in a strap arrangement shown in Figure 6.2.3-5, which shows the mobile foot restraint (MFR) at the end of one of the positioning arms.

This enables him to have complete freedom of hand/arm movement. Such work includes mating electrical fittings, erecting structure and aligning optical transmission hardware. Table 6.6.1.4-1 lists some design requirements for the EVA foot restraint.

With the use of an MMU, he is capable of leaving the work station and returning.

He is outfitted with his life support system and selected work tools. With the two positioning arms, there will be times when a job can utilize both astronauts simultaneously.

As the tasks and missions change, so must the training. The degree of difficulty and risk could also increase. Taking everything into consideration, there will be a time when the use of an astronaut may become prohibitive and he must be replaced by a remotely controlled system.

Table 6.6.1.4-1 EVA Restraint General Specifications

Design parameter	*Design requirements/remarks*
Mobility	EVA foot restraints shall maintain foot position to allow the crewman a complete range of motion (roll, pitch, yaw) within the constraints of the space suit.
Restraint spacing	• Center to center distance = 25.4 to 43.2 cm (10.0 to 17.0 in.). • Center dimension shall be determined from analysis of the tasks to be performed.
Load capacity	• Ultimate design load = 623 N (140 lb) minimum in tension and shear. • Torsion = 203 N-m (1800 in-lb) minimum.
Hazards	Foot restraints located within 30.5 cm (12 in.) of equipment where failure would cause injury to the crewman will be identified in accordance with SC-M-0003. Potential areas of damage to flight equipment by the crewman will also be identified.
Material	Metals shall be the primary material for foot restraint fabrication. Other rigid or semirigid materials may be used when warranted by design constraints. Materials must be approved in accordance with NHB 8060.1.

*Reference 1. NASA General Specification SC-E-0006
2. ICD - HSD-3-0045-02-0

6.6.1.5 Telepresence Work System (TWS) - A suitable replacement for the EVA astronaut is a Telepresence Work System (TWS) situated at the end of one of the arms. The TWS concept consists of a work station base supporting two dextrerous manipulators, end-effector grippers and tooling, a stereo camera system, parts storage areas, and an onboard processor system. A TWS concept is illustrated in Figure 6.6.1.5-1.

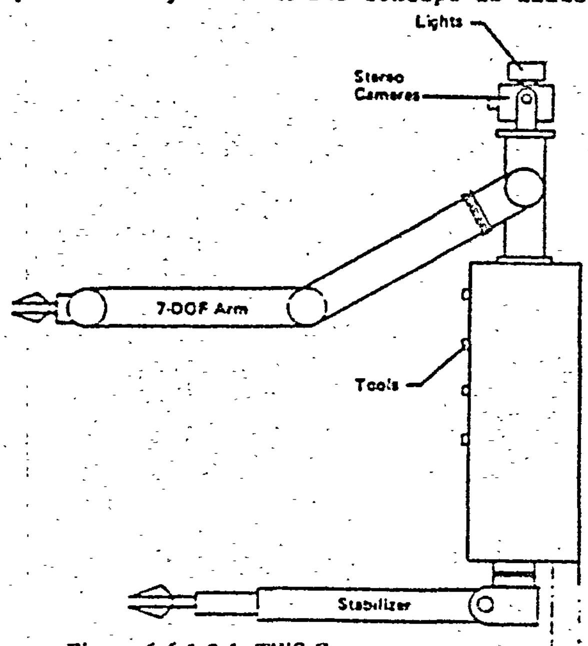


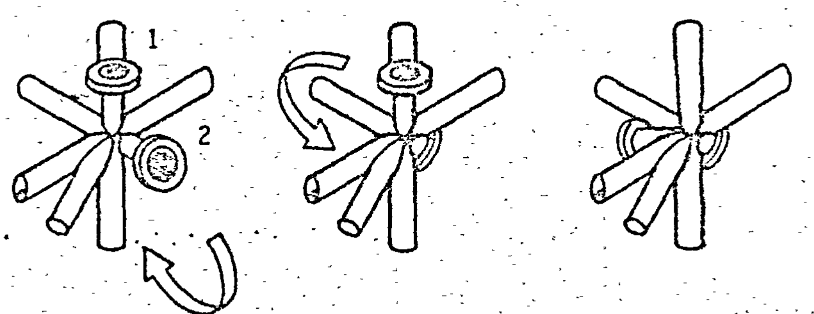
Figure 6.6.1.5-1 TWS Concept

The TWS design can be broken down into four major work areas: the base, the manipulators, the vision sensors and the processors. The TWS base is the mounting structure for the manipulators, cameras, stabilizer, tools and electronics. A 3-DOF stabilizer is needed to support the TWS from any forces and torques generated during work activities. The manipulators will be two lightweight, stiff, 7-DOF arms. The system will embody anthropomorphic (suited astronaut) features. Its sensor options will include stereo vision and force reflection capabilities. A dedicated computer and microprocessors will accommodate a high-order language. Bilateral positioning will be used to control the system.

The TWS kinematic reach and dynamic strengths will be equal to or greater than an EVA astronaut. Light and strong state-of-the-art materials will be used on the base and on the manipulators. The dexterity of the arms will be preserved with a three-roll-wrist. Accommodators might be utilized in some assembly tasks. Some weight is saved with the elimination of extensive thermal protection and life-support hardware but regained with additional hardware.

6.6.1.6 Other Design Considerations -

a) Structure and Nodes - The nodes are an integral attachment part of the MRMS and the structure. For the Space Station IOC, each joint will have a minimum of two nodes as shown in Figure 6.6.1.6-1. On an end section, there would be three nodes.



Swivel Deployable Nodes

Figure 6.6.1.6-1 Node Configurations

The figure above also depicts those same nodes folding inward as well as different trusses folding inward. This is necessary for deployable trusses where the boxes tuck in flush against each other. To fold the nodes, the joint would have to be rotatable, perhaps in a centroidal joint or a ball-socket swivel. See Figure 6.6.1.6-2 for different examples of structural attachments. The joint would be compactly configured until deployment, when the various trusses would rotate outward and lock in the final configuration.

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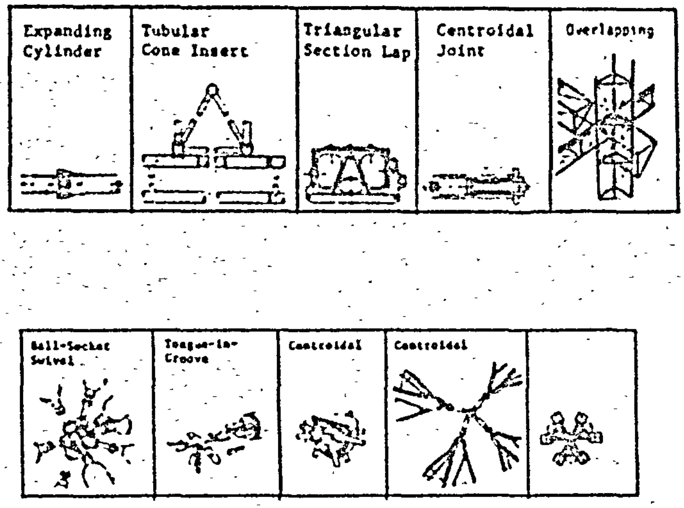

Figure 6.6.1.6-2 Structural Attachment Techniques

Overlapping joints or adjacent box trusses without common sides are inaccessible by the MRMS. See Figure 6.6.1.6-3. The spacing of the nodes are symmetrically and critically located.

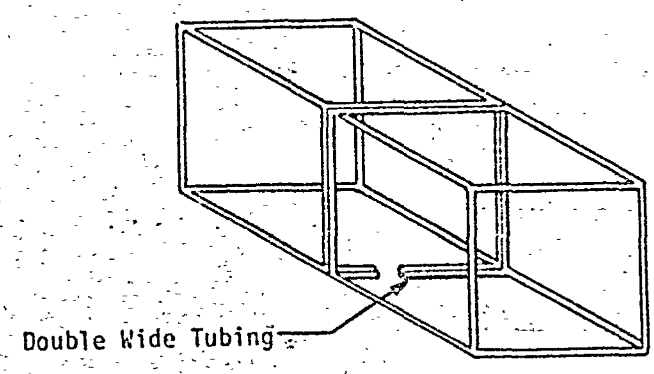

Figure 6.6.1.6-3 Inaccessible Node Configuration

Unwanted flexures of the structure could possibly throw the node spacings off and make them difficult to locate with the drawbar. Initial concepts of the structure utilized two-inch round or square tubing. The box sections are stiffened with diagonal cross members. Electrical wires and connections are integrated into the tubings for ease of assembly.

A major criteria for the structure is its packaging for delivery into orbit. Figure 6.6.1.6-4 illustrates methods of stacking and folding different truss assemblies. The Space Station reference scenarios have most of the station deployable with some sections erectable.

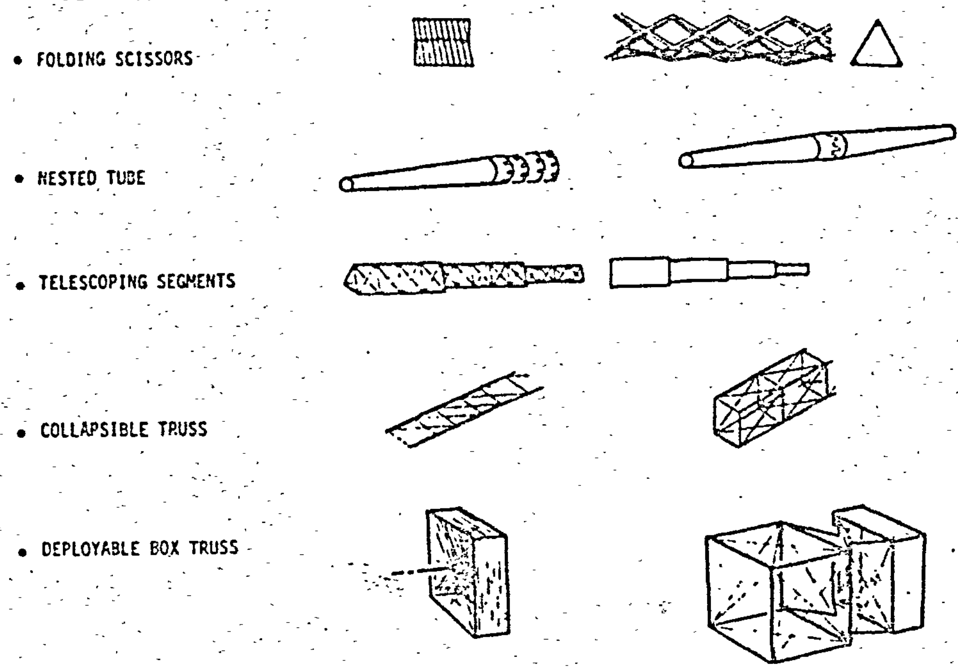

Figure 6.6.1.6-4 Truss Assembly Packaging Configurations

b) Cargo Structure Attachment - Most of the packages and experiments on the Space Station have to be hard mounted to the structue. A modular approach to attaching packages to the box truss is to attach the track level to the box. They can be placed on the nodes and locked. With the MRMS moving up one side of the structure, it leaves the two adjacent sides free to mount experiements or other cargo packages and assemblies. Figure 6.6.1.6-5 shows the MRMS in relationship to the experiments or other cargo elements.

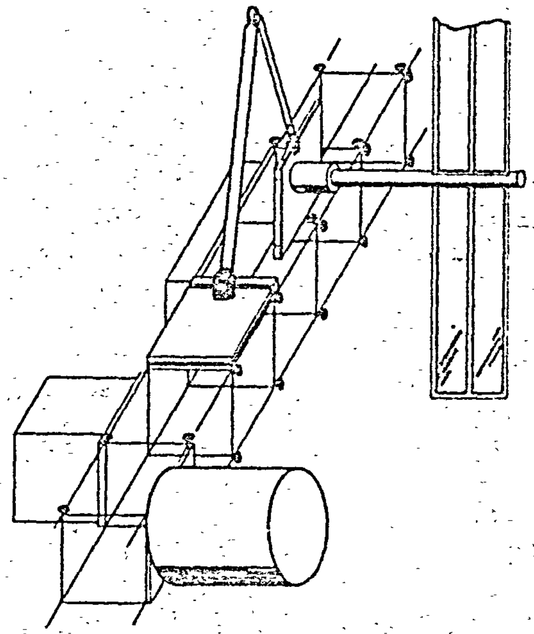

Figure 6.6.1.6-5 Cargo Emplacement by MRMS

This method of attachment is suitable for replaceable or temporary packages that have to be removed periodically. If a package is larger than one cube, the track layer will be rectangular, 9 feet wide x 18 feet long, and taking three nodal rows. One disadvantage for this method of attachment is the inability to mount two square tracks adjacent to each other. The two packages would have to be combined and attached to a rectangular track.

c) <u>MRMS Plane Changes</u> - Besides moving in two orthogonal directions, another major concept involves a plane change. Figure 6.6.1.6-6 illustrates two concepts. Concept I features a special cube with a hinged face. When the MRMS is affixed to this face, it is hinged 90°. Once its direction has changed, the vehicle inches forward onto the next plane.

Concept II uses another hinged-type face that rotates about its axis. The face extends out in a transverse direction to the structure. The MRMS moves onto the face and affixes itself. The face is rotated 180° and pivoted perpendicular to its original direction. The vehicle then crawls forward onto the adjacent plane.

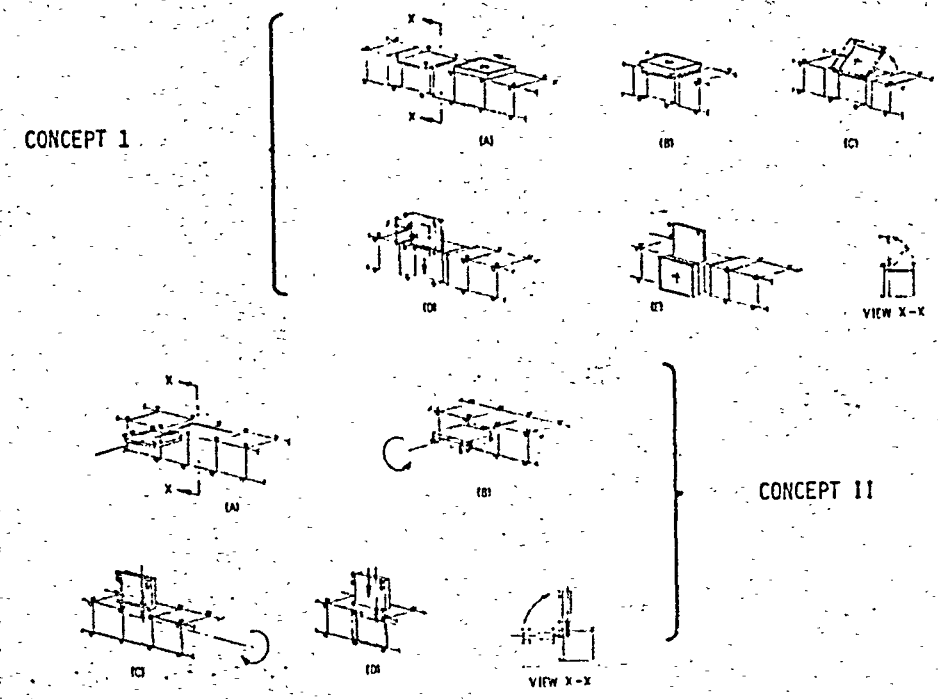

Figure 6.6.1.6-6 MRMS Plane Changes

A third concept does not use a special plane change structure. A face would be built on the solar panel gimbal. When the MRMS attaches onto the face, the gimbal would turn 90° and the vehicle would then be at the next plane. Unfortunately, the solar gimbals are not located at convenient spots.

d) MRMS Translation - The MRMS inches forward a square at a time to translate in a longitudinal direction. For a transverse translation, the drawbar and the switches are rotated 90°. By repeating this process, the MRMS can weave back and forth to build a double wide structure or even an entire platform (See Figure 6.6.1.6-7).

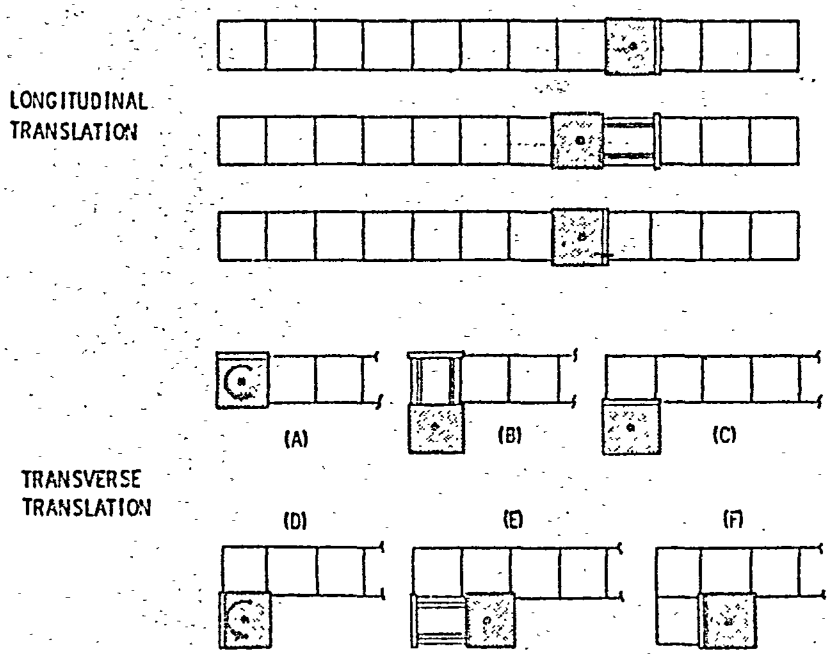

Figure 6.6.1.6-7 MRMS Translation

6.6.2 Commonality

A number of assembly and construction support equipment candidates were identified during the concept investigation phase of the four reference missions. Many of the potential candidates were obviously significant to the study and will require much further detailed analysis. Others with less significance in terms of functional capability, technology drivers, and design features have minimal impact on the final results.

Therefore, it was necessary to reduce the number down to a few of the most representation candidate systems as quickly as possible. In performing the screening assessment the following basic objectives were used:

1) Use as a point of departure the Space Station Reference Document;
2) Identify future supporting research and technology items;
3) Technical feasibility with a logical evolutionary path;
4) High usage probability with projected longevity; and
5) Where support equipment implementation could result in incompatibilities with the physical Space Station or program milestones.

The resulting first cut at a common generic list is summarized in Table 6.6.2-1. This list is a combination of items identified in the four reference missions with duplications combined under generic terms and less significant items left out. Also shown on the right hand side of the table is a first cut at the perceived level of automation that can be applied to this candidate list based on a nominal evolutionary progression.

Table 6.6.2-1
Summary of Support Equipment Candidates and Level of Perceived Automation

Primary Support Equipment Candidates	Candidate for Automation Growth
1. Shuttle Remote Manipulator (RMS)	Med
2. Mobile Remote Platform	High
3. Mobile Remote Manipulator System (MRMS)	Med
4. MRMS with 2-20 ft Arms (RMS Derivative)	High
5. Telepresence Work Effector (EVA Analog)	High
6. Mobile Foot Restraint (MFR - Shuttle)	Low
7. Closed - Cherry Picker	Med
8. Universal Docking (Berthing) Unit	Low
9. Fasteners (Inherent in Design)	High
10. Fastener Tools, (clamp, weld, rivet, etc)	High
11. Universal Tool Storage Unit	Med
12. Portable and Mobile Lighting/Camera Unit	High
13. Portable Control Box/pendant	Med
14. Special Function Manipulators (5-DOF or Less)	High
15. Carousel Mechanism (Satellite Assem Fix)	High
16. Structure Deployment Aid	Med
17. Alignment and Surface Accuracy Tools (Gross)	High
18. Alignment and Surface Accuracy Tools/Sys (Fine)	High
19. Checkout Tools, (Mechanical, Electrical and Data)	High
20. Portable Deployable Sun Shade	Med
21. Special Purpose End Effectors (Manipulator Exchange)	High

In addition to common support equipment types there is also commonality of subsystems and components between different equipments. Table 6.6.2-2 presents a brief example of this concept and should be considered as a groundrule for future Space Station studies.

Table 6.6.2-2 Example of Common Use Subsystems and Components

MRMS - Components/Subsystems	Legacy
Manipulator (Crane Type)	Shuttle RMS
Rotary Drive	MMS - Flight Support System
Manned Foot Restraint	Shuttle MFR
EVA Operations	Shuttle MMU
MRMS - Advanced Component (All Multiple Use)	**Legacy**
20 ft Manipulators (6 DOF)	Derivative of RMS
Special Purpose Manipulators (5 DOF or less)	Derivative of RMS
Dual Arm EVA Analogue	Use also for Smart Servicer on OMV and OTV
Module Attachment Device	MRMS - Base Plate
S/C Assembly/Dia Adj. Mechanism	MRMS - Base Plate with Rotary Drive

6.7 AUTOMATION ASSESSMENT

It is the objective of this section to pursue areas of automation and robotics as they pertain to autonomous systems and assembly activities on space station. This will assure that such advanced technologies relevant to this area be made an integral part of the planning and development for a manned space station. Output expected from this effort is the identification with supporting rationale, of promising advanced robotics or automation technologies, not in use in prior or existing spacecraft.

6.7.1 Evaluation of Automation Concept

An evolution of automation on both the system and subsystem levels will be required to enable operational productivity in the initial as well as growth versions of the station. The increasing level of automation over a period 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 name of the game, which results in trying to automate as many as possible subsystems and payloads.

Productivity as it applies here could take the form of reduced risk of human error, reduced crew time spent on laborious or monotonous tasks, thus freeing them for tasks requiring their unique capabilities, and 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, etc. The need for space automation in manned 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 automatible jobs. Past implementation of automatic features consisted initially as a bottoms-up approach in which single components of automation were developed, followed by linked components of automation were developed, and eventually combined into integrated systems. Some of the past examples have used standalone, application dependant solutions and would build upon these in 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 illustrated in Figure 6.7.1-1.

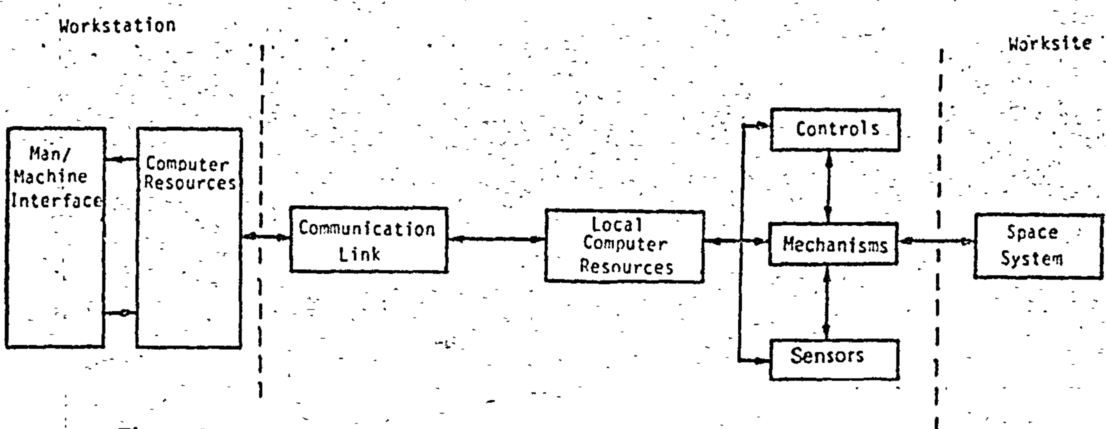

Figure 6.7.1-1 Human Interactive Automation Model

The area on this figure on the far right is the spacecraft worksite and the mechanical hardware represents the space station structural components and the mobile remote manipulator system (MRMS) that was just discussed in Section 6.6. The key to making this hardware operate comes under the direction of the man/machine and computer combination. A proposed evolutionary flow in this area is shown in Figure 6.7.1-2.

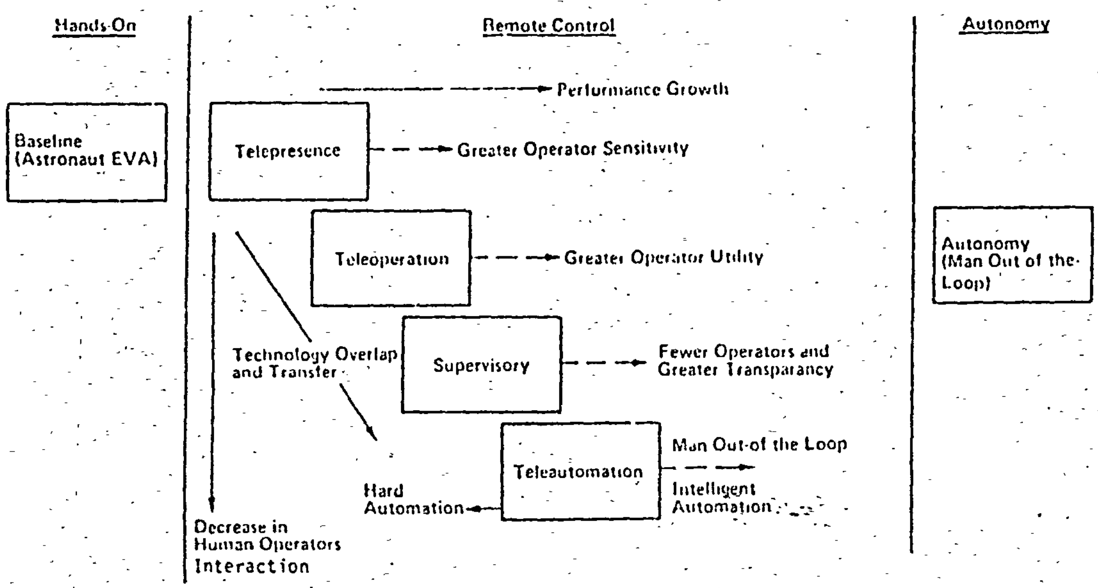

Figure 6.7.1-2 Remote Operations Overview

Shown on this schematic is a logical transition phase going from an EVA hands-on capability to an autonomous condition. Terms used to display this flow can be considered a subset of remote control. Definitions for these terms or concepts as they apply to the study are presented in Section 1.5 of this report. Distinction between these evolving concepts are vague in many respects but do have some specific differences that provide unique capabilities. For example, telepresence is the most human intensive control mode in this group but 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 in general 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 such signals. Technology in the form of sensory perception has a considerable overlap or technology transfer from one concept to the other. Sensors must be selected where the data feedback signals are compatible with direct display through the CRT screen or to the computer and adaptive control software.

In the supervisory concept the human operator is elevated to a higher level of command in which the procedural programming language leads to an objects-level and eventually to a goal or task-level programming language. This is the stage in the evolutionary flow at which integration of intelligent automation has a major starting place. The mix between "hard" and "intelligent" automation is a function of the tasks being performed. As the number of dynamic variables increase, along with the need for both an inherent modifiable knowledge base system and a dynamically changing rule base, the basic concept is driven towards intelligent automation. This initial capability, while primitive, provides a test bed for eventual technology transfer to teleautomation and on-orbit autonomy.

This brings us down to the concept of teleautomation in which a machine located at a remote control station interacts with the control system to either update the knowledge base or modify software in order to carry out a predesigned function or series of actions initiated by an external stimulus (e.g. offline programming).

Many technologies with high degrees of sophisticated automation are required to achieve this level of remote control. The degree of automation provided through this concept can range between "hard" to "intelligent" automation. Capabilities within this range are derived at the "hard" end by well defined variables operated on in a conventional, sequential computational mode. At the other end is "intelligent" automation which uses vague and dynamic variables that are operated on in a parallel or non-connected mode using rules and heuristics. The ideal system architecture for this concept is one that uses an optimum mix of "hard" and "intelligent" features in a proper balance. The balance should be dynamic with a sensitivity based on task type and complexity and sophistication of sensory perception data feedback.

It is obvious that the degree of operator interaction desired, the operator skill levels required and the resulting technologies applied are all very intertwined with the amount of overlapping highly dependent on overall task complexity. Various task functional flows and decompositions have been performed and discussed in Section 6 of this report. Using only this task data, it is very difficult to apply automation features to them, since the data is limited in areas of performance tradeoffs and resulting economic benefits. To provide a more knowledgeable comparison, Table 6.7.1-1 is presented to show trends in required operator capabilities as a function of generic job categories. As shown on this table, terminology used to identify remote operator classes has been selected based on the generic similarity to both space and ground operations. For example, the capabilities (skill, knowledge, experience, etc) required for ground manufacturing types could be similar to those identified for fabrication of beams or material processing in space. Manipulator system functions and automation technologies at residential or commercial construction sites seem to be similar to assembly and construction functions required of large space systems. Also, operators of cranes or even airplanes could have task activities similar to OMV or OTV remote operators where skills and cognitive attributes are significant design drivers.

There are two important points made here; (1) a human operator is narrowly focused in a limited set of information and skills related to a job and as such software architecture used to replace a few or many of these capabilities will also have a very narrow focus, and (2) the degree of supervisory or automation control given over to machines will be dependant on the flexibility, adaptability, or intelligence desired or required of the task.

Table 6.7.1-1 Remote Control Operator Types

REMOTE OPERATOR CLASS	TASK	ACTIVITY	SKILL LEVEL	MEMORY	SENSORY	MANIPULATIVE DEXTERITY
Manufacturing Assembly Fastening Inspection	Assembly Line, Fixed	Repetitive, Routine Structured Worksite	Low (Teleauto)	Small / Medium	Vision/Touch	Task Dep. Low DOF
Construction Mat. Handling Fastening	On-Site Mobile	Batch, Activity Sets	Medium (Supervisory)	Medium	Vision/ Stereo	Medium High DOF
Maintenance Remove/Rep. Diagnostics Multi Access	Versatile, Scheduled, Unscheduled	One-of-a-kind, Module Replace, Troubleshooting Unstructured Worksite	Considerable Training (Telepres.)	Very Large	Sensor Fusion Vision/Stereo Force Touch	Fine High DOF
Information Monitor Scheduling Planning	Housekeeping Workstation Fault Det. Isolation Recovery	Data Analysis Predictions Advisory	Considerable Training (Supervisory)	Very Large (Arch.)	Vision/Touch Data Fusion	N/A
Transporter	Mobility (Driver)	Scene Depen., Crane Driver	Low (Tele-operator)	Medium	Vision Contact Range	Gross / Medium DOF

6.7.2 Control Evolution Concept

Using the steps developed and shown in Figure 6.7.1-2 and the basic philosophy flow of slowly transferring the human operators 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 and displayed in Figure 6.7.2-1. This figure shows a series of overlays that demonstrates the anticipated evolution of a top level control system for the advanced MRMS concept discussed in Sections 6.2.3 and 6.6. Each stage in this control concept is represented by a different shade of blocks in sequential time periods. A brief discussion of each stage is presented below:

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 graphics 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 adapting 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.

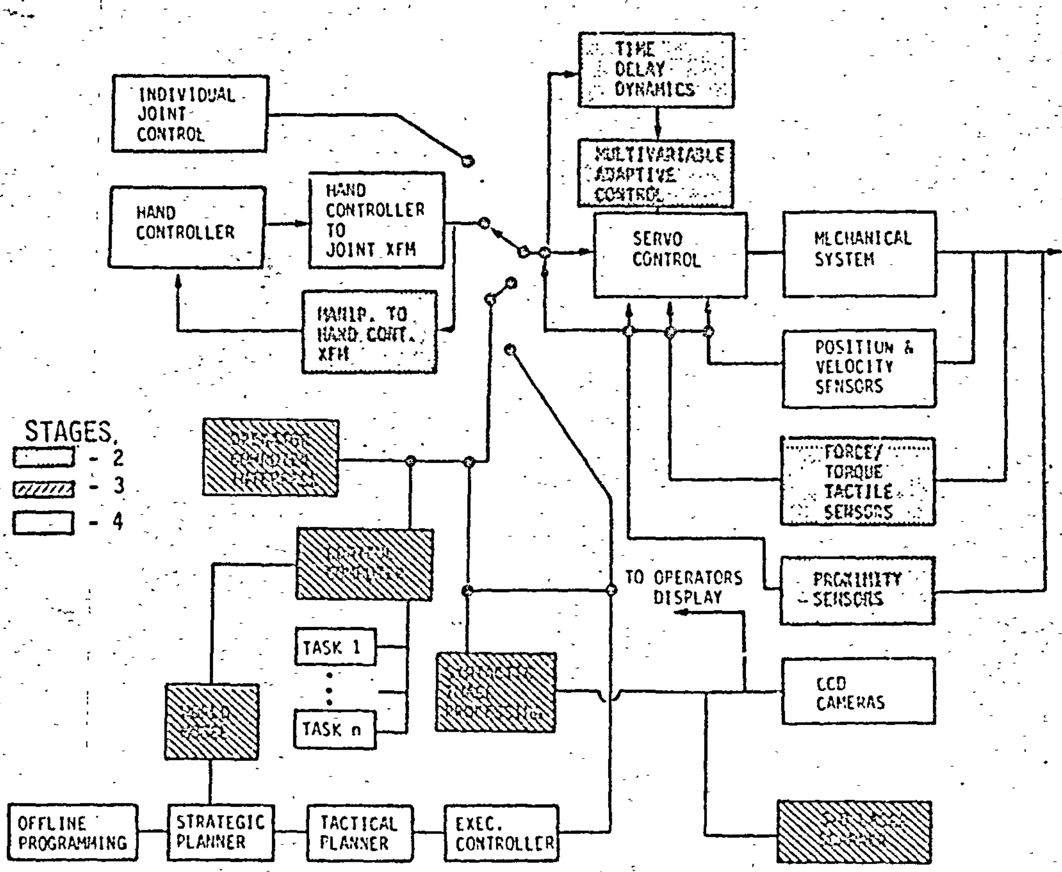

Figure 6.7.2-1 Remote Control Automation Enhancement

Figure 6.7.2-2 shows the overall control system evolution based on a time-phase consistent with the simple mission model representing assembly and construction trends. As indicated the initial IOC station (1991) is expected to use a resolved rate manipulator control system which is current technology. From this point forward, integration of performance capability was incorporated into the reference MRMS from both a technology "push", i.e., force feedback hand controller, and also a technology "pull" requirement. For example, the benefit or feasible application of a force feedback hand controller to the assembly and construction tasks has not been given much support in any of the prior related studies. Part of the rationale used dealt with the problem of time delays for ground operators and a combination of working volume constraints and crew restraints needed for zero gravity by on-orbit operators. The remaining evolutionary steps follow a logical waterfall schedule based on a sequential need priority and a technology build up estimate.

This estimate took into account a seven year span from the time it was considered mature on ground to when it should be incorporated in the station. Also, selected technology in this overall area is moving ahead at a rapid pace and could be available prior to a real need date.

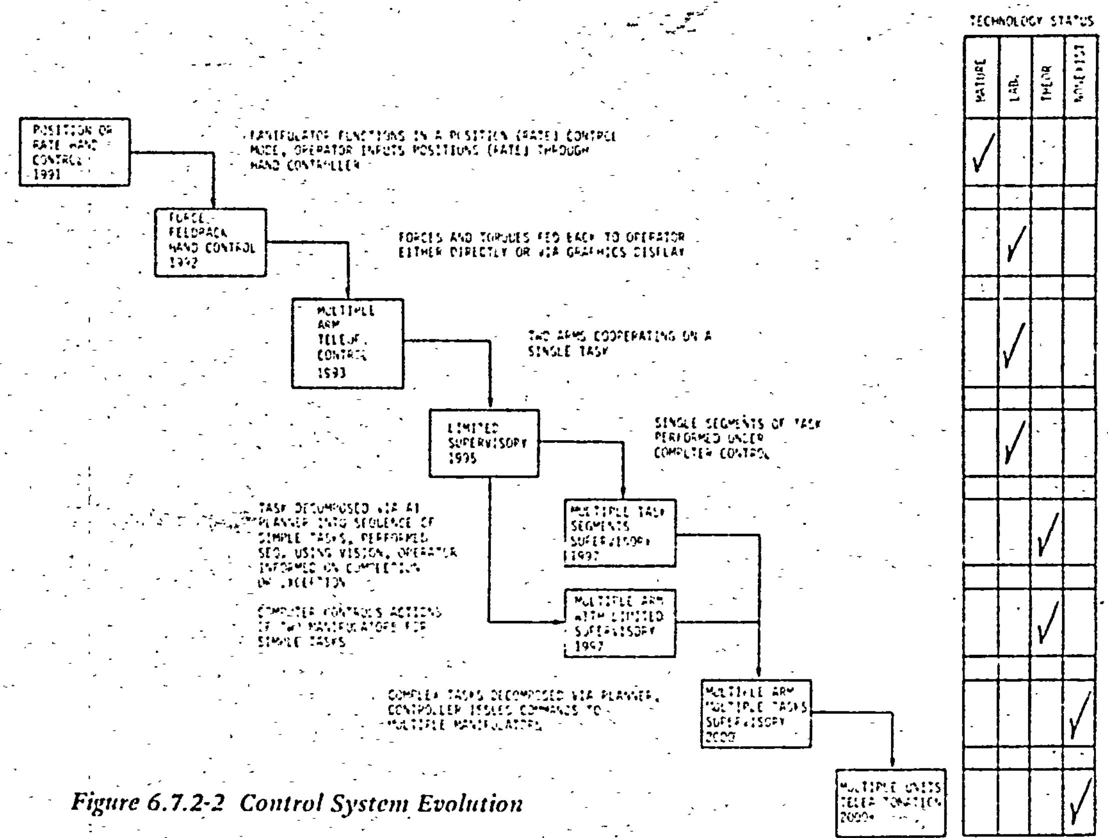

Figure 6.7.2-2 Control System Evolution

6.7.3 Technology Assessment

A matrix was prepared using data developed to bound the automation hardware concepts in Section 6.6, the control system complexity evolution concept generated in Section 6.7.2 and the waterfall time phase estimate presented in Figure 6.7.2-2. The intent of this matrix, as summarized in Figure 6.7.3-1, was to assess the primary and ancillary technology drivers needing additional study, research, development and verification to warrant implementation as the major piece of large space system (LSS) assembly and construction support equipment. The matrix format combined the block categories and terminologies presented in Figures 6.7.2-2 and 6.2.4-1.

Results of this assessment have indicated areas of key technologies, state of the art, level of relevant activity and some of the potential impacts on space station.

TECHNOLOGY STATUS

			Technology Status				Research Emphasis				
Automation Drivers	Issues	Key Technologies	1	2	3	4	A	B	C	D	Potential SS Impacts
MMS (BASIC) (1991 IOC)	- Teleoperated (SS)	- Data Transmission Formating	•					•			
	- Teleoperated (Ground) - Time Delay	- Predictive Displays			•					•	
	- Bandwidth	- Operator Selection/ Training				•			•		
	- Position or Resolved Rate	- Seven DOF Hand Controller		•						•	- Provide Flexible Interface for Hand Controller
Force Feedback Hand Controller (1992)	- Crew Productivity	- Man/Machine Task Allocation			•				•		- Design Task and Interface for Man and Machine
	- Exchangeable EE	- Special End Effectors		•				•			- Standard EE Grip Interfaces on SS
	- Sensory Perception	- Stereo Vision		•				•			- Provide Bandwidth for Space-to-Ground TV
		- Image Processing		•					•		- Integrate Sensors Prior to Need
	- Telepresence	- Proximity, Touch and Force Sensing		•						•	- Embed Up in Arm Segments
(2) 20 ft Arms, Adjustable Segments (1993)	- Low Weight Arms/Advanced Actuators	- Advanced Materials/ Integration		•				•			
	- Onorbit Serviceable Arm	- Replaceable Arm Segments	•						•		
	- Dual Arms, Operation	- Adaptive Control			•				•		- Requires More Sensors and More Sensitive Data
		- Sensor Fusion			•					•	- Provide Additional Signal Wires, Shielded
	- Structured Worksite	- Dual-Arm Coordination				•				•	
		- High-Speed Processing		•					•		- Requires Larger Access and Working Envelopes
Dexterous TWS (EVA Analog) (1995)	- Multihanded Tasks	- Low Weight Dexterous Arm		•					•		- Provide Rest or Stabilization "Hard" Points at Work Sites
	- Unstructured Work Site	- 3 DOF Co-Axis Wrist (3 Axes Act.)		•					•		- Use worksite design that is compatible with manipulator EE interfaces
		- Dual-Arm Coor. On Single Item				•				•	- This System Compatible with Crew Interface
	- Limited Supervisory (Test Bed)	- Knowledge-Based System				•				•	- Codify Expertise and Experience at Program Start
		- Expert System				•			•		- Provide for Onboard Symbolics Machines
	- Machine Vision-Range	- 3-D Vision and Scan Lasers			•				•		- Precode All Worksite Areas
Multiple Tasks Elements Being Worked by Multiple Arms (1997)	- Multiple Tasks	- Executive System Controller			•				•		- Force Functions into Software, Evaluation Flexibility
	- Computer Vision	- Image Understanding		•					•		- Precode All Components and a Location Grid
	- Supervisory (Ground)	- Processing Location (Ground vs Space)			•			•			- Space Qualification of Hardware
	- Teleoperated Maintenance	- Multifinger Coor. on Compliant EE		•				•			- Provides Greater SS Interface Flexibility
		- Strategic and Tactical Planners				•				•	-
Multiple Arms Working Multiple Tasks (2000)	- Progressive Increase in Data Storage	- Massive Memory		•				•			- Design To Accommodate Optical Disk Data Storage
	- Operational and Historical	- Computational & Archival									-
	- Expected Increase in Maintenance Act.	- Intelligent Controllers				•		•			
	- Supervisory (Gnd & Space)	- Flexible Maintenance			•				•		- Provide Test Parts for Automated C/O & Testing
Multiple Units Teleautomation (2000+)	- Remote Automation Support	- Offline Programming				•		•			- Provide Reprogrammable Software Onorbit
		- Archival Memory Management				•		•			- Provide Updateable, Secure Library

Figure 6.7.3-1 Automation Technology Assessment

Technology Status

1. Mature
2. Laboratory
3. Studies
4. Nonexist

Research Emphasis on Need

A. Minimal
B. Acceptable
C. Moderate
D. Major

The information in Table 6.7.3-1 was derived from the Research Emphasis column of Figure 6.7.3-1 plus other selected items.

Table 6.7.3-1 Key ACSE Technologies

Selected Technology Group
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

6.8 AUTOMATION SUMMARY

In addition to identifying the major, top-level autonomous systems architecture, and related artificial intelligence features, and the assembly and construction support equipment and related technology implementation, it is important to also consider overall system implications. Those considered in this section included areas of commonality among the individual support equipment, specific system functions, processing hardware and software, areas of overlapping technology, types and priorities across a wide spectrum of system elements, and a summary development plan to show time phasing and key milestones. A final area assessed was the forecasting of "scars" that should be included into the IOC design to accommodate future growth.

6.8.1 System Commonalities

Several significant areas of commonality exist within anticipated ACSE to support large space systems assembly in space concepts. Many studies have been conducted that assessed all options, ranging from fabricate on earth and deploy in space to launch raw materials from ground to orbit and totally construct on orbit. As a result of these studies, a space station reference configuration has been established that fabricates inherent deployable sections, i.e., Shuttle cargo bay compatible, on ground, and then assembly of these sections on orbit with human and machine support. Section 6.6.2 of this report has compiled a common list of generic assembly and construction support equipment (Table 6.6.2-1) that is common to many future satellite system assembly and construction approaches based on the current Space Station reference.

Much of the technology required to develop this equipment is common to two or more of these items. Table 6.8.1-1 shows a matrix that indicates a cross interaction and results in identification of high use technologies and key support equipment that represents a wider range of Space Station functions. As shown in this matrix technology developed for items 1 through 5 are applicable to the other items at various levels of sophistication.

6.8.2 Technology Priority Ranking Process

The key technology priority ranking process used here was based on a simple assessment technique. The emphasis during this part of the assessment was to compare each technology discipline against each of the selected parameters. Due to the vagueness in this area, and in some cases a lack of comparison data, the results are intended to show trends rather than exact conclusions. The approach used in arriving at the final priority ranking depended on a combination of evaluation procedures that looked at data from the other parallel study results,

Table 6.8.1-1 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)	o	o	o									
2) Mobile Remote Platform	o	o	o									
3) Mobile Remote Manipulator System (MRMS)	o	o	o	o			o					o
4) MRMS with 2-20 ft Arms (RMS Derivative)	o	o	o	o	o	o	o	o	o	o	o	o
5) Telepresence Work Effector (EVA Analog)	o	o	o	o	o	o	o	o	o	o	o	o
6) Manned Foot Restraint (MFR-shuttle)		o	o									
7) Closed-Cherry Picker		o		o	o	o		o		o	o	
8) Universal Docking (Berthing) Unit		o					o					
9) Fasteners (inherent in design)			o	o						o		
10) Fastener Tools (clamps, weld, rivet, etc.)		o	o							o		
11) Universal Tool Storage Unit		o										
12) Portable & Mobile Lighting-Camera Unit		o	o	o			o	o	o		o	
13) Portable Control Box-Pendant						o		o				o
14) Special Function Manipulators (5-DOF or less)	o	o	o	o	o		o			o		o
15) Carousel Mechanism (satellite Assem. Fix)	o		o	o						o		
16) Structure Deployment Aid		o								o		
17) Alignment & Surface Accuracy Tools (Gross)	o				o		o	o			o	
18) Alignment & Surface Accuracy Tools-- System	o				o		o	o	o		o	
19) Checkout Tools (Mechanical, Elect., & Data)	o	o	o				o			o	o	
20) Portable Deployable Sun Shade	o		o									
21) Special Purpose End Effectors (Manipulator Exchange)		o	o	o		o	o			o		o

other related studies, trends derived during study, initial guidelines, and on the experience/judgment of study participants. An initial prioritization process used was to separate the least-preferred features from the most-preferred features. A merit of value 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 6.8.2-1 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.

Table 6.8.2-1 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

6.8.3 Development Plan

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, where manned elements 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 augment 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 is presented in Figure 6.8.3-1 that follows the various key technologies through the major fabrication and test cycles. This plan has been generated using five primary phases to 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

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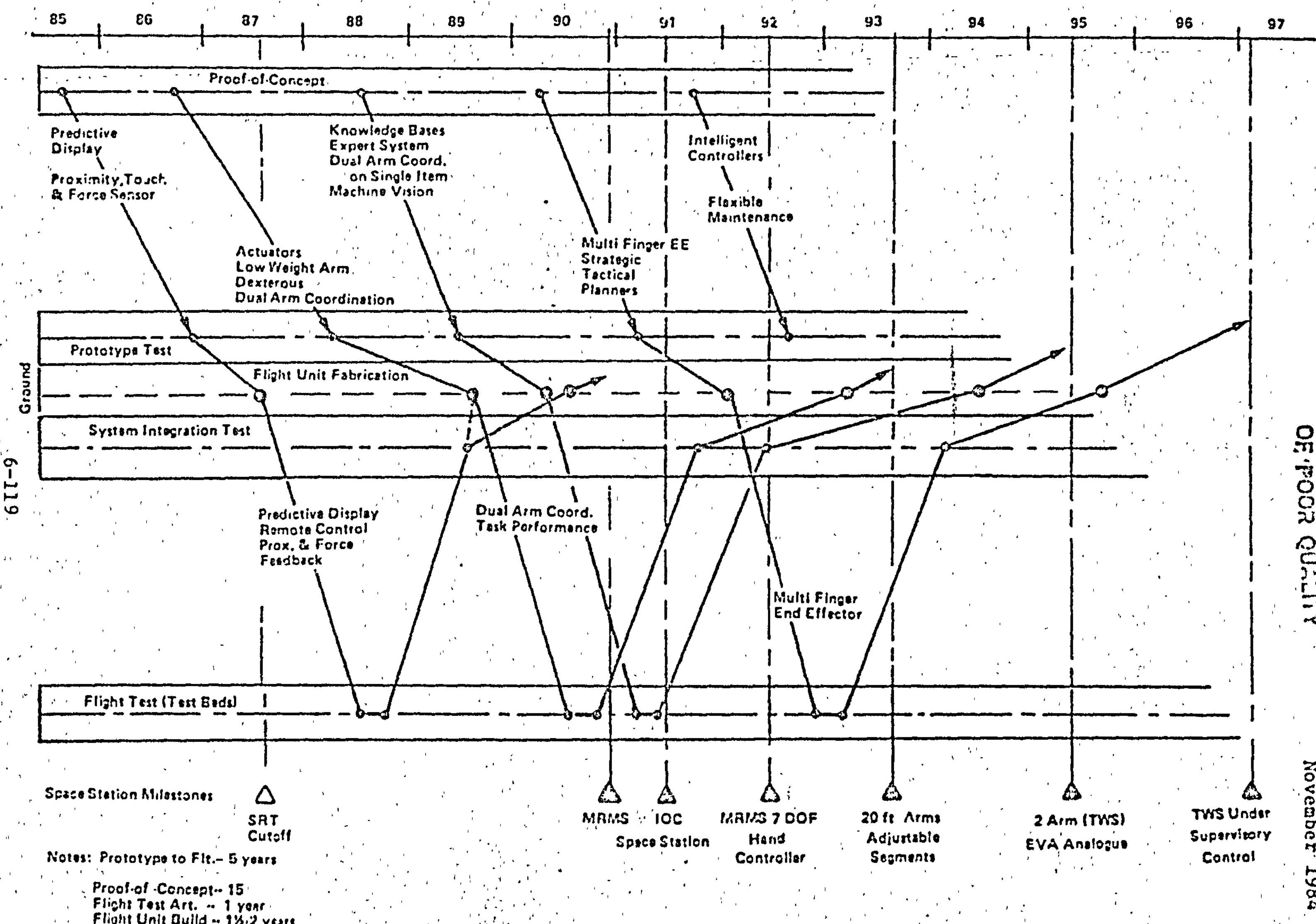

Figure 6.8.3-1 ACSE Technology Development Plan

flight test bed, 5) systems integration, and 6) space flight operations verification. Each of these phases are discussed in the following paragraphs. Also, refer to Reference (39) in Appendix A.

6.8.3.1 Design Study - The ACSE design study will be conducted over a period of nine months in order to generate the design requirements and specifications for the various items. A significant portion of the design specifications related to product configuration, useful life, environmental requirements, quality assurance provisions, and delivery requirements will be very similar or identical for all equipment. Based on the design requirements, common components and subsystems, i.e., manipulators, mechanisms, etc., along with common capsules for manned operations would be identified. Other outputs of this study would include a program statement of work, a work breakdown structure (WBS), and preliminary cost estimates for the balance of the ACSE development and demonstration program. An important part of this study effort is identification of facilities (labs, support tools, and software models).

6.8.3.2 Proof of Concept Models - This phase is planned for a period of 15 months to develop the preliminary design for the selected groups of hardware items that are categorized as ACSE. Proof of concept hardware will be fabricated and tested where preliminary evaluations are required. In the cases where scaled models will be cost effective as design/test aids, they will also be used. This phase will build on the vast design experience from the NASA manned space projects, particularly Apollo and Skylab, and the STS. Off-the-shelf components will be used where possible to ensure a cost-effective design development phase. Although materials and processes may not be flightworthy, the space and Shuttle compatible materials will be identified during this phase. Manufacturing will be conducted in close liaison with design personnel to reduce design change turnaround. The test activities will provide basic parametric data such as weight, power, volume, operating rates, and efficiencies. Zero gravity ground simulation tests may be performed using the NASA low gravity aircraft and other simulation facilities, if equipment is compatible. Where applicable, some of the proof-of-concept hardware would be disassembled from the equipment and used in the next phase of the program.

In addition to program progress meetings, there are four typical formal reviews that should be conducted as required:

- System Requirements Reviews - This review presents the initial overall system specifications along with subsystem and programmatic specifications.

- Preliminary Design Reviews - These reviews present preliminary ACSE designs and identify how the design requirements and specifications are being met.

- Critical Design Reviews - These reviews present detailed design of the ACSE items and supporting analyses for NASA approval prior to the start of manufacturing.

- Post Test Reviews - These reviews will present results of the various tests--the anomalies and corrective actions. Considerations will be presented for the test planning of the other phases of the program.

6.8.3.3 Protoflight ACSE - This phase is planned as a 12 to 24 month period of performance, depending on the specific subsystem, basically divided into 6 months for design and studies, 8 to 16 months for manufacturing, and 2 months for ground testing. The studies in support of this phase will primarily produce the interface control documents related to the Orbiter test bed activities and the construction equipment, the stowage and deployed envelopes for the ACSE, and the definitions of the ACSE subsystems. The detailed design activity will produce flight-type engineering drawings, supported by structural and thermal analyses, and failure modes and effects analyses. Subsystems to include power, controls, and communications as defined from the previous study will be designed for each of the ACSE items. The designs must consider common usage hardware, serviceability, and maintainability due to the projected missions for the ACSE, formal quality assurance and test plans will be developed for controlling the hardware items. Preliminary plans will be submitted for NASA approval, and a process for reporting anomalies and thorough corrective actions will be mutually agreed upon. The ACSE will be fabricated from materials and with processes that have been certified as being flightworthy and compatible with the space and Orbiter environments. Formal quality assurance and engineering change controls will be imposed to ensure hardware configurations are consistent. Component procurement for later flight operations will require the same flight hardware standards.

Ground testing will be performed to verify the integrity of each ACSE item. The testing would include electromagnetic compatibility (EMC), vibration and shock, and thermal-vacuum environments with functional operations during the thermal-vacuum tests and before and after each environment. Crew member operations will also be included.

In addition to regularly-scheduled program meetings, formal reviews to include a PDR, a CDR, and Post-Test Review will serve the functions as previously described in paragraph 6.8.3.2.

6.8.3.4 Shuttle Test Bed - This phase of the program will be 6 to 9 months, depending on the Shuttle launch schedule and load complement.

The ACSE item and supporting subsystems will be stowed in the Orbiter cargo bay, verifying the integrity of all interfaces. In the case of the Shuttle sortie flights for task board operational verification of the ACSE, the Orbiter payload specialist station controls will be installed and functionally verified as well.

Formal reviews will include SRR, PDR, CDR, and Post Test Reviews with JSC personnel.

6.8.3.5 System Integration - This phase of the program will be 3 to 9 months duration, depending on Space Station integration simulation model schedules and availability of cargo bay space. During this period, the specific ACSE hardware items will be integrated with all associated subsystems and a system end-to-end verification accomplished. The flight readiness review will be conducted to ensure all related program activities have been successfully completed and that no open action items exist.

6.8.3.6 Space Operations - It is our estimate that a major amount of activity will take place in the 1985-1995 timeframe to accomplish the necessary space verifications of each of the ACSE items. The availability of the more complex equipment must be scheduled to permit adequate test/verification time.

A point of reference for space demonstration span times is the Apollo Command Module/Lunar Module docking interface. In the case of the ACSE, many of the hardware items will be of comparable complexity and therefore adequate schedules must be provided.

6.8.4 Space Station Automation Growth Impacts Onto IOC

The overall emphasis of this study is to project into the future and forecast initial requirements needed to adapt to future uncertainties. This approach is necessary for a logical evolvability but presents a conflict with low front-end program costs. However, it has become increasingly apparent that sequential development, over long operational periods (approx. 20 years), along with constanly-evolving and challenging requirements are most probable. To deal with this reality requires a program design approach that defines, designs, and maintains the overall Space Station with flexibility as a driving guideline. One way to provide flexibility is to incorporate into the initial system the ability to expand or extend the system in any dimension, i.e., function, performance, operation, hardware, software, etc. This should be done in a cost-effective manner that incorporates a structured and modular implementation capability. Some of this capability can be achieved by including,early in the program design and build,"scars" that are compatible with future station modifications and growth. A first cut at some of the potential "scars" that are indicated in this assessment are shown in Table 6.8.4-1.

Table 6.8.4-1 Space Station Scarring Projections for A&C

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.

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APPENDICES

APPENDIX A

BIBLIOGRAPHY

Appendix A

Bibliography

1. Anderson, J.L.,:"Progressive Autonomy," NASA, Washington, 1984.

2. Bekey,I.,:"The Importance of the Space Station as an Element of the Total Space Station Architecture," AIAA 83-7102, AIAA Symposium on the Space Station, Arlington, Virginia, 1983.

3. Bekey, I.,:"Big Comsats for Big Jobs at Low User Costs," Astronautics and Aeronautics, February 1979, p 42-56.

4. Beggs, J.M.,:"Space Station: The Next Logical Step, "Aerospace America, September 1984, p 46-53.

5. Brooks, T.L., and Cunningham, R.,:"Visual and Tactile Feedback Handle Tough Assembly Task," Robotics Today, p 27.

6. Carlisle, R.F.,:"Space Station: Technology Development," Aerospace America, September 1984, p 54-55.

7. Garman, J.R.,:"Forecasting Trends in NASA Flight Software Development Tools," AIAA Computers-Aerospace Conference, Hartford, Connecticut, 1983.

8. Healy, T.J.,:"Machine Intelligence and Communications in Future NASA Missions," IEEE Communications Magazine, 1981.

9. Hodge, J.D.,:"The Space Station Program Plan," Aerospace America, September 1984, p 56-59.

10. Hollingum, J.,:"Which Way for Vision Sensing," Sensor Review, April 1984, p.58.

11. Kirkman, D.,"U.S. Urged to Establish Colony on Moon," Rocky Mountain News, Denver, Colorado, October 20, 1984, p. 36.

12. Maldrop, M.M.,:"Artificial Intelligence in Parallel,"Science, Vol. 225, August 10, 1984, p. 608-611.

13. Mangin, C., and D'Agostino, S.,:"Flexible Automated Assembly Systems," Assembly Engineering, March 1984, p. 30.

14. Mayer, M.,:"Here Comes Ku-Band," Forbes, May 21, 1984.

15. Pittman, R., Leidich, C., Massey, F., and Swenson, B.,:"A Modular Approach to Developing a Large Deployable Reflector," NASA, Ames Research Center, California, 1983.

16. Powell, L.E., Cohen, A., and Craig, M.,: "Space Station Design:"Innovation and Compromise," Aerospace America, September 1984, p 70-73.

17. Runge, F.,:"20.0 M Diameter LDR Deployment Presentation," McDonnell Douglas Astronautics Company, Huntington Beach, California.

18. Saranson, P.N., Guilkis, S., and Kuiper, T.B.H.,:"Large Deployable Reflector (LDR): A Concept for On Orbiting Submillimeter-Infrared Telescope for the 1990's," Optical Engineering, Vol. 22, No. 6, December 1983.

19. Schreiber, R.R.,:"Research in Robotics: Some Critical Issues," Research in Robotics, August 1984, p. 66.

20. Tucker, R.B.,:"Trend-Watchers," United Magazine, October 1984, p. 35.

21. Waterbury, R.,:"Computerized Assembly Process Planning," Assembly Engineering, February 1984.

22. Whelan, C.R.,:"Communications Satellite Move to Higher Frequencies," High Technology, Vol. 4, No. 11, November 1984, p. 48.

23. Yoji, U. and Yonemoto, K.,:"Japan's Robotic Research for the Next Generation."

24. Space Station Reference Cofiguration Document. JSC 19989, NASA, Johnson Space Center, Texas, 1984.

25. NASA Space Station Technology Model, Vol. III., NASA, Washington, 1984.

26. A Manned-Machine Space Station Construction Concept. Tech Memorandum 85762, NASA, Langley Research Center, Virginia, 1984.

27. Space Station Mission Requirements. NASA, Langley Research Cernter, Virginia, June 1984.

28. Evaluation of Automated Decisionmaking Methodologies Integrated Robotic System Simulation, Final Report. NAS1-16759, NASA, Langley Research Center, Virginia, 1984.

29. A Mobile Work Station Concept for Mechanically Aided Astronaut Assembly of Large Space Trusses. NTP 2108, NASA, Langley Research Center, Virginia, 1983.

30. Analysis of Large Space Structures Assembly. NAS8-32989, NASA, Marshall Space Flight Center, Alabama, 1983.

31. Definition of Technology Development Missions for Early Space Station Satellite Servicing, Second Interim Review. NAS8-35081, NASA, Marshall Space Flight Center, Alabama, 1984.

32. Autonomous Rendezvous and Docking, Final Report. NAS8-34679, NASA, Marshall Space Flight Center, Alabama, 1983.

33. Power Subsystem Automation Study, Final Report. NAS8-34938, NASA, Marshall Space Flight Center, Alabama, 1983.

34. Remote Orbital Servicing System (ROSS) Study, Final Report. NAS1-16759, NASA, Langley Research Center, Virginia, 1982.

35. Study of Automated Rendezvous & Docking Technology, Final Report. JPL-955363, Jet Propulsion Laboratory, California, 1979.

36. Application of Advanced Technology to Space Automation, Final Report. NASW-3106, NASA, Marshall Space Flight Center, Alabama, 1979.

37. Design Study of Teleoperator Space Spider, Final Report. NAS8-32620, NASA, Marshall Space Flight Center, Alabama, 1979.

38. Intergrated Orbital Servicing System (IOSS), Final Report. NAS8-30820, NASA, Marshall Space Flight Center, Alabama, 1979.

39. Orbital Construction Support Equipment, Final Report. NAS9-15120, NASA, Johnson Space Center, Texas, 1977.

40. Proto-Flight Manipulator Arm, Final Report. NAS8-31487, NASA, Marshall Fligh Center, Alabama, 1977.

41. Earth Orbital Teleoperator Systems Concepts & Analysis, Final Report. NAS8-31290, NASA, Marshall Flight Center, Alabama, 1976.

42. Orbital Assembly & Maintenance, Final Report. NAS9-14319, NASA, Johnson Space Center, Texas, 1975.

43. EMES: An Expert System in Spacecraft Energy Management. Conference on Intelligence Systems and Machines, Rochester, MN, 1984.

44. Optimization of Parabolic Box Truss Reflector Structures. AIAA 83-0930, 24th AIAA Conference, 1983.

45. Development and Application of the MMU, Work Restraint System, Stowage Container, and Return Line Tether. IAF Paper 81-39, 32nd International Astronautical Federation, 1981.

46. "Many Routes Lend to Flexible Assembly," Assembly Engineering, April 1931, p. 42.

47. "Trend Shifts in Satcom Orbit Position," Aviation Week and Space Technology, March 12, 1984.

48. "Concepts Pondered for Design of "Space Farm," Machine Design, October, 25, 1984, p. 2.

49. "Some Space Stations Should Grow Their Own Food," Machine Design, April 21, 1983, p. 16.

50. "Space Station Data Management: A System Evolving from Changing Requirements and a Dynamic Technology Base," AIAA Computers - Aerospace Conference, Hartford, Connecticut, 1983.

APPENDIX B

ACRONYMS AND ABBREVIATIONS

A&C	Assembly and Construction
ACSE	Assembly and Construction Support Equipment
A/D	Analog-to-Digital
ADP	Automatic Data Processing
AI	Artificial Intelligence
AL	Airlock (Module)
ARE	Air Revitalization Equipment
ASE	Airlock Support Equipment
ATV	Autonomous Transport Vehicle
BAC	Boeing Aerospace Company
BIU	Bus Interface Unit
C&D	Control and Display
CDR	Critical Design Review
CE	Common Equipment
CG	Center of Gravity
CONT	Control
CPC	Computer Program Component
CPCI	Computer Program Configuration Item
CSI	California Space Institute
DBMS	Data Base Management System
DC	Direct Current
DM	Data Management
DMS	Data Management System
DOD	Department of Defense
DOF	Degrees of Freedom
ECLS(S)	Environmental Control and Life Support (System)
EMC	Electromagnetic Compatibility
EP	Electrical Propulsion
EPGS	Electrical Power Generation System
EVA	Extravehicular Activity
FCC	Federal Communications Commission
FOC	Final Operational Configuration
FSS	Flight Support Structure
GE	General Electric
GEO	Geosynchronous (Geostationary) Earth Orbit
GHZ	Gigahertz
GN&C	Guidance, Navigation and Control

HAB	Habitation
HAC	Hughes Aircraft Company
H&H	Health and Hygiene
HLOA	Highest Level of Automation
HM	Habitat Module
H/W	Hardware
H/X	Heat Exchanger
ID	Interface Device
I/O	Input/output
IOC	Initial Operational Configuration
IVA	Intervehicle Activity
JPL	Jet Propulsion Laboratory
KB	Knowledge Base
KBS	Knowledge Based System
KWE	Kilowatts Electrical
LAB	Laboratory
LaRC	Langley Research Center
LDR	Large Deployable Reflector
LEO	Low Earth Orbit
LM	Landmark Mission
LOG	Logistics (Module)
LSS	Life Support System
MBPS	Megabits per Second
MCAT	Man/Computer Access Terminal
MEO	Medium Earth Orbit
MFR	Mobile Foot Restraint
MMC	Martin Marietta Corporation
MMU	Manned Maneuvering Unit
MOD	Module, Modular
MOPS	Millions of Operations per Second
M/P	Manufacturing/Processing
MPM	Manipulator Positioning Mechanism
MRMS	Mobile Remote Manipulator System
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NAU	Nautical
NC	Numerical Control

OCSE	Orbital Construction Support Equipment
ODDNET	Optical Data Distribution Network
OMV	Orbital Maneuvering Vehicle
ORU	Orbital Replacement Unit
OSI	Operator System Interface
OTV	Orbital Transfer Vehicle
PDR	Preliminary Design Review
R&D	Research & Development
RFI	Radio Frequency Interferance
RH	Relative Humidity
RMS	Remote Manipulator System
R&S	Resupply and Storage
R&T	Research and Technology
SDP	Standard Data Processor
SHE	Safe Haven Equipment
SRI	Stanford Research Institute
SRR	System Requirements Review
SS	Space Station
SSAS	Space Station Automation Study
SSS	Space Station System
STS	Space Transportation System (Shuttle)
S/W	Software
TBD	To Be Determined
TBR	To Be Resolved
TDAS(S)	Tracking and Data Acquisition Satellite (System)
TDM	Technology Development Mission
TDRS(S)	Tracking and Data Relay Satellite (System)
TIM	Technical Interchange Meeting(s)
TT&C	Telemetry, Tracking and Control
TWS	Telepresence Work System
VHSIC	Very High Speed Integrated Circuit
WBS	Work Breakdown Structure

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